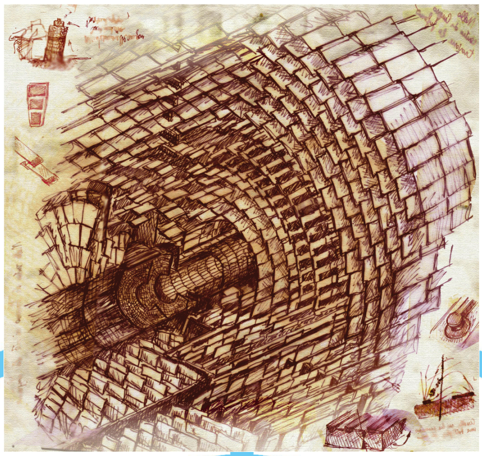
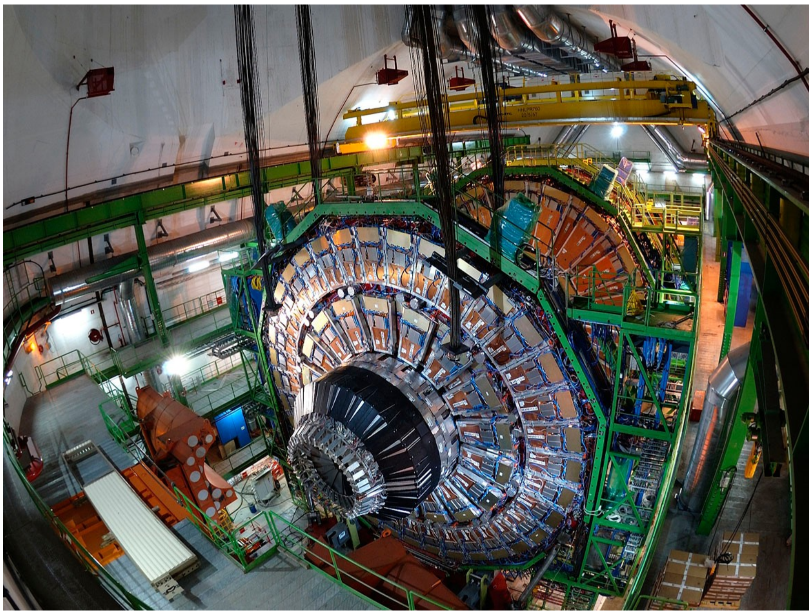


DESY
Summer Student Program 2011

Tracker Alignment at CMS

Report

Leslie Lamberto Lazzarino



Abstract

The CMS tracker is the largest silicon tracker ever built. For its performance to be the best possible, a precise alignment of all its 18000 silicon sensors is crucial. In section "Tracker Overview", a short description of the CMS tracker is given. In section "Alignment Parameters of Sensors and High-level Structures", the track alignment procedure is explained. In section "Software Setup", the software used for the alignment studies is described. In the sections "Bow Parameters Comparison" and "Prompt Alignment", the setup and the results of my studies are presented. In the first one bow parameters determined in the years 2011 and 2010 are compared. The bow parameters have been introduced into the alignment procedure recently, so they haven't been studied as much as other alignment parameters yet. In the second one the dependence of the alignment of high-level pixel structures on the number of tracks used and the effects of additional alignment iterations on the results are studied. Prompt alignment is a fast alignment meant to be performed in the 48 hours time window between data taking and the start of prompt reconstruction.

Contents

1 Introduction

During my stay at DESY I worked in the CMS alignment group. My work results are presented in the sections 5 and 6 of this report.

2 Tracker Overview

2.1 What is a tracker?

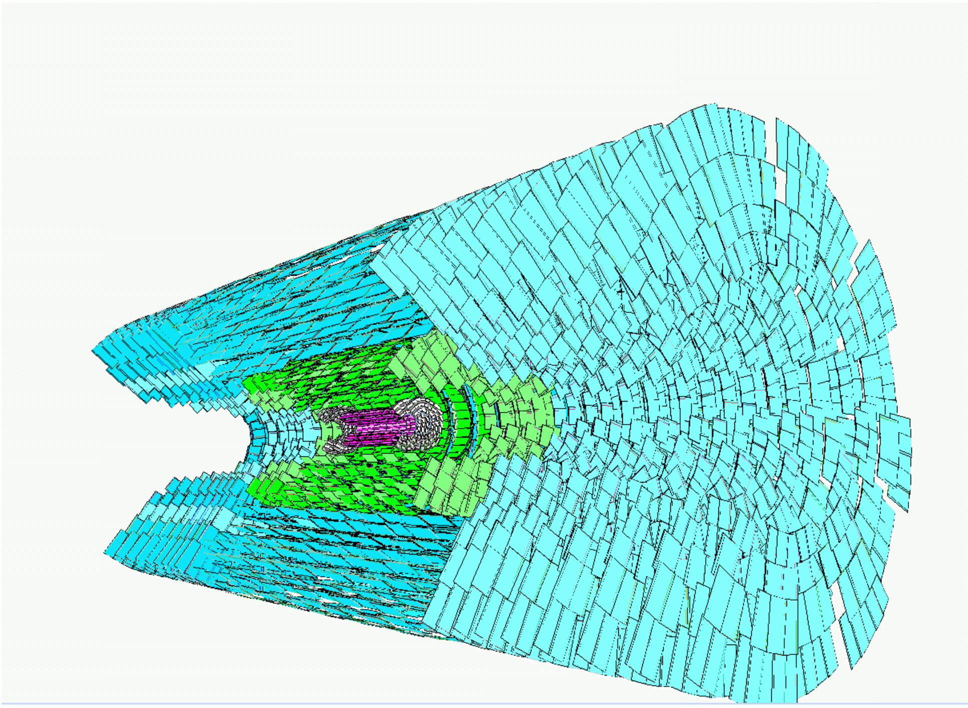


Figure 1: The CMS tracker

A tracker is a detector used in High Energy Physics to measure e. g. the momentum of charged particles. The tracker surrounds the beam pipe, where the nominal interaction point is located, and it operates in a magnetic field generated by a solenoid magnet. The charged particles produced in the collisions traverse the tracker subdetectors, moving along helixes due to the Lorenz force pointing perpendicular to the magnetic field. The detectors measure spatial hits, while a tracking algorithm reconstructs tracks and determinates the particle momentum and vertices. Figure 1 shows the structure of the CMS tracker. The central part (modules are oriented parallel to the beam line) is called barrel, where detectors are placed on cylinders called layers, while the ends (modules are oriented perpendicular to the beam line) are called end caps. There the modules are placed on disks, further subdivided into rings. A tracker isn't made only of measuring devices and beam pipe, but it also contains support structures - e.g. power cables, electronics and cooling systems. The structures are designed to be as light as possible, in order to limit the contribution from multiple scattering.

2.2 CMS Tracker

2.2.1 Main Features

The CMS tracker is a silicon-only tracker. The CMS tracker has a a dimension of 5.4m×2.5m. Other trackers like the ATLAS one use silicon detectors in the inner part, up to one half of the radius, but for the outer parts the gaseous detectors are exploited. The latter are cheaper but have a worse resolution.

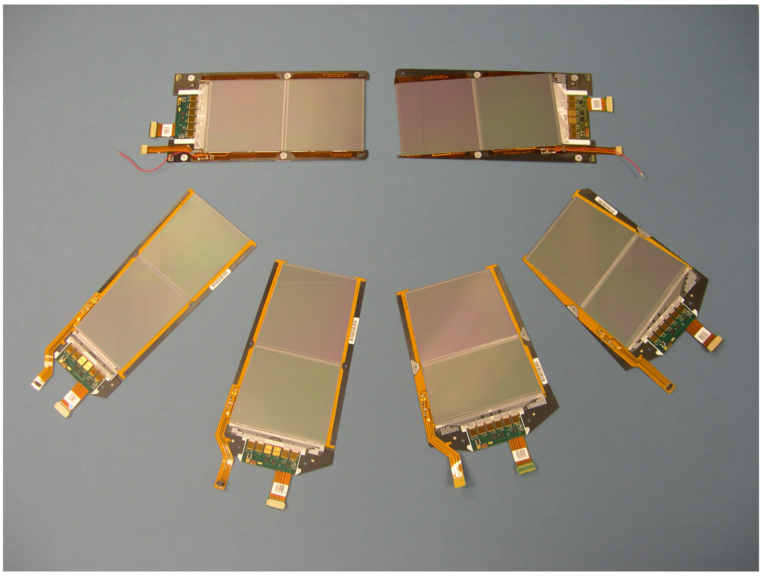


Figure 2: TOB (top) and TEC (bottom) double detectors

The construction of the CMS tracker entirely in silicon was possible because of three reasons:

- the usage in the outer parts of 6 inch strips (previously, only up to 4 inch strips were produced),
- electronics costs drop,
- the usage of an automated mounting process for strips.

The CMS tracker is the largest silicon tracker ever built: it consists of $200m^2$ of silicon modules. It is operated in a 4T solenoidal magnetic field. The tracker is subdivided into 4 main sections: the pixel detector, TIB/TID, TOB and TEC+/TEC-.
During normal operation the silicon sensors are severely damaged by radiations. The amount of the damage is decreased by cooling the modules down to -10C. However, the pixel detectors are designed for a 2 to 3 years operation in the LHC environment, while outer parts are designed for 10 years.

2.2.2 Subdetectors

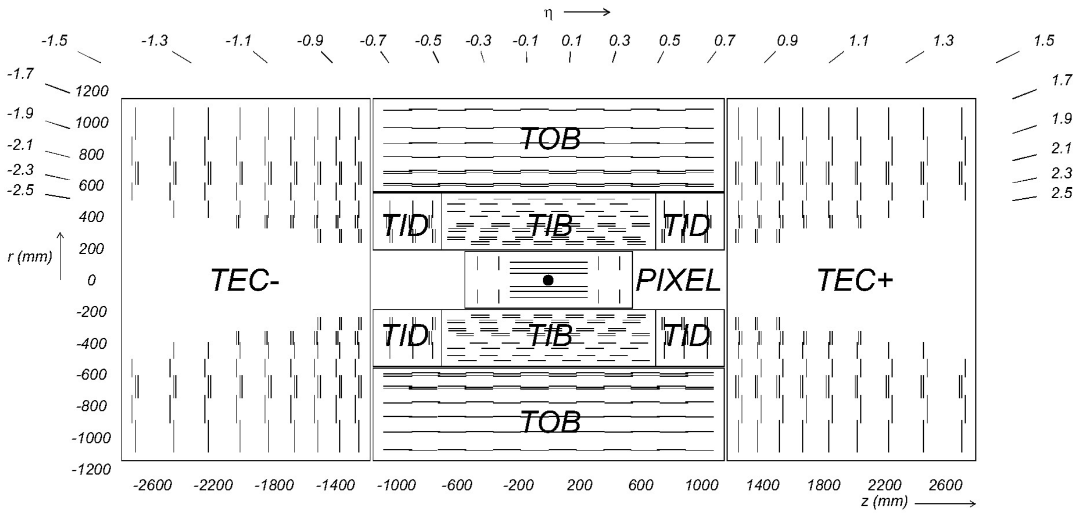


Figure 3: Subdetectors of the CMS tracker: double lines indicate stereo module. These modules provide a precise 2D spatial information

The pixel tracker consists of silicon pixel modules, with a pitch much smaller than that of the silicon strips. It is divided into the barrel pixel tracker (BPIX), composed of 3 layers, and forward pixel tracker (FPIX), composed of 2 disks in each direction. The layer radii are 44mm, 73mm and 102mm, while the disks distances from the nominal interaction point are 34.5cm and 46.5cm, respectively. The pixel modules are $\approx 320\mu m$ thick with a resolution of about $10\mu m$ in the $r\phi$ direction.
The TIB is composed of 4 layers, while the TID is composed of 3 disks. The strip sensors are $\approx 320\mu m$ thick and provide a resolution of $23\mu m$ (inner 2 layers) or $35\mu m$ (outer 2 layers) resolution.
The TOB consists of 6 layers, with silicon strips being $500\mu m$ thick, to provide a better signal to noise ratio. This feature is necessary because of the stronger electronic noise due to the increased strip lenght.
The TEC+/TEC- are composed of 9 disks, with 7 rings of modules labeled 1 to 7 from the innermost one.

2.2.3 Performance

In order to reconstruct tracks and vertices with a precision of a few micrometers it is mandatory that the position of the individual modules is known with a better precision. Therefore, precision alignment is crucial.

3 Alignment Parameters of Sensors and High-level Structures

3.1 Alignment Goal

The goal of Alignment is to determine as well as possible the position and orientation of all tracker sensors. Alignment reduces the impact of sensor misalignment on track quantities. These misalignments disturb the obtained resolution of track reconstruction. Alignment position errors can only be neglected if they are typically one order of magnitude smaller than the intrinsic sensor resolution. Therefore, position uncertainties of a few μm must be obtained. Nowadays, the statistical accuracy of the CMS alignment is so precise that systematic uncertainties start to dominate the overall precision. In former and in recent alignment studies it was found that the sensors in each pixel half barrel move coherently as a function of time. In this report a detailed investigation of the effect of these movements on alignment will be presented in section 6.

3.2 Tracker Alignables

There are two kinds of objects that are aligned - sensors and high-level structures. In the past the moduls in the outer TOB and TEC were treated as one object, even though they consist of two sensors. In the alignment presented here, individual sensors parameters for double modules were determined. High-level structure alignment was introduced to study and to compensate for correlated misalignments. Three levels of high-level structures exist:

- small support structures on which sensors are glued like rods in the barrel or petals in the end caps,
- bigger support structures where small support structures are assembled like half layers in the barrel and half disks in the pixel end caps,
- the six subdetectors, where bigger support structures are assembled.

High-level structures are used for various reasons: they are useful for alignment studies of large stucture movements which is e.g. usefull if the number of tracks is only limited. Thus, the movements of high-level structures as a function of time, that was discovered in previous alignment studies, can be monitored during data taking, with reasonably small track statistics.

3.3 Alignment Parameters

There are three types of alignment parameters considered for sensors: shift parameters, rotation parameters and bow parameters. Shift parameters are called u, v and w as indicated in figure 4.

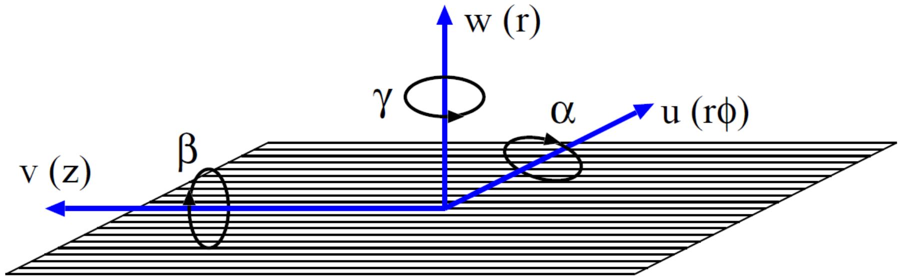


Figure 4: Shifts and Rotations

u is the direction in which the more precise resolution is achieved (usually $r\phi$, may vary e.g. for modules mounted on petals (figure 5) and stereo modules, which are double modules, one over the other with a little rotation angle relative to each other, used to have 2D measurements), v is the direction in which the less precise resolution is achieved (usually z in the barrel, r in end caps). w is the direction normal to the surface, where no measurement information exist. Shift parameters are usually measured in cm.

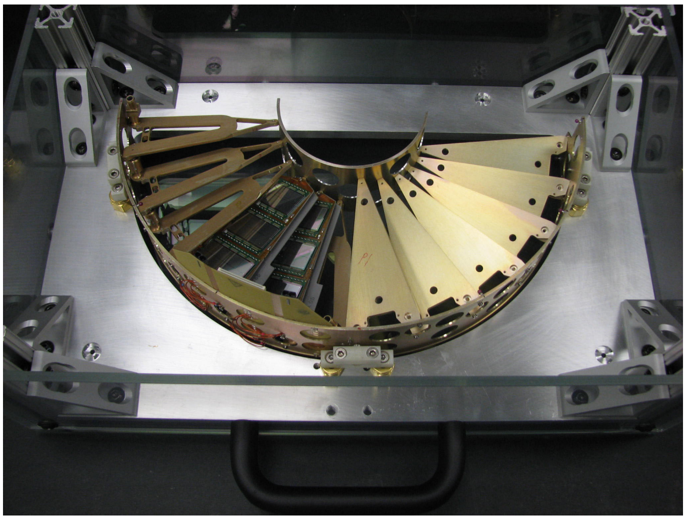


Figure 5: FPIX Petals

Rotation parameters are called α, β and γ. The variable α is the rotation around u direction, β around v and γ around w. Rotations are usually measured in radiants. Bow parameters are called w_{20}, w_{02} and w_{11}, their definitions are shown in figure 6.

w_{20} is the bow in the u direction, w_{02} is the bow in the v direction, w_{11} is the mixed term. Bows are second order shape corrections. The latter can be parametrised with coefficients of a second-order polynomial. Bow parameters are expressed in terms of sagitta, which is the distance between sensor edges and middle points in the z direction in figure 6). Typically all 9 parameters are determined, so modules have 9 or 18 (double modules) parameters determined, except for FPIX modules, where no bow parameters

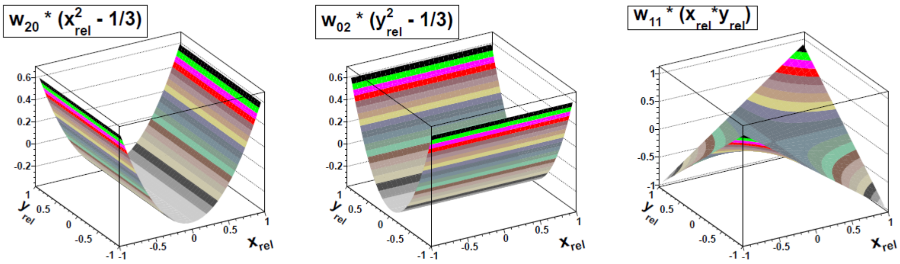


Figure 6: The Bow Parameters

are determined due to a low track statistic in that region. For high-level structures only shifts and rotations are determined. The high-level structure position is defined as the mean position of all its subcomponents. There's an interesting thing to note: some coordinates are better determined than others, for example usually u is better determined than w. This does not necessarily result in a bias because the CMS tracker was designed such that regions which are more sensitive to track parameters were equipped with sensors with high spatial resolution.

3.4 Alignment Procedure

The starting information are given from the mounting precision and the initial survey. We have large uncertainties in these measurements, due to uncertainties in each level of assembling. For example in the end caps the mounting uncertainties of sensors to petals, petals to half disks, half disks to subdetectors are adding. After commissing the position information are given by the LAS. The laser alignment system has a precison in theory of $100\mu m$. Only some position measurements are provided by the LAS: it doesn't provide information about pixel subdetectors and TIB and TOB internal misalignments. Due to the limited spatial information provided by the LAS and the mounting precision a track-based alignment procedure is mandatory. The aim of track based alignment is to reduce the global χ^2, determining both sensor and track parameters. Cosmic muons are also used to improve results and decrease the correlation between displacements because there are displacements of sensors which have the same χ^2 and are indistinguishable with only collision tracks. Also beam halo tracks are sometimes used, to connect different part of the tracker. Hierarchy alignments are introduced as constrains: sensors movements are allowed only if they don't change the position of the corresponding high-level structure, else the high-level structure is moved.

4 Software Setup

4.1 Millepede II

The program Millepede II is used for the determination of alignment parameters. Millipede solves the alignment problem with 20000 modules in a reasonably short time of typically a few hours. It was initially developed to have a fast solution of an alignment problem with 13000 modules and 60000 alignment parameters at the beginning, one order of magnitude more than in previous HEP experiments. Now due to the determination of bow parameters around 200 000 parameters have to be determined. For Millepede II the problem has to be linearized. In order to compensate for large misalignments, iterations are sometimes necessary. The minimization of the global χ^2 leads to a system of millions of equations (one for every local track parameter), plus n for the global parameters. The particular shape of the matrix representing the system is exploited to solve the problem. Millepede II consists of two independent tools: Mille and Pede.

4.1.1 Mille

Mille is a software written in C++ (however, also a Fortran-version exists), and it is used to collect the data. Not all input tracks are used, badly reconstructed ones are rejected, and various cuts can be applied on track candidates. Mille interfaces directly with the CMS software framework.

4.1.2 Pede

Pede is a high-performance Fortran program. It is a multi-threaded software, used for solving the alignment problem. It takes data from the Mille binaries without interacting with the CMS software framework directly. Pede itself is experiment independent.

4.2 Root

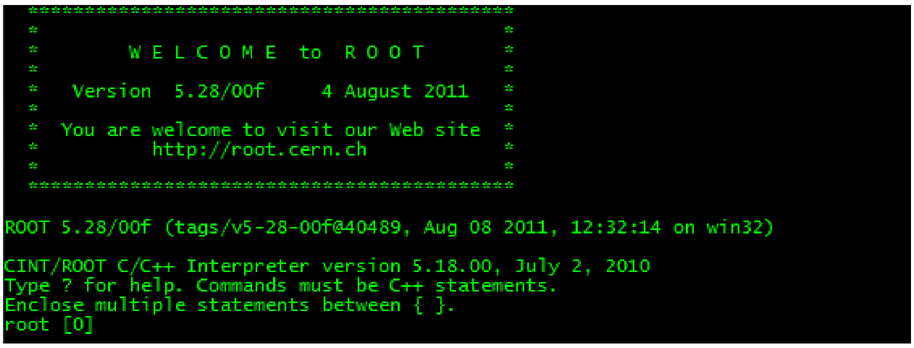


Figure 7: The ROOT Shell Interface at Start Up

ROOT is an open source framework for data processing, developed at CERN. Now it is a program with a seventeen years development history used by nearly every HEP physicist in the world. In this report ROOT 5.28 (figure 7) was used to make all the histograms and plots in sections 5 and 6. For section 5 histogram production and section 6 data manipulation the ROOT classes PlotMillepede and CompareMillepede were used as provided by the CMS software framework.

5 Alignments Comparison

5.1 Data Sets

In the following three alignments are compared: "TBDkbMinBias", "TBDkb" and "2010full". TBDkbMinBias and TBDkb have similar alignment configurations. The first one is the new 2011 alignment that will be used for the next rereconstruction, while the second one was one of the other candidates. The difference between the two is induced by the used track sample: TBDkbMinBias uses additionally 3 million low momentum tracks. "2010full" is an alignment done using mostly minimum bias and cosmic muons tracks from 2010 (until summer). I plotted for each sensor on the X axis the bow parameters from TBDkbMinBias, on the Y axis the bow parameters from the other alignment. If there are six plots shown in two rows, than this means that for single modules and double modules the first set of sensor parameters are shown in the first row, whereas for double modules the second set of sensor parameters are shown in the second row. Therefore the plots show the correlations between the bow parameters determined in those two alignments. If there would be a perfect correlation between the alignments results, all histogram points would have been on the diagonal, meaning that determined parameters are exactly the same. In the case of missing correlation, the points form an irregular shaped lump (with center on the diagonal). Systematic effects could cause an overall bias.

5.2 Results

5.2.1 TBDbkMinBias vs. TBDkb

I've compared the results for the five subdetectors of the tracker (as I said before, in FPIX bow parameters aren't determined).

- For all barrel sub detectors (BPIX, TIB, TOB) and for TID the determined bow parameters are very similar. In the figures 8 and 9 you can see results for BPIX and TOB).
- For TEC, some systematic deviations for w_{20} parameter are observed for the double sensors (rings 5-7, figure10), while for the single sensors in rings 1-4 the correlation is as good as for the barrel detectors.

I have further analyzed the results for the outer rings of TEC, in order to better locate and understand the problem.

- Rings 5 and 6 look like rings 1-4 with a pronounced correlation, while systematic differences in TEC are limited to the 7th ring (figure 11).
- There is not only the systematic displacement visible, but also the distribution of the differences of the parameters is not following a normal distribution, like for other sensors parameters and for the w_{02} and w_{11} parameters, but we have a distribution similar to a truncated normal distribution (figure 12).

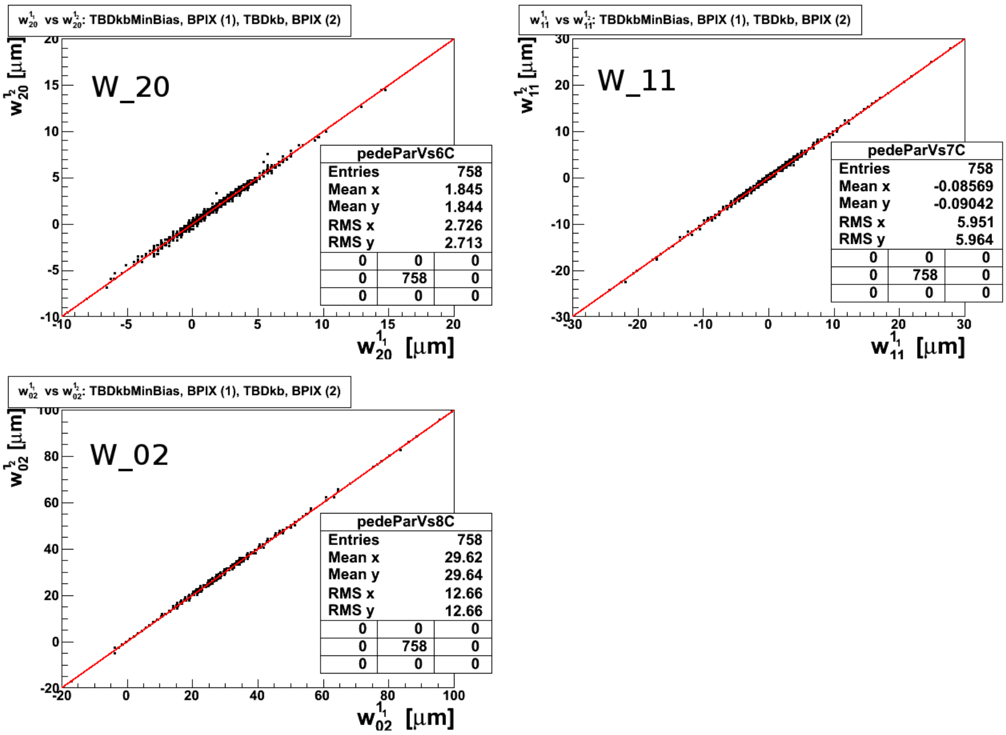


Figure 8: TBDkbMinBias vs. TBDkb: BPIX

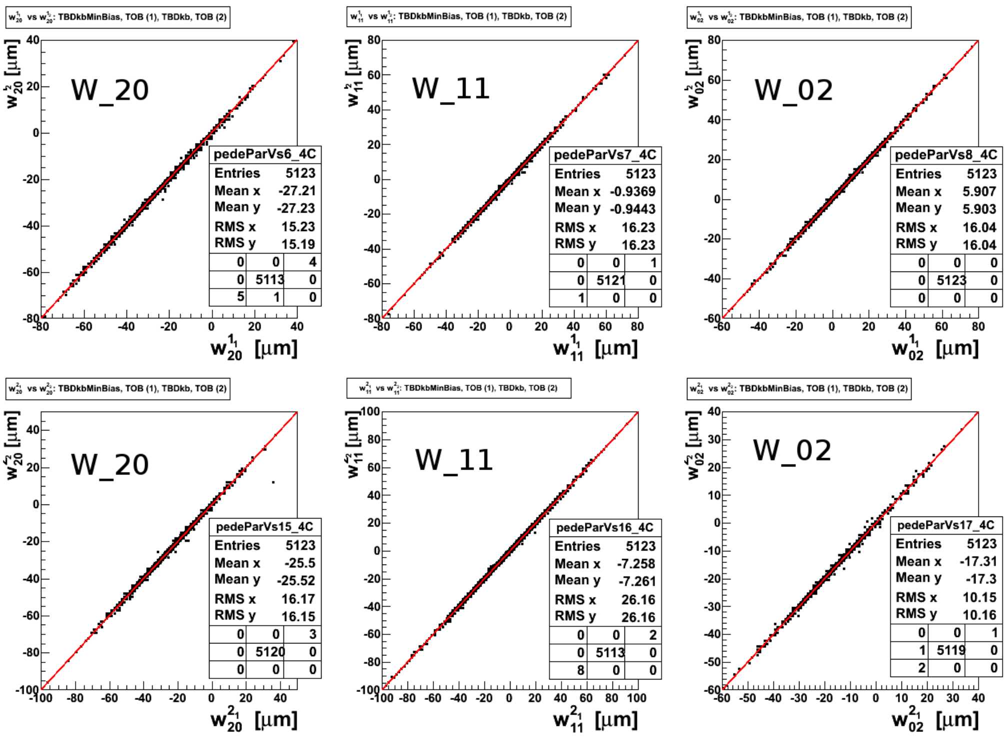


Figure 9: TBDkbMinBias vs. TBDkb: TOB

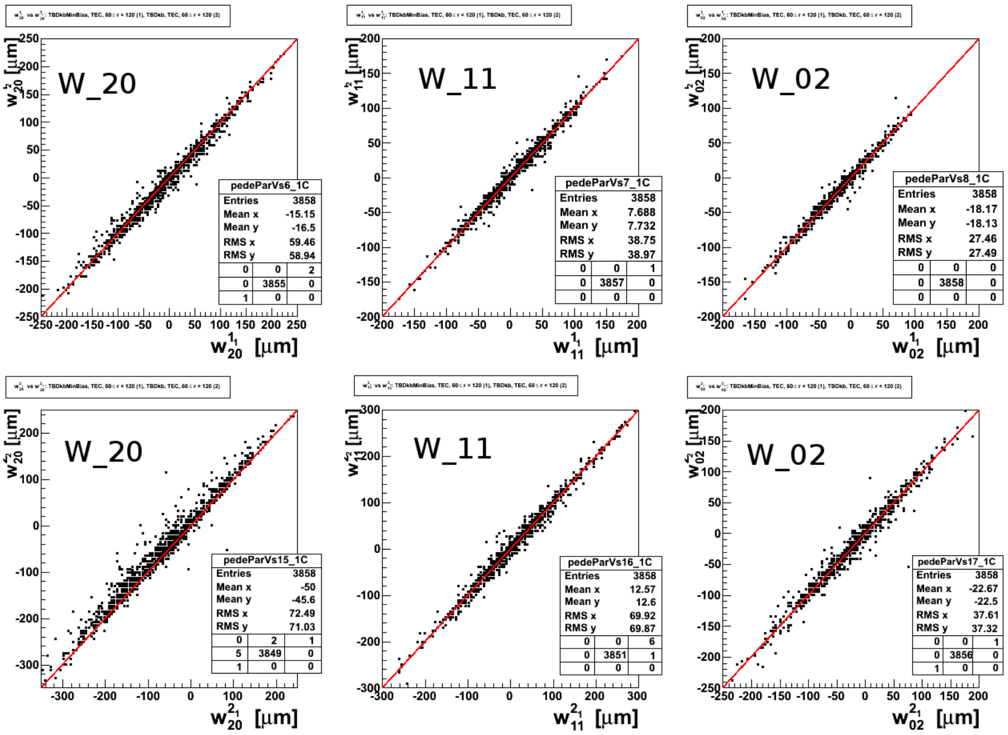


Figure 10: TBDkbMinBias vs. TBDkb: TEC, rings 5 to 7

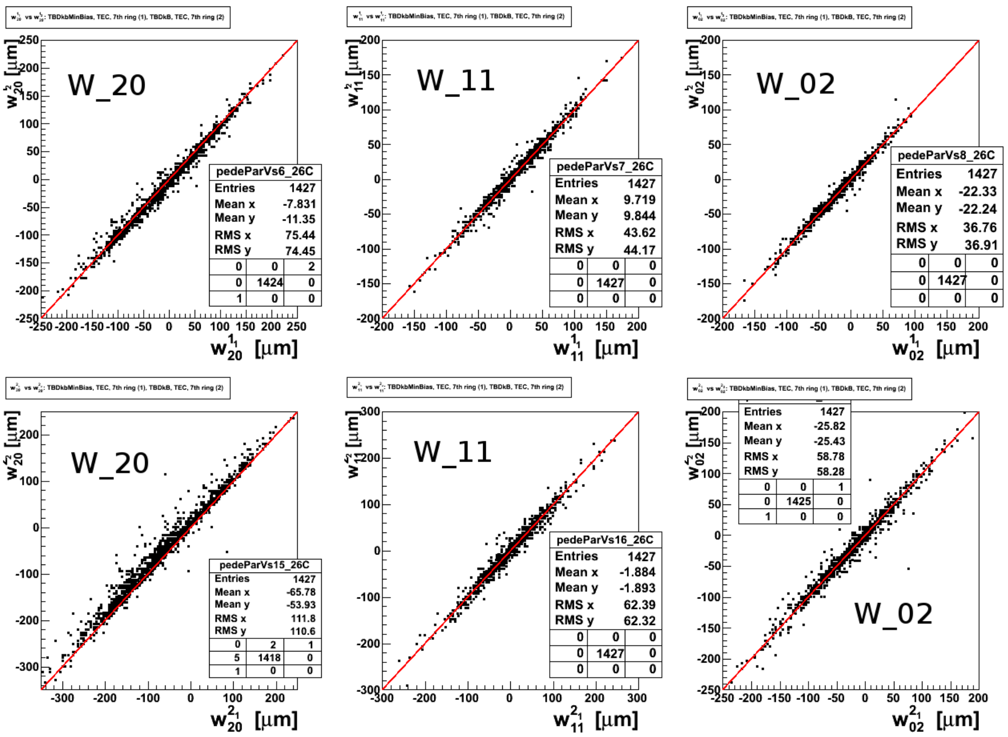


Figure 11: TBDkbMinBias vs. TBDkb: TEC, 7th ring

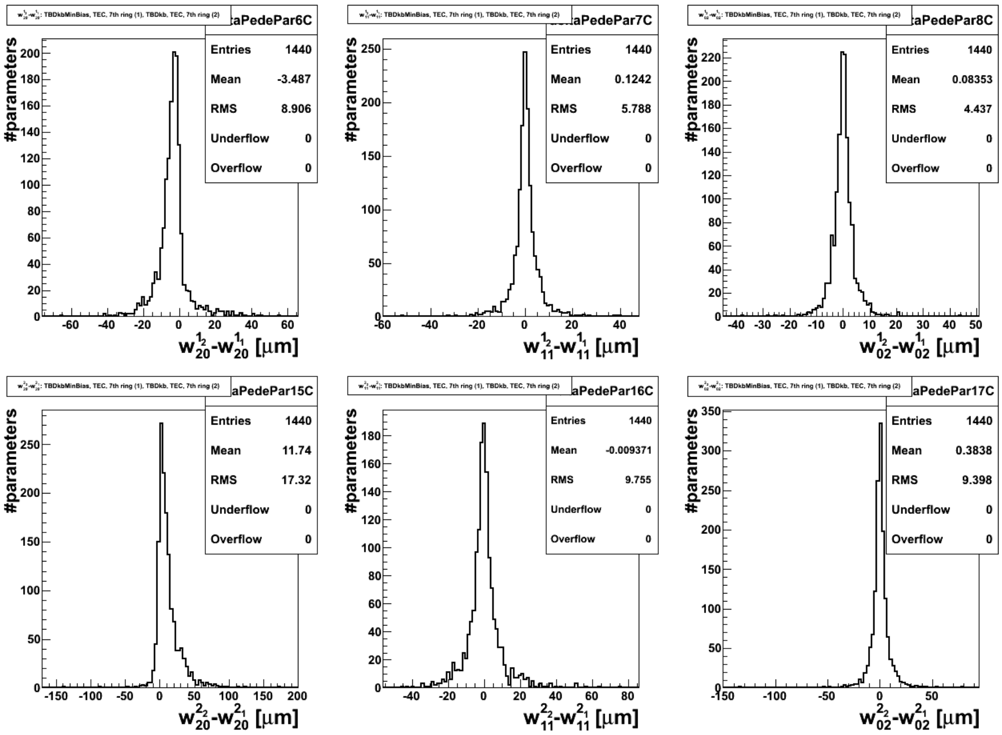


Figure 12: TBDkbMinBias vs. TBDkb: TEC, ring 7, delta

- We can see nearly exactly the same effect in TEC+ and TEC- (figures 13 and 14). Even the mean displacement is the same, with differences smaller than 4%.

This interesting result for TEC ring 7 is probably related to the worse accuracy of Millepede in the determination of alignment parameters for the outer layers. This is due to the fact that the 7th ring is the outermost layer. Thus here the outmost hits of the tracks are measured. However, the absolute contribution of the effect is negligible compared to the observed sagittas range (-200 to 200 μm): w_{20} for first sensors has a $-3\mu m$ mean difference, w_{20} for second sensors has a $11\mu m$ mean difference.

5.2.2 TBDbkMinBias vs. 2010full

The differences between the two TBDbk and 2010full results are, as expected, much bigger than between the two 2011 alignments. Rather different results were obtained depending on the subdetector considered. For BPIX we have a good correlation for the w_{02} and w_{11} parameters, but only a less pronounced correlation for the w_{20} parameter (figure 15).

This small correlation is caused by the relatively small sagittas for w_{20}, which are in the order of $10\mu m$. Further investigations showed that the situation is exactly the same in all the three pixel layers.

For TIB (figure 16)and TID (figure 17) we can see a good correlation between the results.

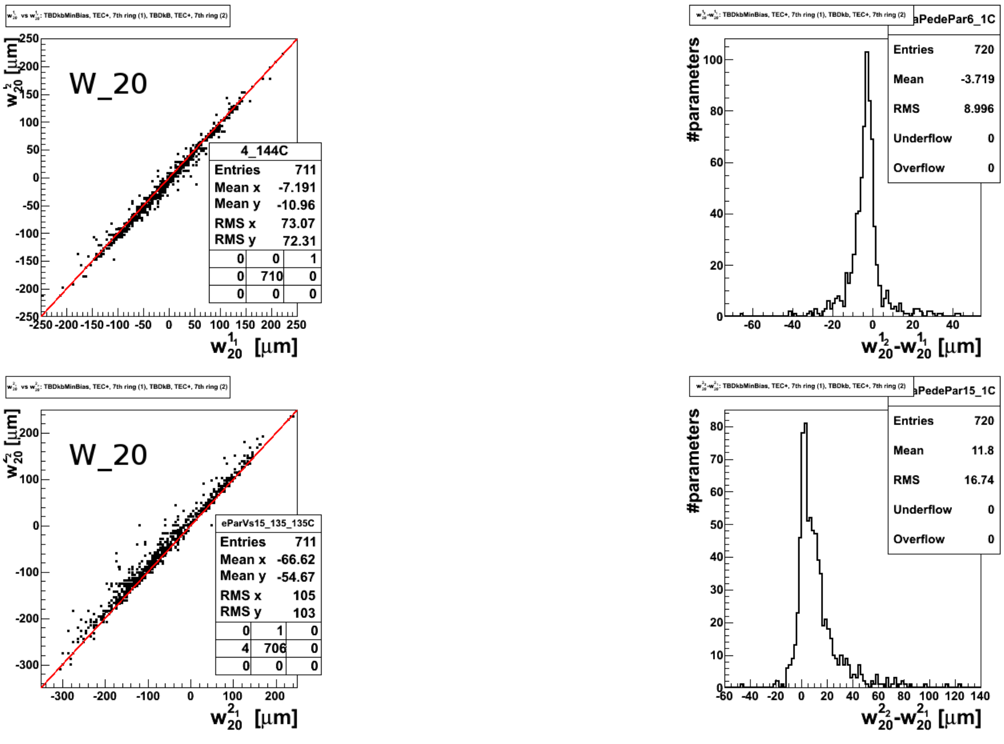


Figure 13: TBDkbMinBias vs. TBDkb: TEC+, ring 7

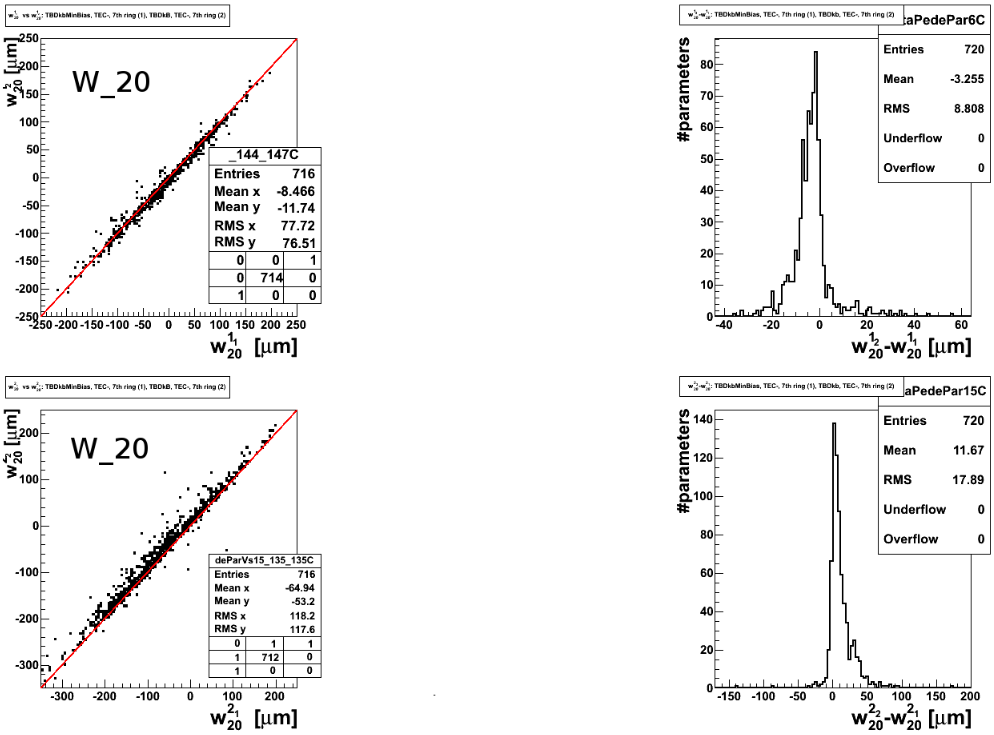


Figure 14: TBDkbMinBias vs. TBDkb: TEC-, ring 7

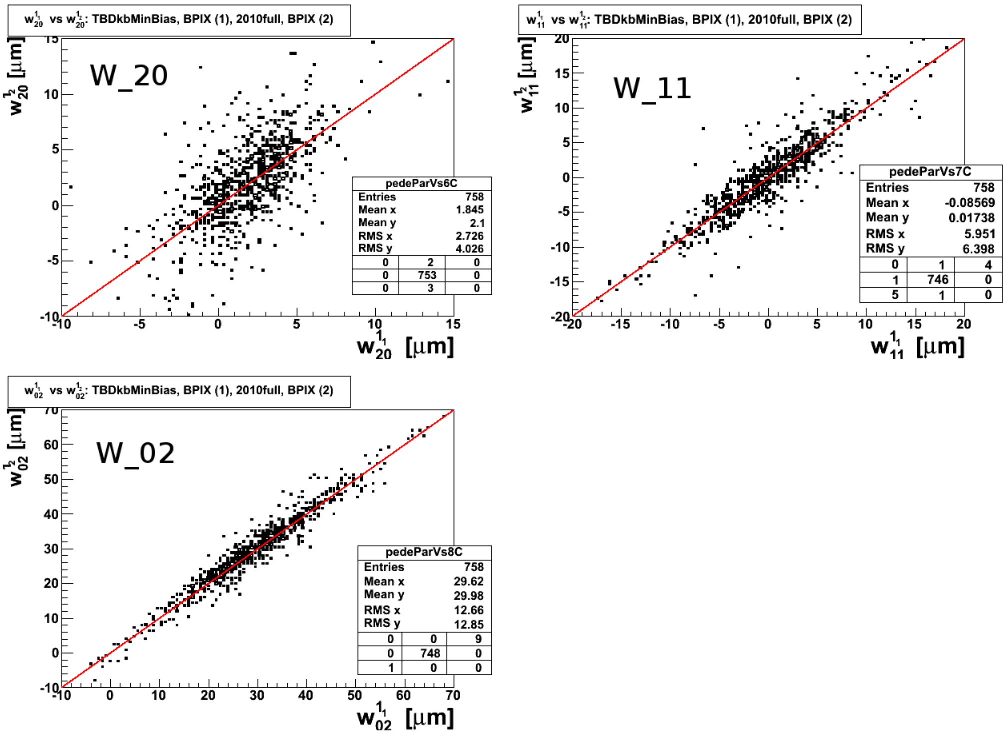


Figure 15: TBDkbMinBias vs. 2010full: BPIX

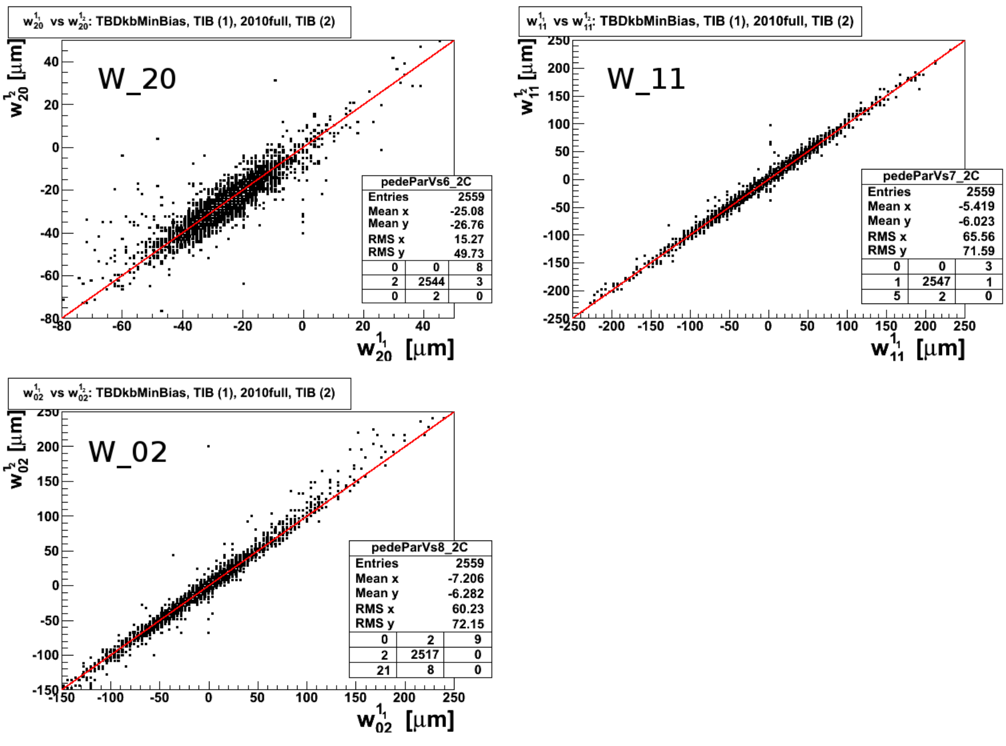


Figure 16: TBDkbMinBias vs. 2010full: TIB

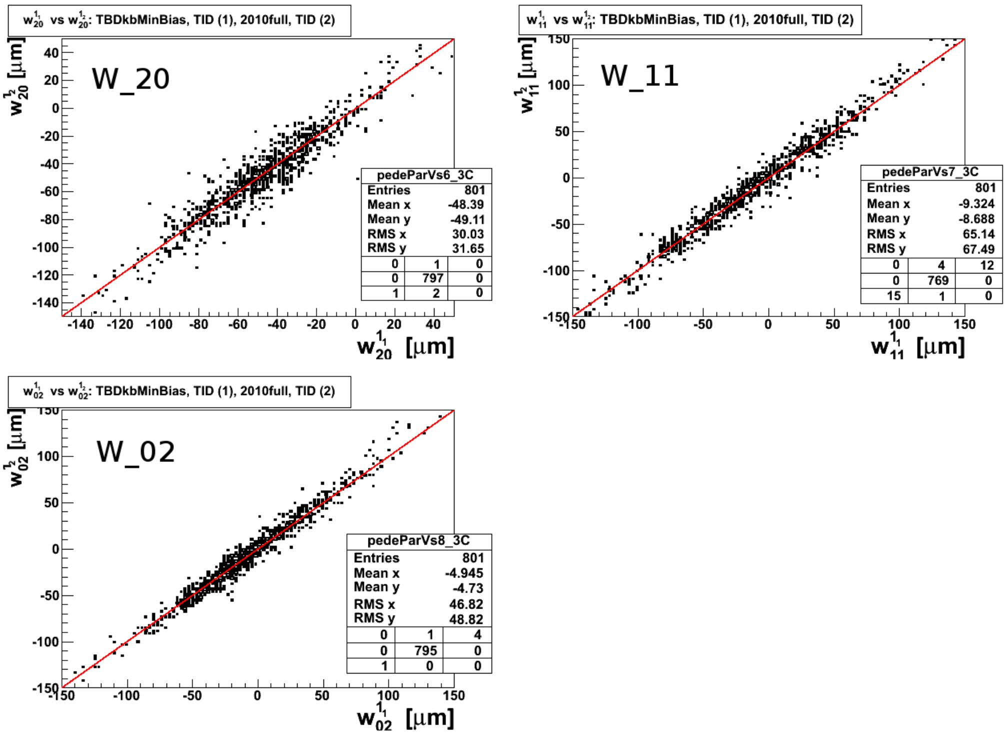


Figure 17: TBDkbMinBias vs. 2010full: TID

For TOB, the overall correlation is worse (figure 18).

The correlation seems to decrease from layer 1 to layer 6. We have good correlation for layers 1 and 2 (figure 19), less correlation for layers 3 and 4 (figure 20), and worse for layer 5 (figure 21)and 6 (figure 22): especially in layer 6 we can see only a tiny correlation.

For TEC we have results similar to the TOB. The correlation seems to decrease with increasing ring number. There is mostly a reasonable correlation for rings 1 to 4 (figure 23).

In ring 5 there is a good correlation for some bow parameters (w_{20} and w_{11} for the first sensor, w_{11} for the second) but it is worse for others (w_{20} and w_{02} for the second sensor, w_{02} for the first one) (figure 24).

In rings 6 (figure 25) and 7 (figure 26) there is little correlation for any bow parameter.

5.3 Conclusions

Comparing TBDkbMinBias and TBDkb the results for the bow parameters look very similar. However, w_{20} in TEC ring 7 exhibits small systematic differences, which are similar in TEC+ and TEC-. Comparing TBDkbMinBias and 2010full pronounced correlations for the inner detectors are observed. However, in TOB and TEC the situation gets worse at larger radii, which is true especially in TEC ring 7.

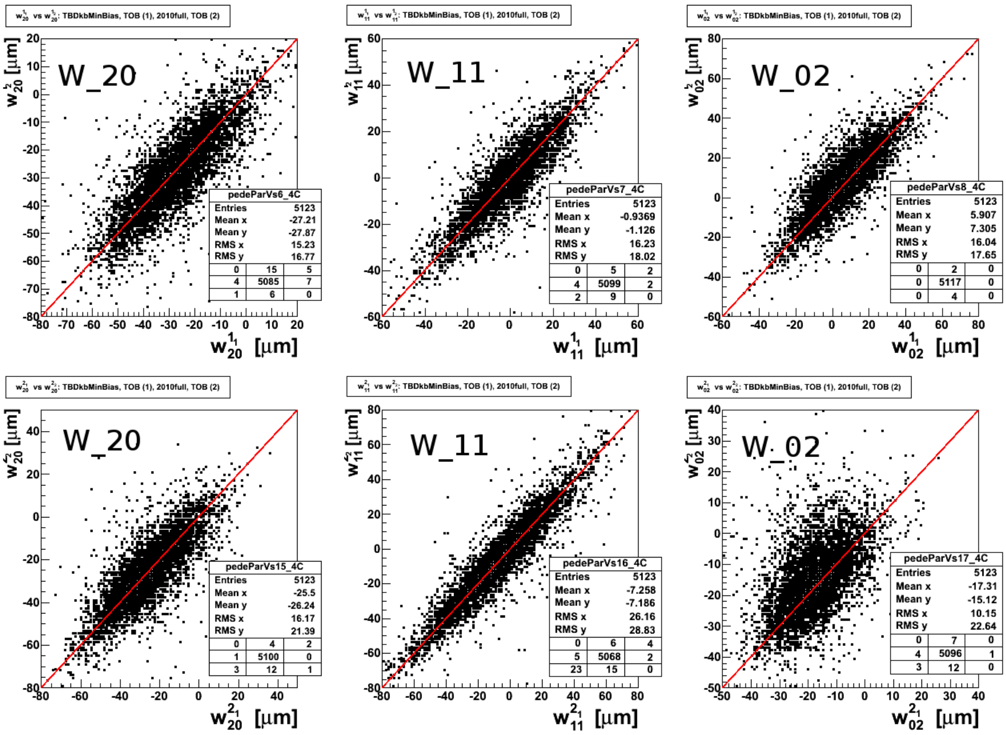


Figure 18: TBDkbMinBias vs. 2010full: TOB

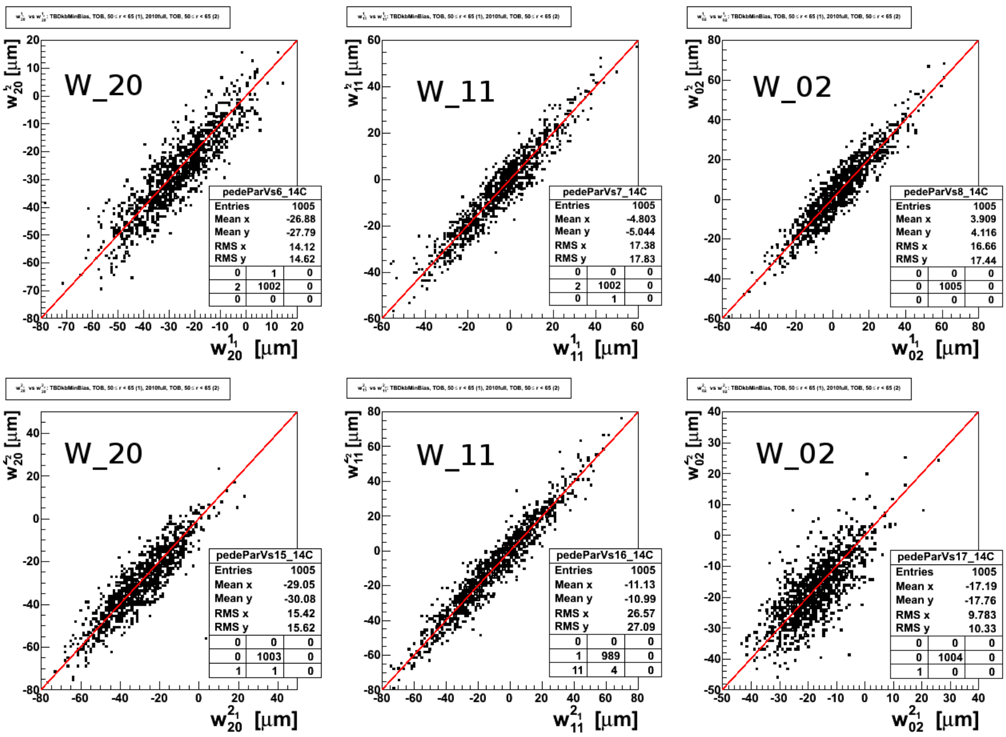


Figure 19: TBDkbMinBias vs. 2010full: TOB, 1st layer (2nd layer is similar)

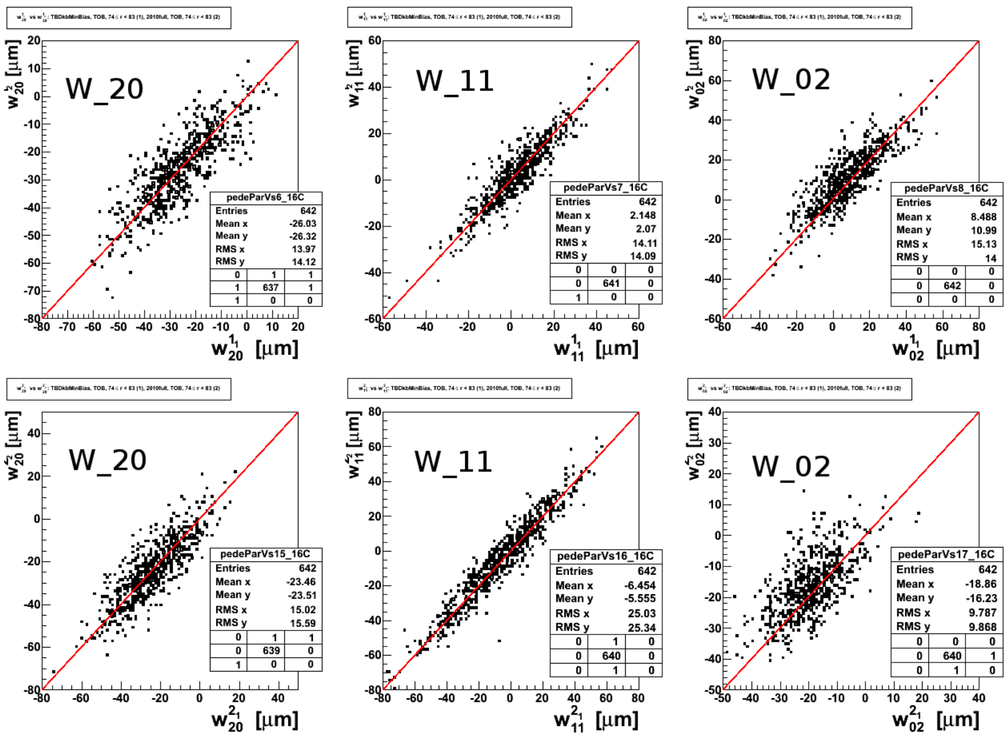


Figure 20: TBDkbMinBias vs. 2010full: TOB, 3rd layer (4th layer is similar)

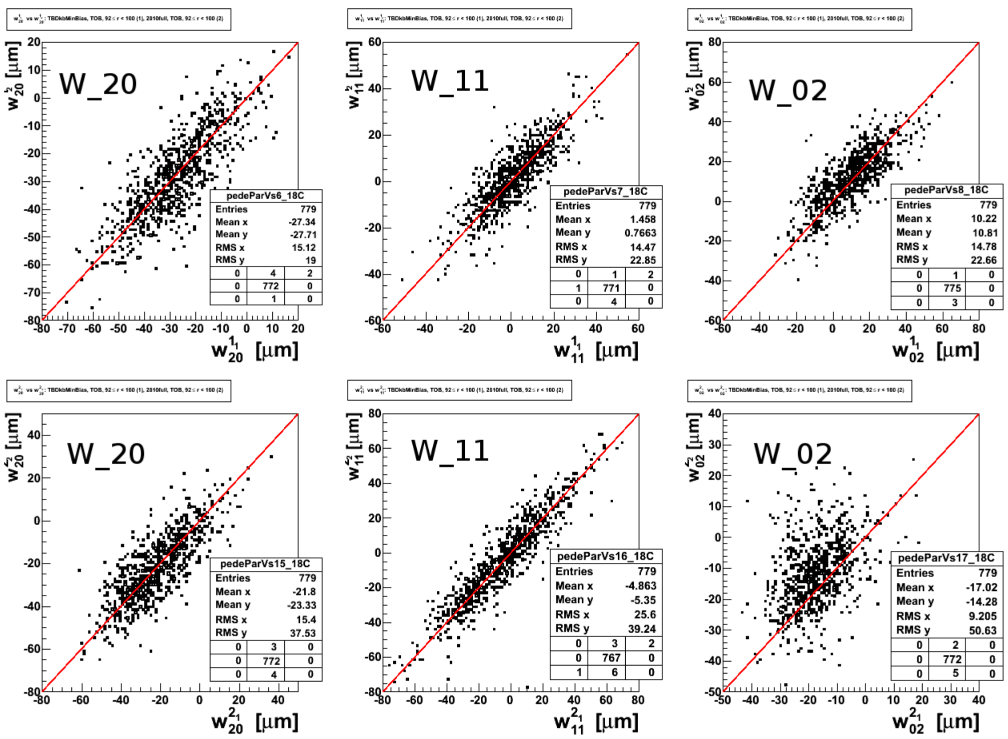


Figure 21: TBDkbMinBias vs. 2010full: TOB, 5th layer

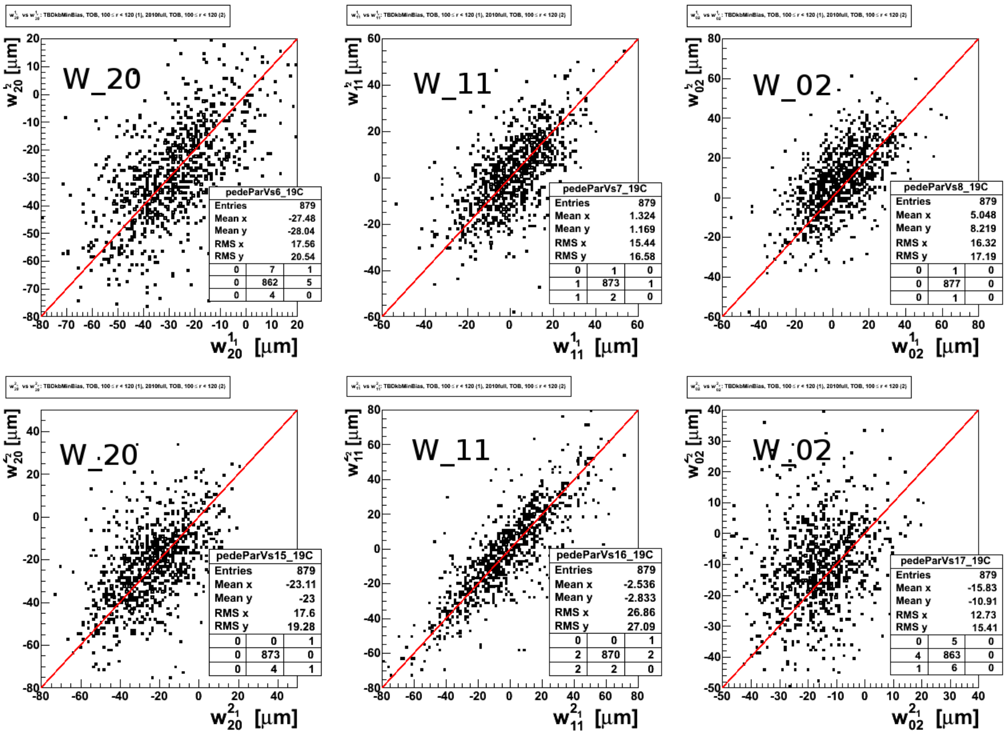


Figure 22: TBDkbMinBias vs. 2010full: TOB, 6th layer

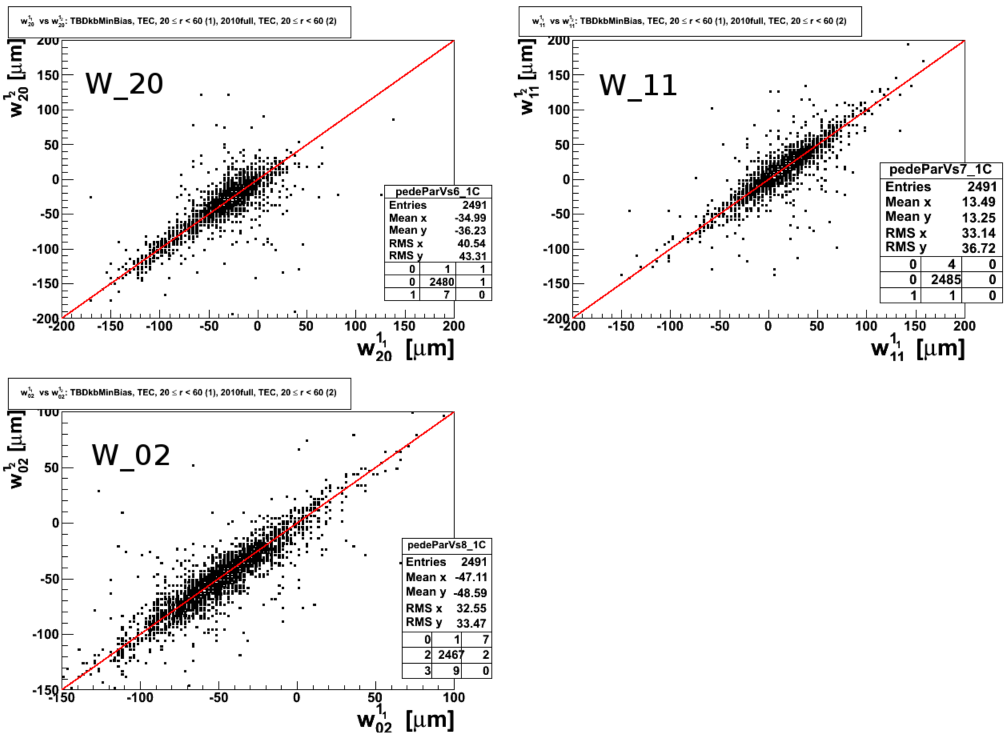


Figure 23: TBDkbMinBias vs. 2010full: TEC, rings 1 to 4

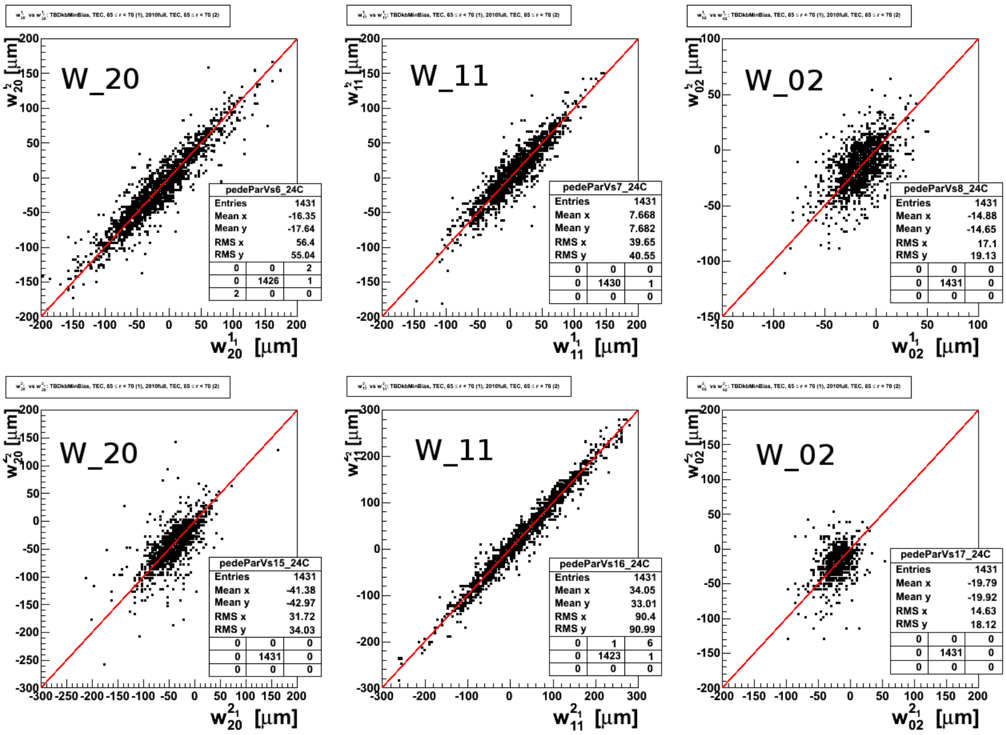


Figure 24: TBDkbMinBias vs. 2010full: TEC, 5th ring

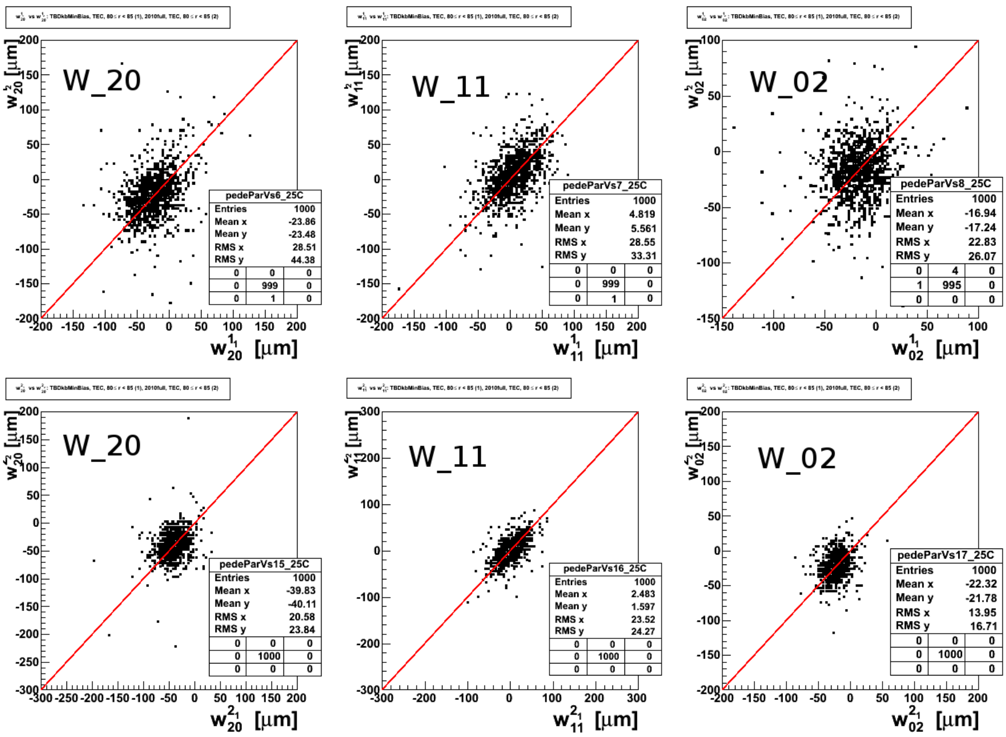


Figure 25: TBDkbMinBias vs. 2010full: TEC, 6th ring

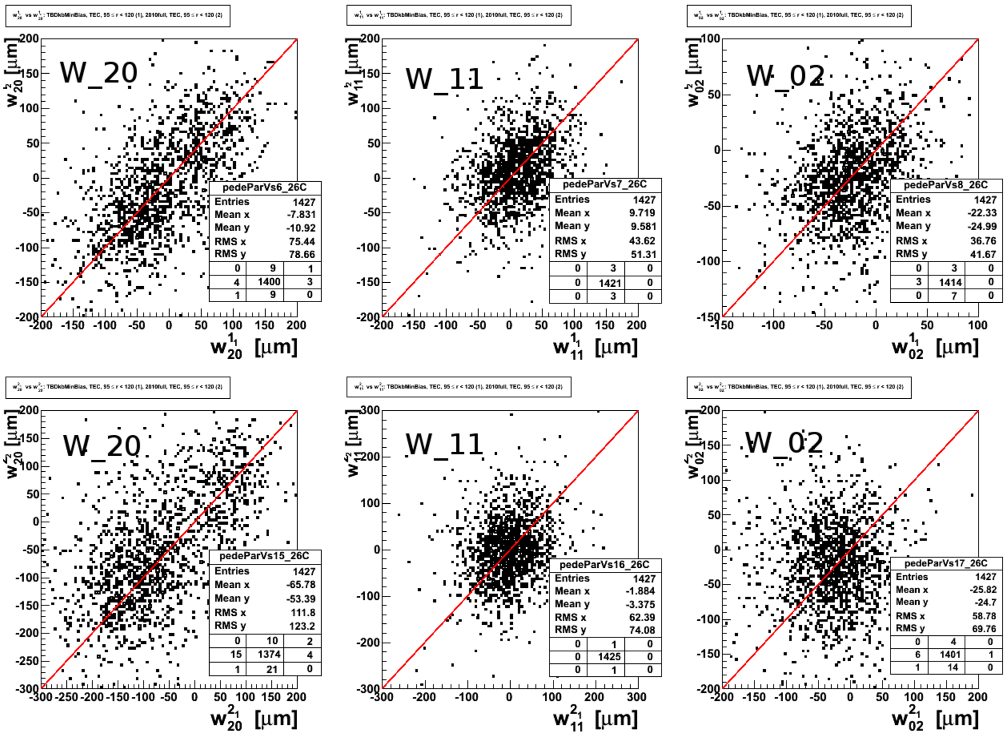


Figure 26: TBDkbMinBias vs. 2010full: TEC, 7th ring

6 Prompt Alignment

6.1 Purpose of Prompt Alignment

In recent alignment campaigns in 2010 and 2011 it was found that the high-level structures in pixel detector (6 half layers and 8 half disks) move in time. Their movements, even in a few months, are quite large (up to $50\mu m$ or $40\mu rad$).
Two reconstructions are performed after the data taking: express reconstruction and prompt reconstruction. The first one takes place immediatly after data taking, while the second one is performed 48 hours after data taking. If it would be possible to run an alignment in that time window, the prompt reconstruction would have been improved. However, full alignment is really processor-time consuming, therefore a simplified alignment procedure has to be found in the following. This fast alignment procedure is called "Prompt Alignment" in the following.

6.2 Approach

I made some studies with misalignment scenarios to simulate prompt alignment situations. Tracks of loosely selected muons were used. This means that not only muons are selected, but also the tracks of other particles. This simulates the kind of data selection we can make right after the data taking with express reconstruction results. The tracks used are from the runs 163078-164060, taken between April 9th to May 4th. The start geometry is the new 2011 alignment foreseen for the next re-reconstruction.

6.3 Results

I have studied two misalignment scenarios, one with misplacements compatible with observed pixel movements and one with much larger misplacements. I have called the first one "Reasonable Scenario", the second one "Testing Limits Scenario". Then I tried to iterate the alignment on the obtained results, to see if significant improvements are achieved.

6.3.1 Reasonable Scenario

The misalignments used are chosen to be compatible with observed movements (figure 27).

For BPIX I have chosen misplacements of $5-10\mu m$ for u, $12-17\mu m$ for v, $50-60\mu m$ for w, with opposite signs for different half barrels. This is only one kind of pixel movement seen, also movements in the same direction have been spotted. The results you can see in figure 28

For FPIX I chose misplacements of $5\mu m$ for u, $10\mu m$ for v, $40\mu m$ for w, with all movements away from the nominal interaction point. The results you can see in 29

With $\approx 10^5$ tracks the remaining misalignments are smaller than 5%, which is equivalent to $3\mu m$. Residual differences are even smaller than needed. Increasing tracks number results in very small further improvements.

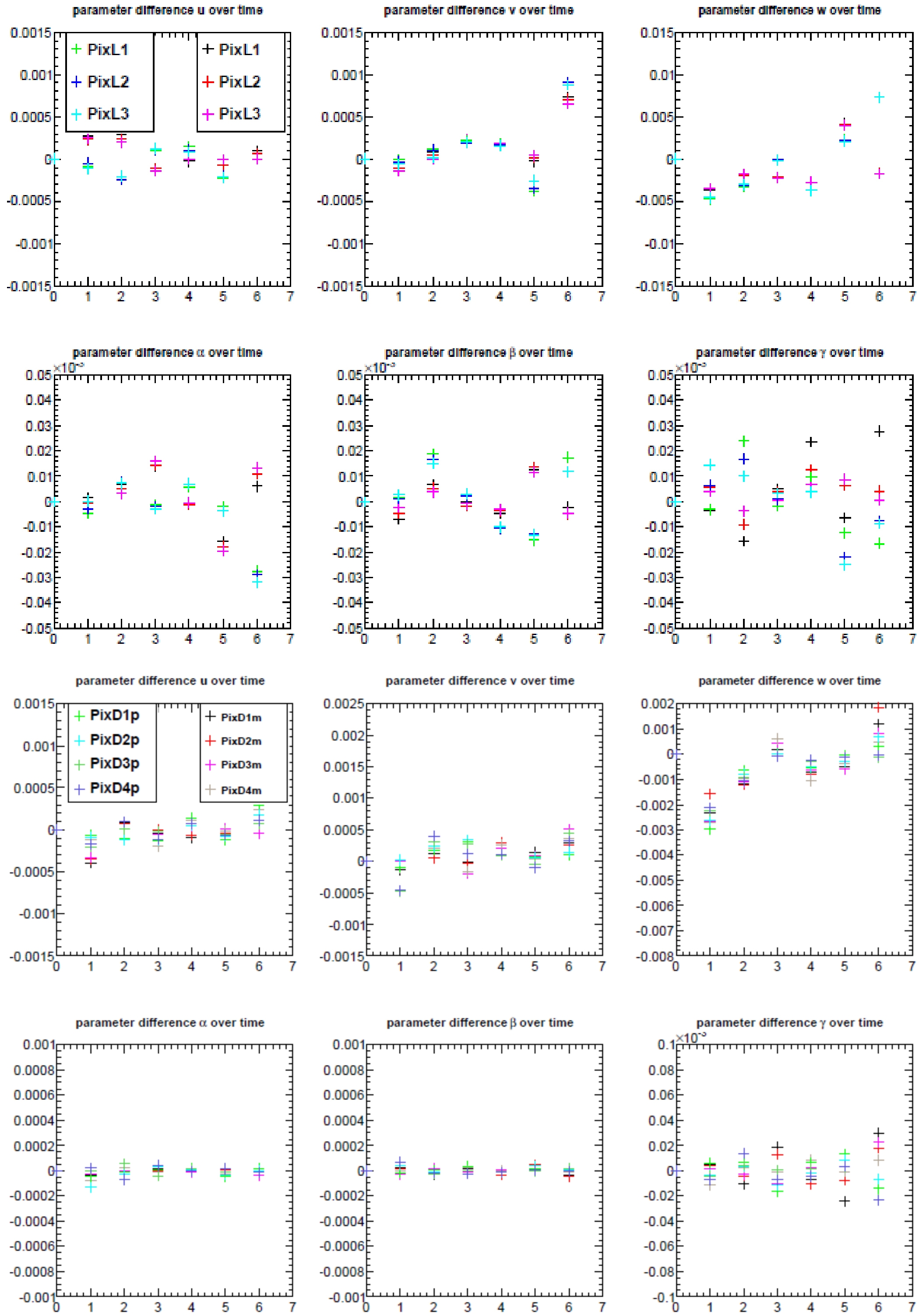


Figure 27: Time movements plots by Jula Draegers

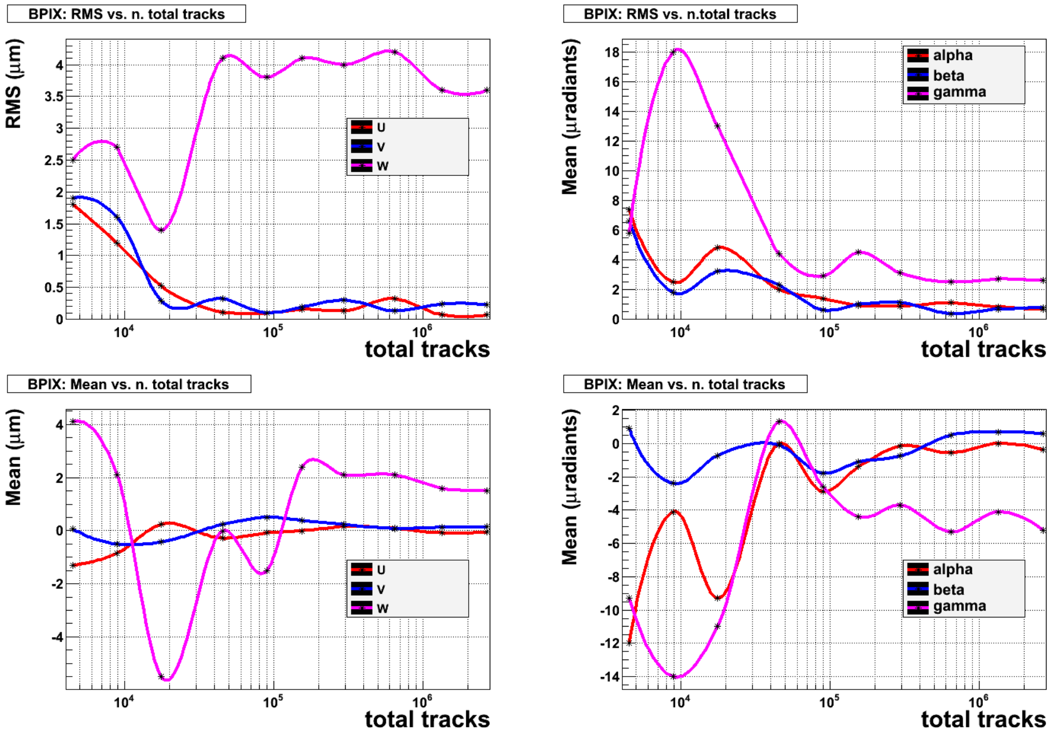


Figure 28: Reasonable Scenario: BPIX results

6.3.2 Testing Limits Scenario

The misalignments used are chosen to be much larger than observed movements. For BPIX I have chosen misplacements of $40-70\mu m$ for u, $300-400\mu m$ for v, $90\mu m$ for w, with opposite signs for different half barrels. The results are depicted in figure 30.

For FPIX I have chosen misplacements of $5\mu m$ for u, $10\mu m$ for v, $40\mu m$ for w, with all movements away from the nominal interaction point. The results you can see in figure 31.

With $\approx 10^5$ tracks the remaining misalignments is worse than in the Reasonable Scenario, especially for RMS ($\approx \times 10$). Increasing tracks number doesn't improve the results.

6.3.3 Testing Limits Scenario Iteration

The first iteration I tried was with the Testing Limits Scenario results, to see if they improve. I used the parameters obtained with 2.5×10^6 tracks, and I used the same number for the iteration. Iteration results comparison with Testing Limits Scenario results is shown in figure 32 for BPIX and in figure 33 for FPIX.

As you can see both mean and RMS are much smaller:the mean is similar to Reasonable Scenario, while the RMS is even better.

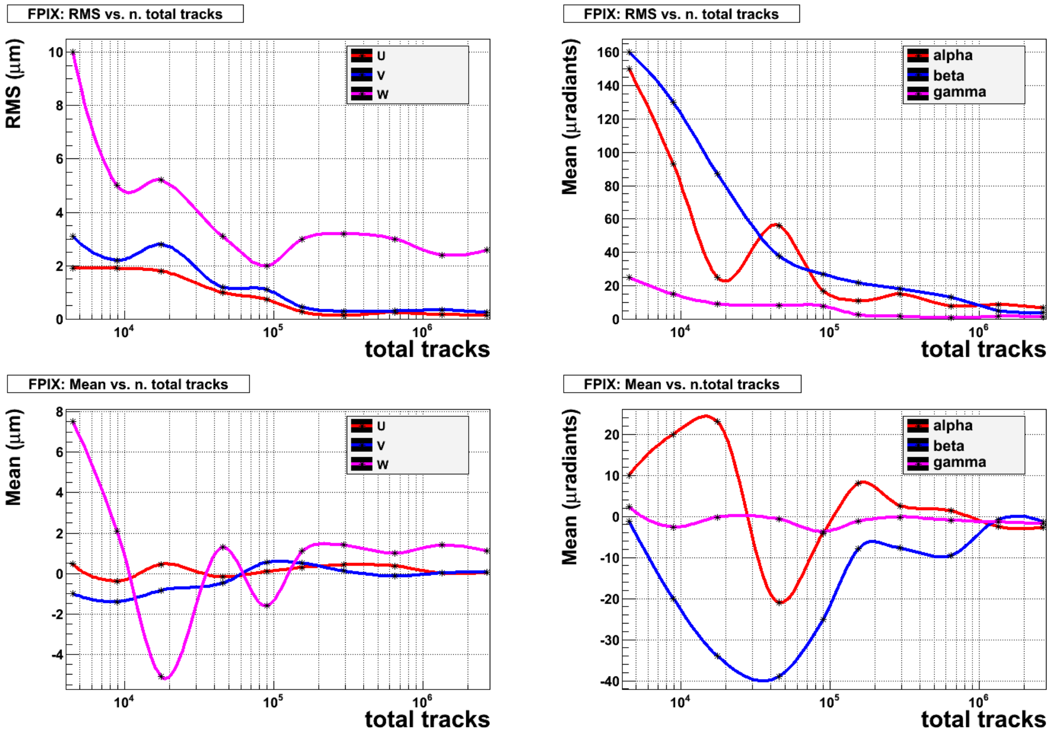


Figure 29: Reasonable Scenario: FPIX results

6.3.4 Reasonable Scenario Iteration

I tried to iterate the Reasonable Scenario results, to see if they improve too, despite being already good. I used the parameters obtained with 2.5×10^6 tracks, that were just a bit smaller than the 10^5 track results, and I iterated the alignment using different numbers of tracks. Iteration results are plotted in 34 for BPIX, in 35 for FPIX.

As you can see with 2.5×10^6 tracks, results are similar to the Reasonable Scenario without iteration. Whith less tracks, iteration increases RMS and mean. This could be because the starting geometry used wasn't perfect. Or this could mean that, if pixel movements between two prompt alignments are too small, or if there aren't many tracks used, prompt alignment could incorrectly determine alignment parameters. These scenarios should be properly tested.

6.4 Conclusions

In the Reasonable Scenario we have very good results already with $\approx 10^5$ tracks and minor further improvements with more than 10^5 tracks. In the Testing Limits Scenario the mean is worse than in the Reasonable Scenario, and also the RMS is ≈ 10 times worse. Results don't improve increasing the number of tracks beyond 10^5. Iterating Testing Limits Scenario alignment results improve, mean becomes similar to the Reasonable Scenario and the RMS is even better than in the Reasonable Scenario. Iterating

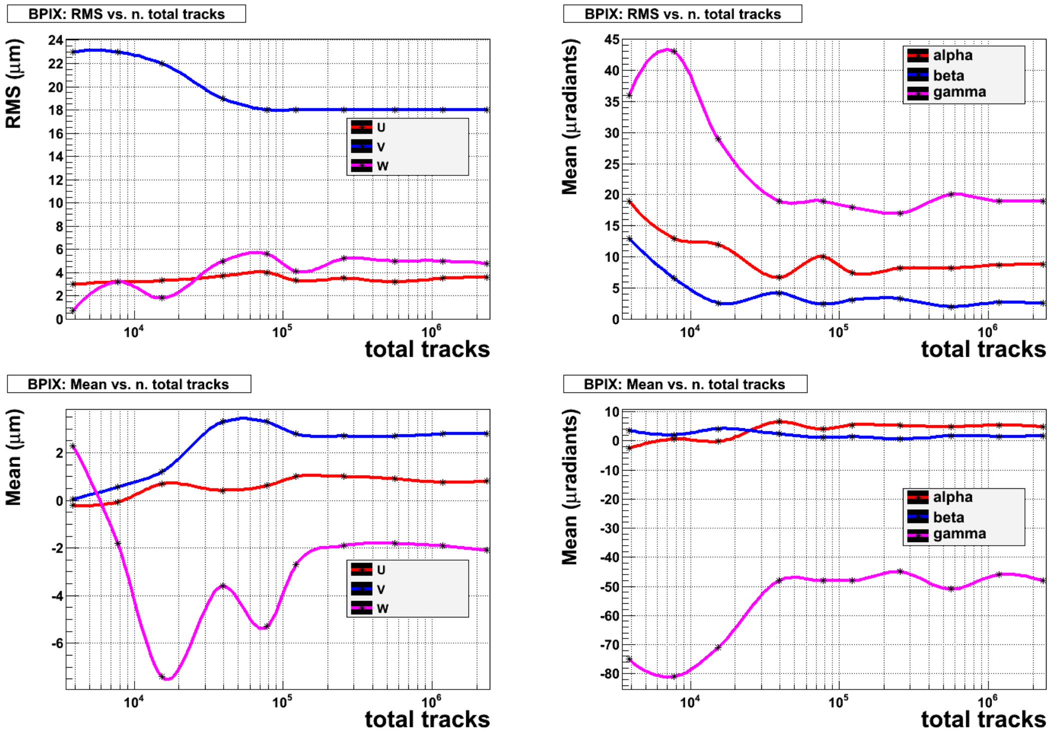


Figure 30: Testing Limits Scenario: BPIX results

Reasonable Scenario alignment doesn't decrease misplacements, and if it is performed with a small number of tracks can lead to a less precise alignment. Many things still need to be tested: for example how the alignment precision depends on the number of tracks passing trough every single part and how this process works with really small pixel movements.

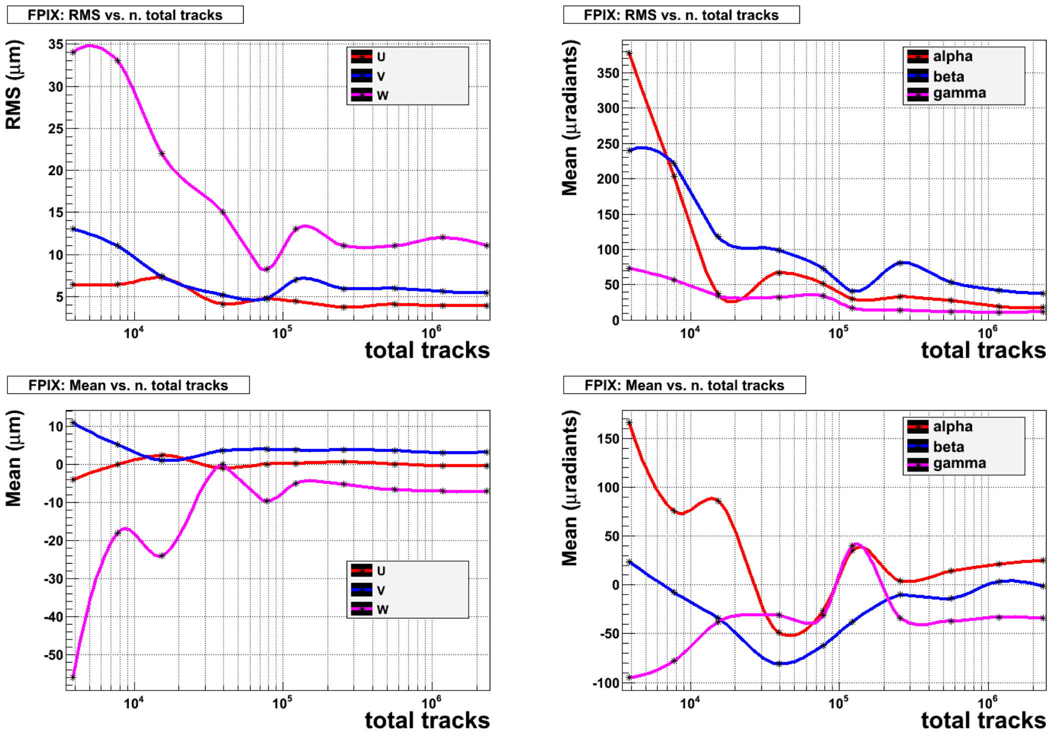


Figure 31: Testing Limits Scenario: FPIX results

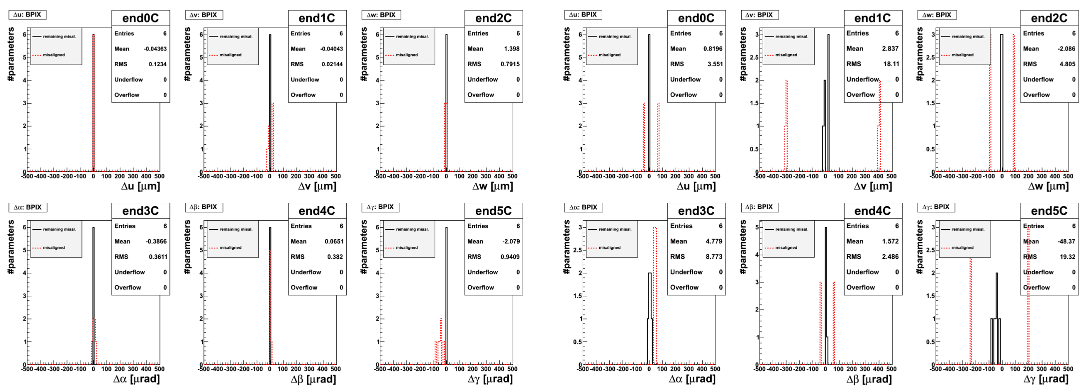


Figure 32: Testing Limits Scenario Iteration vs. Testing Limits Scenario: BPIX results

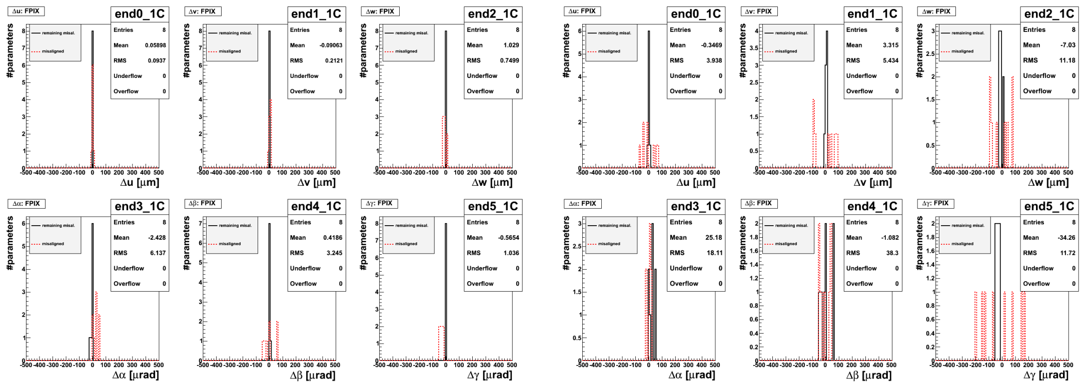


Figure 33: Testing Limits Scenario Iteration vs. Testing Limits Scenario: FPIX results

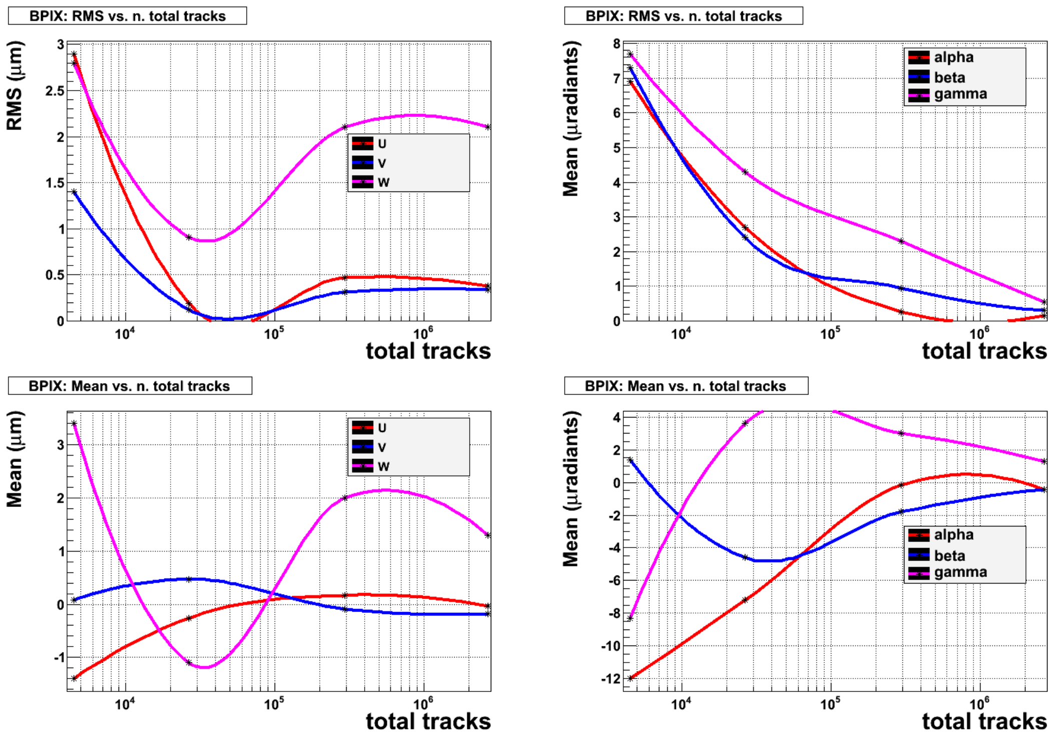


Figure 34: Reasonable Scenario Iteration: BPIX results

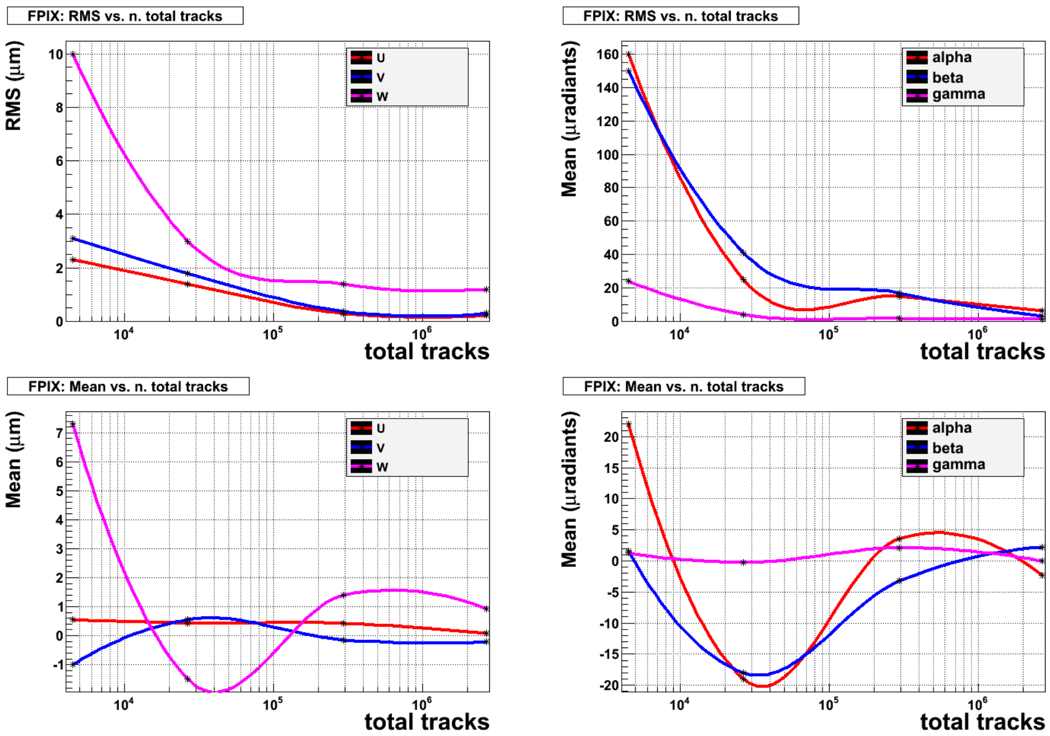


Figure 35: Reasonable Scenario Iteration: FPIX results

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References

[1] Calibration and Alignment of the CMS Silicon Tracking Detector, 2007, Hamburg, *Markus Stoye*

[2] The CMS experiment at the CERN LHC, 2008 IOP Publishing Ltd and SISSA, *CMS Collaboration*