

Arbeit zur Erlangung des akademischen Grades
Master of Science

Alignment studies for the LHCb SciFi Detector

Nils Breer
geboren in Unna

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Lehrstuhl für Experimentelle Physik IV
Fakultät Physik
Technische Universität Dortmund

Erstgutachter:	Prof. Dr. Albrecht
Zweitgutachter:	Prof. Dr. Weingarten
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Abstract

Kurzfassung

Hier steht das selbe wie im Abstract nur auf deutsch.

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1 Introduction

2 Particles and The Large Hadron Collider

Whenever a new detector is build the position where it is physically mounted is roughly where it should be. In order to check this, survey measurements are performed to check the position with a precision of $100\mu\text{m}$. To achieve an even bigger precision, *software alignments* are performed.

The reason why alignment is of great importance is that a misaligned detector yields large momentum resolutions, low reconstruction efficiencies and wrong mass estimations. The most prominent area of misalignment is asymmetries for a spectrometer. In the past, alignment solved problems for example a Muon asymmetry in the L0Muon trigger in 2011 and a misalignment in IT boxes which resulted in trigger inefficiency regarding J/Ψ in 2012.

With good alignment, studies on all standard modell particles and hadron states will improve. Yielding better efficiencies on SM particle measurements will result in deeper insights regarding physics beyond the stand modell from high-precision measurements of CP-violating observables as an example.

On a grand scheme upgrading the LHCb and therefore the LHC will bring deeper insights "for" (wrong word) standard modell processes. To understand the universe even better and eventually yield information about the unsolved question of "dark matter" and "dark energy", what is believed to be the bulk of the universes content.

2.1 The Standard Modell

The standard model of particle physics^{2.1} describes the known elementary particles and their interactions. It consists of 12 matter particles, the fermions and five interaction particles, which are called vector bosons.

The fermions 12 spin- $\frac{1}{2}$ particles. Six are called leptons and they are sorted into three families, also called flavors (e, μ and τ) and six are called quarks. Each of those lepton families has a charged lepton¹ and a left-handed neutrino. A particle is called left-handed if its spin direction is opposite to the direction of flight. Right-handed particles have a spin direction pointing with the direction of flight. Neutrinos can

¹can have both händigkeiten

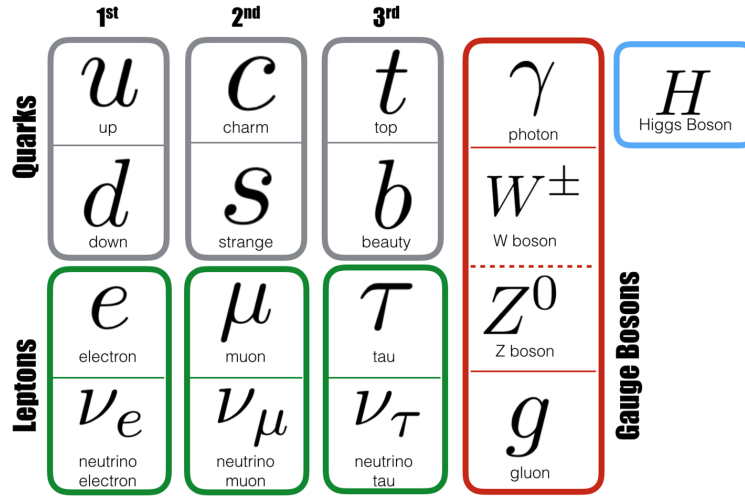


Abbildung 2.1: The standard model of particle physics.

only be left-handed since there is no system where the neutrino can be "overtaken" so the momentum switches and therefore the helicity. A left-handed isospin doublet and a left-handed singlet can be constructed. The leptons can couple via the weak-interaction and if they are charged, also via the em-interaction. Neutrinos can only couple via the weak interaction. Each matter particle also has an antiparticle, with an opposite charge.

The quarks are spin- $\frac{1}{2}$ -fermions and carry an electric charge as well. In each of the three generations there is one isospin doublet. The quarks are ordered by ascending mass. In the first generation are the two lightest quarks, up- and down quark, in the second generation the charm- and strange quark and in the third generation the top- and bottom quark doublet. Quarks carry a color charge, red, green or blue, which is an artificially introduced degree of freedom to guarantee the distinguishability.

The interactions are obtained from the vector bosons mentioned above. The three potent interactions are the electromagnetic(em) interaction, the weak interaction and the strong interaction. Gravitation does not make a significant contribution. The vector boson of the em interaction is the photon which is exchanged between particles. The strength of one of those interactions is described by a coupling constant. In the em interaction this is the fine structure constant[4]. The range of the em-interaction is in principle infinite, but decreases with increasing distance between the interacting particles. The em interaction is described by quantum electrodynamics. The potentials are described by operators, which create and annihilate the photons.

The exchange particles of the weak interaction are on the one hand the W^\pm -bosons and on the other hand the Z-boson. The weak interaction processes are called currents. Changing the charge during the interaction by a W-boson is called charged current. The exchange reaction of a Z boson in, for example, processes such as $e_\nu\mu \rightarrow e_\nu\mu$ is called neutral current. Analogous to the electromagnetic interaction, the potentials are again understood as operators, but here there are no propagators. Propagators are used in *FEYNMAN*-diagrams of QED to represent the interaction particles. A so-called V-A structure is used here instead. Here, V stands for vectorboson and A is the axialvector. This structure is needed to disregard the right-handed particles and left-handed antiparticles, since these lead to the charge-parity violation. Thus the Lorentz factors are adjusted in the following way

$$\gamma_\mu \rightarrow \gamma_\mu(1 - \gamma_5)$$

Quarks couple via the strong interaction which is described by the quantum chromodynamic (QCD). The Eichgroup of the QCD is $SU(N = 3)$ where N is the number of introduced colors as a new degree of freedom. The number of generators is therefore $N^2 - 1 = 8$. The generators are called gluons and they carry color and anticolor, have no mass and carry spin 1. Gluons can, other than photons, couple to themselves. Moreover, the coupling constant $\alpha_s \approx 0.1$. The interaction with quarks is described with a potential.

$$V_{q\bar{q}} = -\frac{4\alpha_s}{3r} + \sigma \cdot r \quad (2.1)$$

with

$$\sigma = 1 \frac{\text{GeV}}{\text{fm}} \quad (2.2)$$

The common eight gluon-wavefunctions are

$$\begin{aligned} \psi_1 &= |r\bar{g}\rangle & \psi_2 &= |r\bar{b}\rangle \\ \psi_3 &= |g\bar{r}\rangle & \psi_4 &= |g\bar{b}\rangle \\ \psi_5 &= |b\bar{r}\rangle & \psi_6 &= |b\bar{g}\rangle \\ \psi_7 &= \frac{1}{\sqrt{2}} (|r\bar{r}\rangle - |g\bar{g}\rangle) & \psi_8 &= \frac{1}{\sqrt{6}} (|r\bar{r}\rangle + |g\bar{g}\rangle - 2|b\bar{b}\rangle) \end{aligned}$$

The second wavefunction describes a gluon interaction with a blue quark and changing the color to red.

Quarks thus tend to attract each other very strongly. If now quark and anti quark are moved away from each other, a lot of energy has to be expended. This energy can become so large that new particles can be created.

Due to the Confinement, quarks cannot exist alone. Instead they form bonding states, so called hadrons. On the one hand there are the mesons, which consist of a quark and an antiquark.

$$|M\rangle = |q\bar{q}'\rangle \quad (2.3)$$

These may be from the same family (i.e. [u,d], [c,s], [t,b]), or from different families. Mesons have a baryon number of 0. Accordingly, quarks carry the baryon number $\frac{1}{3}$. The quarks constructing a meson therefore carries color and the corresponding anticolor. The second type are baryons. The content consists of either three quarks or three antiquarks. However, it cannot be that one quark and two antiquarks and vice versa occur, because baryons must have the baryon number $B = 1$. Because baryons are stable final states as well as the mesons, the sum of their quark colors must be white. Therefore, every (anti)color must occur once in a baryon.

$$|B\rangle = |qq'q''\rangle \quad (2.4)$$

$$|\bar{B}\rangle = |\bar{q}\bar{q}'\bar{q}''\rangle \quad (2.5)$$

2.2 particle decays and hadrons

2.3 The LHC and LHCb

2.3.1 The LHC

The Large Hadron Collider (LHC)[2] is the most powerfull particle-accelerator on planet earth. With a circumference of 26,7km it is also the longest ring accelerator and it lies between 45m and 170m below the surface near Geneva in Swizerland. The tunnel was constructed for the LEP experiment between 1984 and 1989 and is operated by the European Organization for Nuclear Research (CERN). The LHC can produce centre of mass energies of $\sqrt{s} = 13$ TeV in proton-proton collisions during Run 2. After the upgrade the LHC will collide particles with the centre of mass energy of around $\sqrt{s} = 14$ TeV. An image of the accelerators and the experiments is shown in fig. 2.2[1].

By ionizing hydrogen gas, protons are created and accelerated to 50 MeV by the linear accelerator (LINAC 2). Afterwards the beam is injected into the Proton Synchrotron and the Super Proton Synchrotron to a maximum of 450 GeV before the

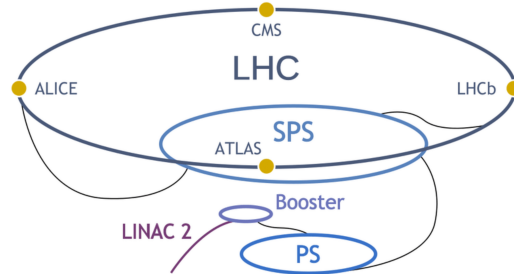


Abbildung 2.2: an overview of the LHC facilities.

beam is brought into the LHC. The beam contains several bunches with around $1,15 \cdot 10^{11}$ protons per bunch and a bunch spacing of 25 ns. The LHC houses four major experiments. ATLAS and CMS are classified as general purpose detectors with a detection range of close to 4π . The interaction in these detectors is located in the very center so that tracks going in every direction can possibly be found. Searches for the Higgs Boson is just one of many physics aspects these detectors are built for. The other two experiments located at the LHC are ALICE and LHCb. The ALICE experiment mainly studies the quark-gluon plasma during the runs with lead ion collisions instead of protons. In this thesis the Scintillating Fibre Tracker (SciFi Tracker) located at the LHCb will be focused on and discussed in the following chapters.

2.3.2 The LHCb

For high energies, b - and \bar{b} -hadrons are heavily produced in a tight forward direction². The LHCb experiment[6] is a forward spectrometer covering $2 < \eta < 5$ in the pseudorapidity range. This experiment's main physics goal is beauty quark

²They are also produced in a tight backward direction but the experiment is only built for the forward cone.

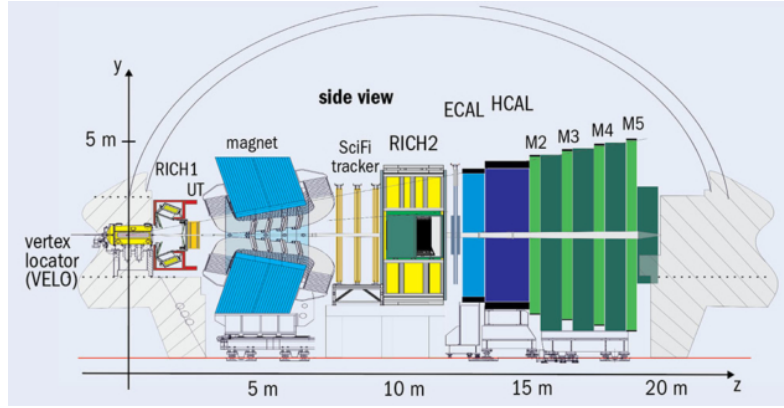


Abbildung 2.3: a sideview of the LHCb experiment.

physics. A sideview of the LHCb is shown in figure 2.3. The LHCb consists of several smaller detector components namely the Vertex Locator (VELO) right on the interaction point, two Ring Imaging Cherenkov counter (RICH 1 and RICH 2), in front of the spectrometers lies the Trigger Tracker and behind them the SciFi Tracker which is the important part of this thesis. Further back a Preshower (PS) is mounted followed by the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL). In the very back, several muon chambers are mounted for every track that is yet to be determined.

In this section, a general overview about the requirements for the SciFi Tracker as well as the layout will be described based on the presentation in the *technical design report*[3] of the upgrade.

The upstream and downstream trackers provide a good precision estimate of the momentum of charged particles so that mass resolution of decayed particles can be precisely measured. For particle identification the reconstructed trajectories of charged particles are used as input for the RICH detectors. The limiting factor for the momentum resolution is multiple scattering for tracks with a momentum lower than 80 GeVc . For tracks with a higher momentum the detector resolution is the limiting factor.

The SciFi Tracker replaced the inner Tracker (IT) and the outer Tracker (OT) and is located in the same place as the downstream trackers that were previously installed.

The instantaneous luminosity after the upgrade is expected to be $1 \cdot 10^{33} \text{ 1/(cm}^2 \text{ s)}$ to $2 \cdot 10^{33} \text{ 1/(cm}^2 \text{ s)}$. The bunch spacing will be 25 ns and the number of proton-proton

interactions per bunch crossing will be $\nu = 3.8$ during the ramp-up phase of the LHC and $\nu = 7.6$ during the active phase.

2.3.3 Layout of the SciFi Tracker

The SciFi Tracker consists of three (T-)stations T1, T2 and T3 with each having four layers ($X1, U, V, X2$). The orientation of these planes with respect to the vertical axis are $(0^\circ, 5^\circ, -5^\circ, 0^\circ)$. Since the beampipe is not exactly parallel to the ground the vertical axis is defined as vertical on the z -axis of the beampipe. The tilted layers are called stereo layers and serve the purpose of 3D hit localization. The layers are 20 mm apart from each other in z -direction within each station. Each layer has four quarters with each quarter having five³ modules. Each module is constructed from four fibre mats. A sideview of the SciFi Tracker is displayed in figure???. The global coordinate system used is of right-handed nature with positive z pointing away from the interaction point following the beam direction. positive y points upwards, towards the surface and positive x and negative x are defined as A-Side and C-Side[3]. For readout purposes the top and bottom half of each element have inverted x - and y -axis. (plot for that?)

To ensure an optimal alignment, a well known geometry is key. Therefore, the fibres must be aligned within $50\text{ }\mu\text{m}$ bis $100\text{ }\mu\text{m}$ in x -direction and must not be more than $300\text{ }\mu\text{m}$ bent in z -direction.

2.3.4 Scintillating Fibres

The scintillating fibre material is a polymer with an organic fluorescent dye added to the polystyrene structure to enhance the yield during the scintillation process. In order to produce and register a photon signal, the ionization energy is deposited in the fibre core firstly. The amount of energy need for the polymer to reach an excited state is just a few electronvolts. The added dye has the particular structure to match the excitation energy. The energy is transferred via the Förster Transfer(source needs to be added). The dye generates excited energy states when particles hit the fibre and deposit their energy. The long fibre mats and the refractive index make sure total reflection on the inside happens which guides the photons to the SiPMs. On the opposite end of the SiPM a full reflective mirror is mounted so the photons travelling to the other end do not get lost but reflected towards the SiPM.

³six for the last (T-)station.

3 The Theory of Alignment

here comes the theory part for general alignment

3.1 Track reconstruction

In order for LHCb to be used for physics, all of the detector hit information has to be converted into tracks, which is a challenging task. The track reconstruction algorithm needs to find the correct hits from each subdetector to build the track. This can be problematic just because of the amount of tracks per events (roughly 100). It is crucial to find all particle tracks and also their track parameters which come from the track fit.

A good track fit is needed in order to find the best estimates for the track parameters and covariances. The estimates are used in the event reconstruction to find the correct tracks for each particle and the decay products. The info provided is used in the RICH rings, ECAL and HCAL and muon detectors. With this information, particle and track parameters such as the invariant mass can be measured and vertex origins can be found. There are several track models that can be used. In general, a track is built from numerous segments which are either straight or curved because of an active magnetic field. Depending on the environment of the track either model is good. The track segments are called track states and are defined by a position in x and y at a given distance z where the hit was located, then a tangent direction $t_{x,y}$ at the hit position and a momentum parameter acquired from the track curve inside the magnetic field.[7]

$$\vec{r} = \begin{pmatrix} x \\ y \\ t_x \\ t_y \\ \frac{q}{p} \end{pmatrix} \quad t_x = \frac{\partial x}{\partial z} \quad t_y = \frac{\partial y}{\partial z} \quad (3.1)$$

The uncertainty of the five-component state vector is a 5×5 covariance matrix C . A track state can be anywhere on the trajectory but is easier to choose it at

3 The Theory of Alignment

real detection points. Combining the track state with a real measurement point is called *node*. The propagation from node $k-1$ to node k is described by a propagation function

$$\vec{r}_k = f_k(\vec{r}_{k-1}) + \vec{w}_k \quad (3.2)$$

.

This means node k is acquired by propagating node $k-1$ through the propagation function f_k and shifting it by the *process noise* \vec{w}_k . LHCb uses process noise to model the scattering. Depending on the type of propagation, linear or curved, a different propagation function is used. for a linear extrapolation, f_k results in

$$f_k(\vec{r}_{k-1}) = F_k \vec{r}_{k-1} \quad (3.3)$$

with the transport matrix F_k

$$F_K = \begin{pmatrix} 1 & 0 & \Delta z & 0 & 0 \\ 0 & 1 & 0 & \Delta z & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (3.4)$$

and Δz being the difference in z between the nodes

$$\Delta z = z_k - z_{k-1} \quad (3.5)$$

Trajectory information for each node is provided by the real measurement where the relation between measurement m_k and track state at a given node k is defined as

$$m_k = h_k(\vec{r}_k) + \epsilon_k \quad (3.6)$$

with the projection function h_k and *measurement noise* ϵ_k . So if the detector only measures the y coordinate of state, the projection function will be

$$h_k(\vec{r}_k) = H_k \vec{r}_k \quad (3.7)$$

with

$$H_k = (0 \quad 1 \quad 0 \quad 0 \quad 0) \quad (3.8)$$

.

When measuring more parameters the measurement matrix H_k and projection matrix have dimension $n \times 5$ with n being the numbers of parameters measured.

With this track model, both noises from the measurement and the process are random and unknown and have an expectation value of zero. They are defined as $W_k \equiv \text{cov}(w_k)$ and $V_k \equiv \text{cov}(\epsilon_k)$.

3.2 The Kalman filter method [7]

In general a track is an ensemble of measurements and track states and the Kalman filter method is used to fit tracks. The idea of the Kalman filter is, to have a starting node and add measurements one by one. In between the addition of measurements, the local track state is updated with the new information. The Kalman filter method is a χ^2 minimising problem for the measurement of the track. Because of the iterative nature of the method, it is fast und also used in other fields than physics, for example GPS and meteorology. The three steps of the Kalman filter will be briefly outlined and later discribed in further detail.

The first step is the Prediction: The next track state of the trajectory is predicted based on the track state at the previous node. The second step is the Filter procedure: By using filter equations, the prediction is updated with measurement information in this node. The prediction and filter are repeated for each measurement. With more measurements added, the estimate for the best trajectory is the track state after each filter step. The final step is called Smoother: When the trajectory is complete, smoother equations are applied from the last node to the previous node. Therefore the information from all measurements is used in both forward- and backpropagation which results in a "smoother" track.

3.2.1 first Step: Prediction

For a given state vector at node $p-1$, the prediction for the p^{th} state vector and its covariance matrix results from the propagation relations

$$\vec{r}_p^{p-1} = f_p(\vec{r}_{p-1}) \quad (3.9)$$

$$\text{Cov}_p^{p-1} = F_p C_{p-1} F_p^T + Q_k \quad (3.10)$$

The superscript of the statevector shows the number of measurements used in the estimate and can be abbreviated with $\vec{r}_p^p \equiv \vec{r}_p$. For a maximum number of n

measurements \vec{r}_p^n is the smoothed state where every measurement is used. Q_p is the process noise in matrix form and it is part of the predicted covariance matrix C_p^{p-1} . Because the first state cannot take measurements from the previous state, an initial prediction is taken from the track finding algorithm instead. The predicted residual between the measurement, m_p and the state vector results in

$$\text{res}_p^{p-1} = m_p - h_p (\vec{r}_p^{p-1}) \quad (3.11)$$

and the corresponding covariance matrix is defined as

$$\text{Cov}_{\text{res},p}^{p-1} = V_p + H_p C_p^{p-1} H_p^T \quad (3.12)$$

.

Here, V_p is the measurement variance. With these metrics the minimal χ^2 for the optimal track states can be calculated via

$$(\chi^2)_p^{p-1} = \text{res}_p^{p-1} (\text{Cov}_{\text{res},p}^{p-1})^{-1} \text{res}_p^{p-1} \quad (3.13)$$

3.2.2 second Step: Filter

During the filter step, the track state is updated with the measurement information. Iteratively, each measurement is added and the filtered state \vec{r}_p and the corresponding covariance matrix is calculated via

$$\vec{r}_p = \vec{r}_p^{p-1} + G_p \text{res} + p^{p-1} \quad (3.14)$$

$$\text{Cov}_p = (\mathbb{1} - G_p H_p) \text{Cov}_p^{p-1} \quad (3.15)$$

, where G_p is the gain matrix of dimension 5×1 and is defined as

$$G_p = C_p^{p-1} H_p^T (\text{Cov}_{\text{res},p}^{p-1})^{-1} \quad (3.16)$$

Afterwards the residuals and its covariance matrix are calculated and the filtered total χ^2 is defined as

$$(\chi_{\text{filter}}^2)_p = \text{res}_p \text{Cov}_{\text{res},p}^{-1} \text{res}_p \quad (3.17)$$

.

The prediction and filter procedure is continued for all measurements until the track is fully reconstructed. Because the last node at $p = n$ has the most information in it, a backward update is performed to infuse the previous nodes with the same information as in last node. This is called *smoother*-step.

3.2.3 third Step: Smoother

The smoother function returns the best possible estimate for track states at the previous nodes. The method used is called *Rauch-Tung-Striebel-smoother*. The idea is to use backward information and construct a smoothed state vector and covariance matrix

$$\tilde{r}_p^n = \vec{r}_p + S_p (\vec{r}_{p+1}^n - \vec{r}_{p+1}^p) \quad (3.18)$$

$$\tilde{C}_p^n = C_p \quad (3.19)$$

and the Smoother-matrix S_p of dimension 5×5

$$S_p = C_p F_{p+1}^T (C_{p+1}^p)^{-1} \quad (3.20)$$

In order to calculate the smoothed χ^2 the residual and corresponding covariance matrix are

$$\text{res}_p = m_p - h_p \vec{h}_p^n \quad (3.21)$$

$$\text{Cov}_{\text{res},p}^n = V_p - H_p C_p^n H_p^T \quad (3.22)$$

An in depth explanation is given in [5].

The χ^2 is calculated analogously to the one during the filter step with the difference being the new residuals and covariances.

3.3 Alignment using derivatives

this will come later. time ran out last week so this will be done later.

4 Main part

4.1 general info

Alignment using tracks and vertices regarding stations, layers and modules. Testing constraints for different degrees of freedom with the goal to find the "perfect" configuration of constraints and alignable degrees of freedoms. The following pre-installed alignment conditions with the survey constraints being

```
"FT : 0 0 0 0 0 0 : 1 1 1 0.0003 0.0003 0.0003"  
"FT/T. : 0 0 0 0 0 0 : 1 1 1 0.0003 0.0003 0.0003"  
"FT/T./Layer(X1|U|V|X2) : 0 0 0 0 0 0 : 0.2 0.2 0.2 0.0001 0.0001 0.0001"  
"FT/.*Module. : 0 0 0 0 0 0 : 0.1 0.1 0.1 0.001 0.001 0.001"  
"FT/.*Mat. : 0 0 0 0 0 0 : 0.05 0.05 0.05 0.1 0.1 0.1"  
were used.
```

The string is the name of the element, the first set of six numbers are hardcoded parameters for each of the 3 translation degrees of freedom and 3 rotational degrees of freedom (Tx, Ty, Tz, Rx, Ry, Rz) and the second set of six parameters are the corresponding uncertainties.

The scale for the translations are mm and the scale for the rotations being rad. A survey uncertainty of 0,0001 stands for 0,1 mrad.

The alignments have been performed with gaudisplitter.

During the Alignment, lagrange constraints can be utilized to minimize the χ^2 under the condition

$$f(\alpha) = 0 \quad (4.1)$$

and adding the lagrange parameter λ to get

$$\Delta\chi^2 = \lambda f(\alpha) \quad (4.2)$$

.

Lagrange constraints are added to fix loosely constrained degrees of freedom and can be used for any linear combination of movements.

4.2 Nulltests and software tests

As a starting point, Alignment v17r1 was used with 5000 events, magnet in upward position and *GoodLongTracks*. The *GoodLongTracks* have the following cuts and parameters:

- minimum $P_{\text{total}} = 5000$ (units? 5000 MeV?)
- maximum $P_{\text{total}} = 200000$ (units? 200 000 MeV = 200 GeV?)
- minimum $p_T = 200$ (units?)
- maximum $\chi^2 = 5$
- track type should be categorized as "long" (what does that mean -> hits in every subdetector)
- maximum number of THoles? is 1

and for the later used *HighMomentumTTracks* the cuts and parameters are:

- minimum $P_{\text{total}} = 50000$ (units?)
- track type should be categorized as "Ttrack"
- maximum $\chi^2 = 5$

At first, a series of tests regarding different degrees of freedom and lagrange constraints is performed to find the optimal solution for the SciFi. This called Nulltests.

The real detector layers are all centered around the beampipe with no shifting in any direction and the goal is to align the layers in the software to mirror the real layers, therefore reduce the shifting as close to zero as possible.

As a baseline the configuration from Florian Reiss is used and improved. In this part, the steps of testing different configurations is described and analysed. Figure ?? is used to demonstrate which degrees of freedom can be used to describe a point in the detector or a shift in coordinates.

Florian made a crucial change in the code in form of a bug fix which resulted in the following configuration:

- dofs: Tx and Rz
- constraints: unconstrained

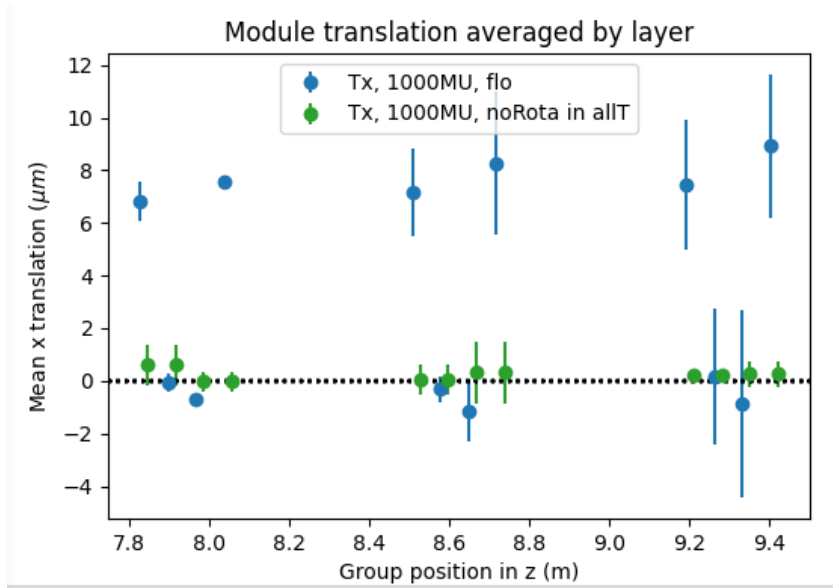


Abbildung 4.1: comparison of different configurations without rotational constraints in every station, magnet up and 1000 events. plotted is translation in x versus global z.

The measurement points are the mean of each layer, therefore the errorbars on Florians measurement are root-mean-square errors and come from the difference between the C-side and the A-side of the detector layer and is NOT the measurement uncertainty. The green measurement used the following configuration:

- here my config for the green plots -> see lxplus i guess

The constraints are selected because... (first of all look them up, then describe) This measurement only used 1000 events and is only used as a guideline to what the actual distribution could look like.

In figure 4.2 the same measurement is performed for 7000 events to get a better picture. In comparison to 4.1 an overall improvement in Florians configuration is visible and the layer-splitting is reduced but still prominent. The green measurement shows no direct improvement since the layers are already pretty close to zero in x-direction, where we want them.

The following measurements used 3000 events because the performance did not change much when using 5000 or even 7000 events. Also, the time the computer needed to finish an alignment run for 7000 events and 10 iterations was a lot longer than for 3000 events.

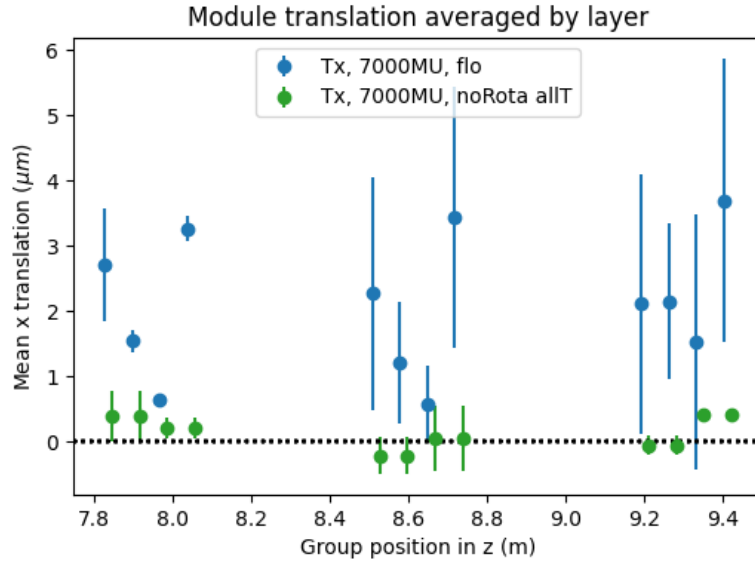


Abbildung 4.2: comparison of different configurations without rotational constraints in all stations, magnet up and 7000 events. plotted is x translation versus global z.

maybe show this plot 4.3

the figure in 4.4 shows that very strict Tx constraints make Tx look better but when comparing to Tz as we can see in figure 4.5 a clear layer separation is visible. Because of the many constraints that are applied to T3, the RMS uncertainty in the other stations get worse.

Looking at figure 4.6, the last two layers in station 3 are separation from the first two regarding x-translation. Especially the last station should be fixed around zero with the constraints added. The sum of all translations should be zero with each individual layer movement being small.

This layer-separation problem will be looked at at a later stage.

4.2.1 rotational constraints

The impact of rotational constraints is looked at now. Firstly, comparing florians starting configuration versus the new one with added constraints. The direct impact to the rotations are quite small but the translations in z- and x-direction show a small improvement to the previous configuration seen in figure 4.4.

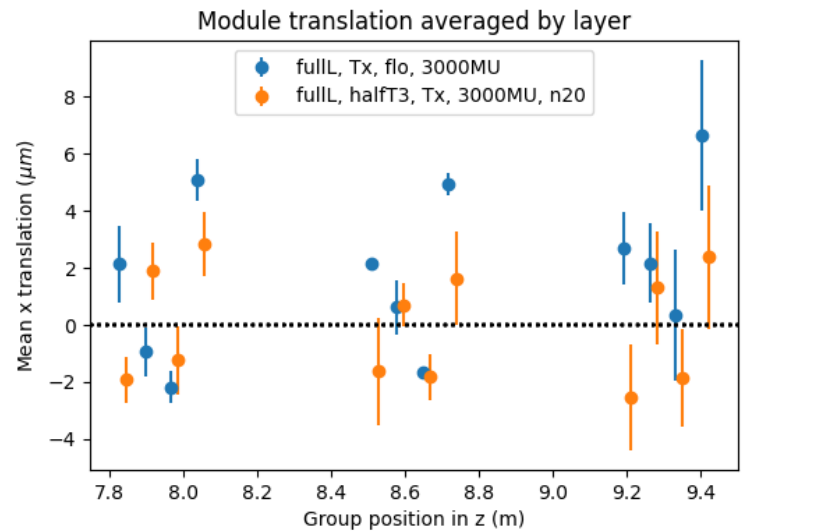


Abbildung 4.3: analysed 20 iterations for x translation behavior (look up exact constraints and dofs)

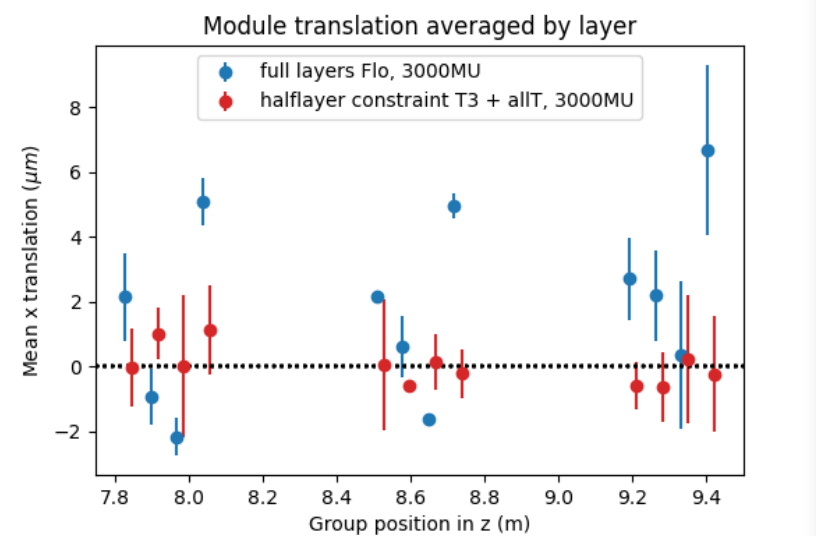


Abbildung 4.4: halflayer constraints and full layer constraint, very strict (look up exact constraints and dofs)

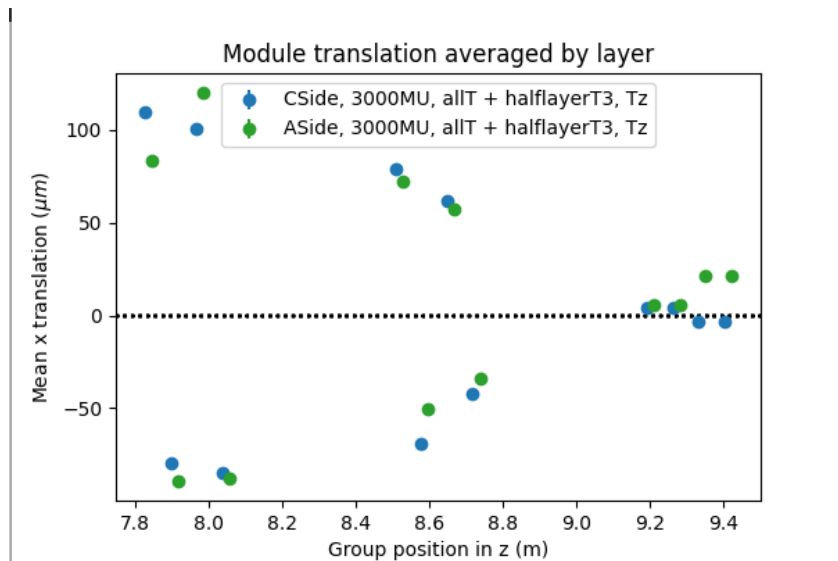


Abbildung 4.5: compare C-Side to A-Side for Translation in z direction. (look up exact constraints and dofs)

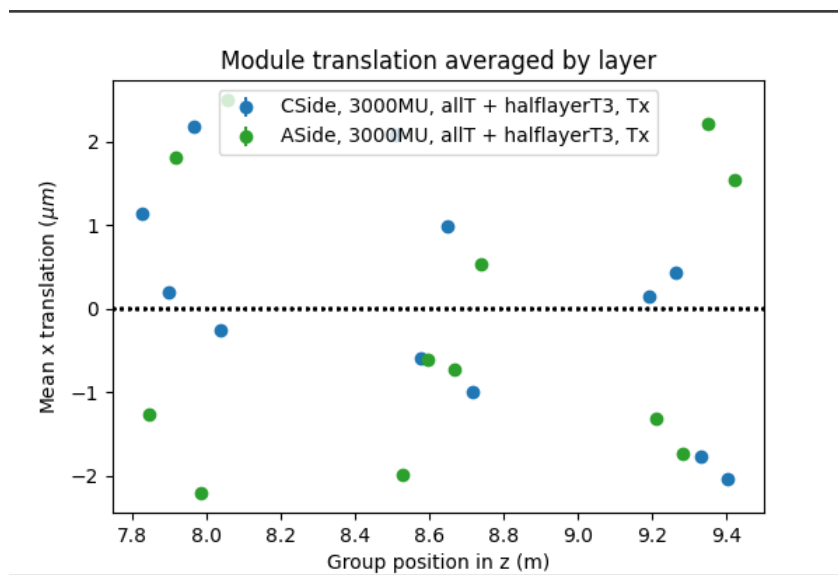


Abbildung 4.6: compare C-Side to A-Side for Translation in x direction. (look up exact constraints and dofs)

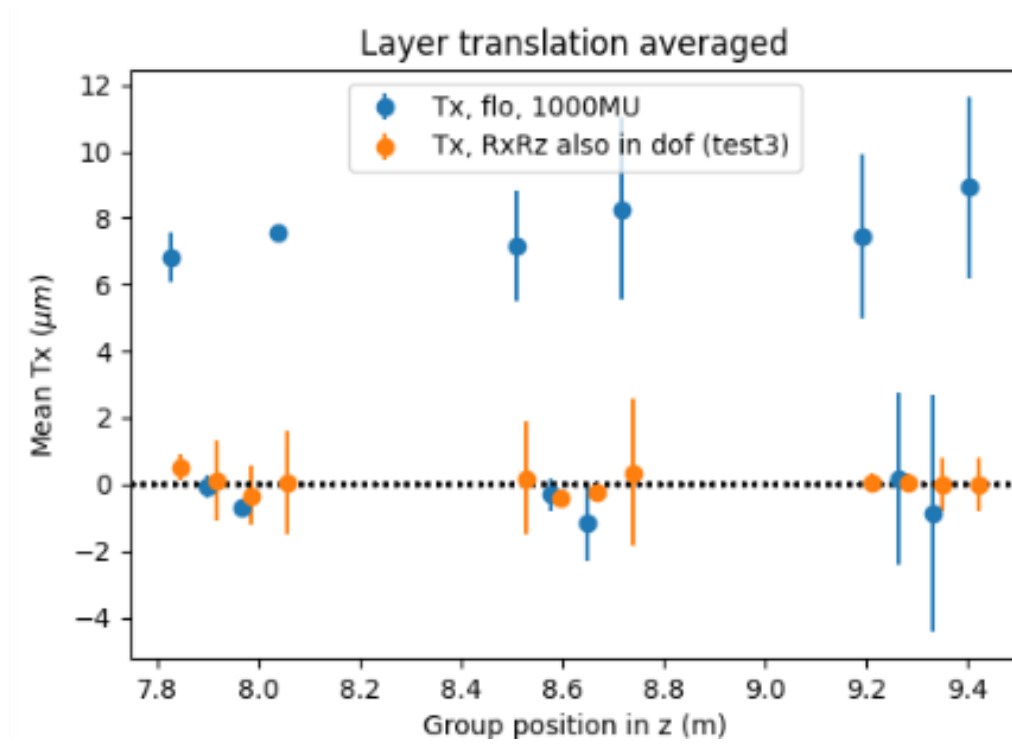


Abbildung 4.7: Tx versus global z.

Now, we have a configuration¹ which is quite ok but has a lot more room for improvement but is nevertheless a better representation than the first draft from florian. Therefore we will now compare further configuration drafts to the "config5" with the following constraints

- constraint 1
- constraint 2
- constraint 3
- ...

and the dataset used is taken from the bookkeeping (what exactly?).

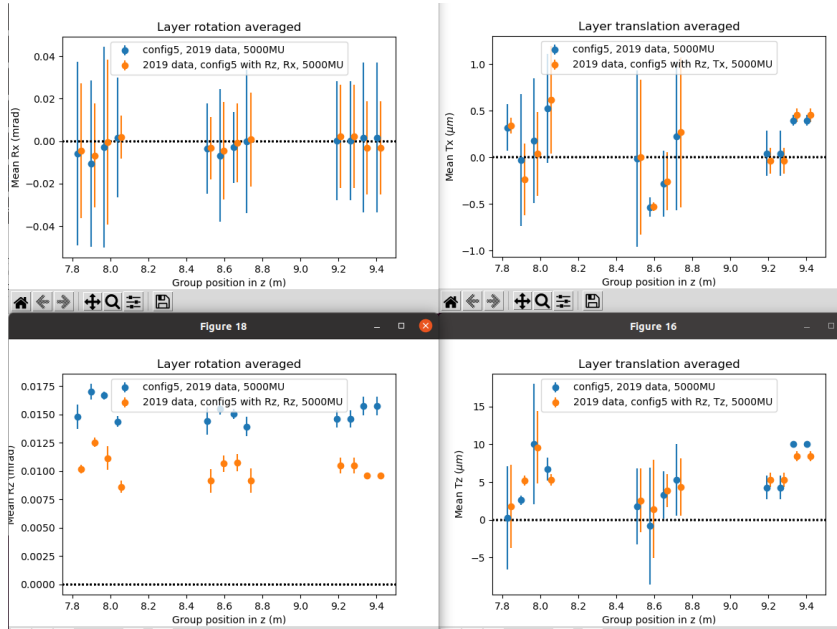


Abbildung 4.8: config5 versus config 5 with Rz constraint for rotational improvement.

In figure 4.8 config5 is plotted against itself but with and added constraint to Rz. The change is the constraint: (fill constraint here). The result is a small improvement in Rz of around 0,005 mrad in every layer. Rx is mostly unchanged and the small differences in Tx are caused by a nudge in the plotting script so that the data points do not overlap. The rotation around z is correlated to the z translation therefore we see small changes in every layer as well. It is noteworthy, that both X-layers

¹The always used configuration will be always called "config5" in the labels

in T2 in the x-translation plot have a quite large RMS uncertainty which means the A-side and the C-side in the X-layers are quite far apart but the mean is right around 0. That is expected since the constraint added only brings the mean of the layer to 0. In future analyses another constraint should be added to also keep the side themselves small.

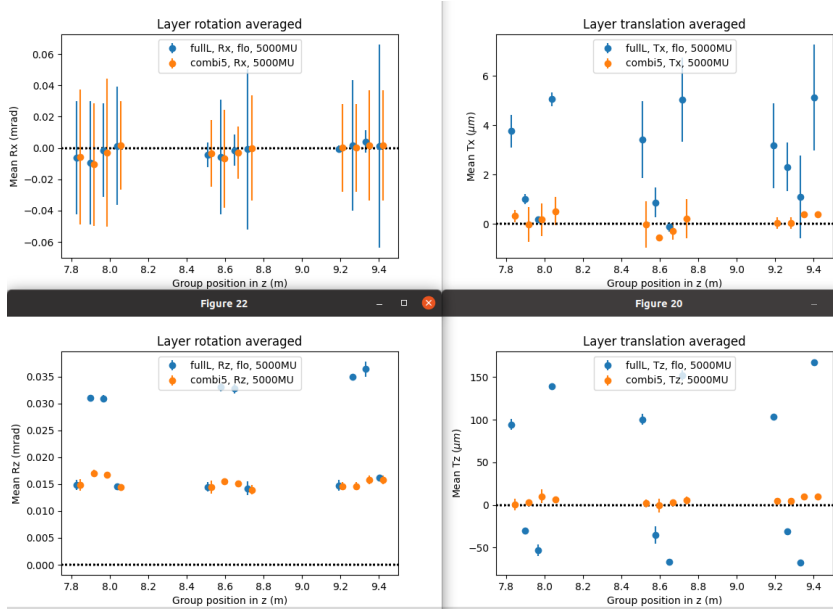


Abbildung 4.9: flo with full layer constraint versus config 5

In comparison to what florians configuration looks like against the new proposed configuration the figure 4.9 can be looked at. The alignment was performed for 10 iterations and the alignable degrees of freedom are Tx, Tz, Rx, Rz. The alignable elements are the stations and the framelayers. The constraints used are:

```
"station3 : FT/T3 : Tx Rz Rx Rz"
"backCframeT3 : FT/T3/Layer(V|X2) : Tx Tz"
"FT/T3X1UCSide : /dd/Structure/LHCb/AfterMagnetRegion/T/FT/T3/Layer(X1|U)/Quarter(0|2) : Tx Tz Rx Rz"
"FT/T3VX2CSide : /dd/Structure/LHCb/AfterMagnetRegion/T/FT/T3/Layer(V|X2)/Quarter(0|2) : Tx Tz Rx Rz"
"FT/T3X1UASide : /dd/Structure/LHCb/AfterMagnetRegion/T/FT/T3/Layer(X1|U)/Quarter(1|3) : Tx Tz Rx Rz"
"FT/T3VX2ASide : /dd/Structure/LHCb/AfterMagnetRegion/T/FT/T3/Layer(V|X2)/Quarter(1|3) : Tx Tz Rx Rz"
```

The first constraint constraints the overall station 3 in Tx, Tz, Rx and Rz. The second constraint restricts the total movement of the last C-frame to be 0 but the individual movement can differ. The last four constraints are C-frame constraints as well but for each halflayer in station 3.

It is good to see that the layer separation in Rz is mostly fixed. But there is still an offset from 0 that is troublesome. This will most certainly have something to do with the clusterbias. Regarding Tx, we(I) have managed to bring down the x-translation to roughly 0 which is a good improvement for the null tests of Tx.

Translation constraints as well as rotation constraints are not the only constraints tested. There are also scaling- and shearing constraints that were tested but resulted in no improvement therefore they are just mentioned.

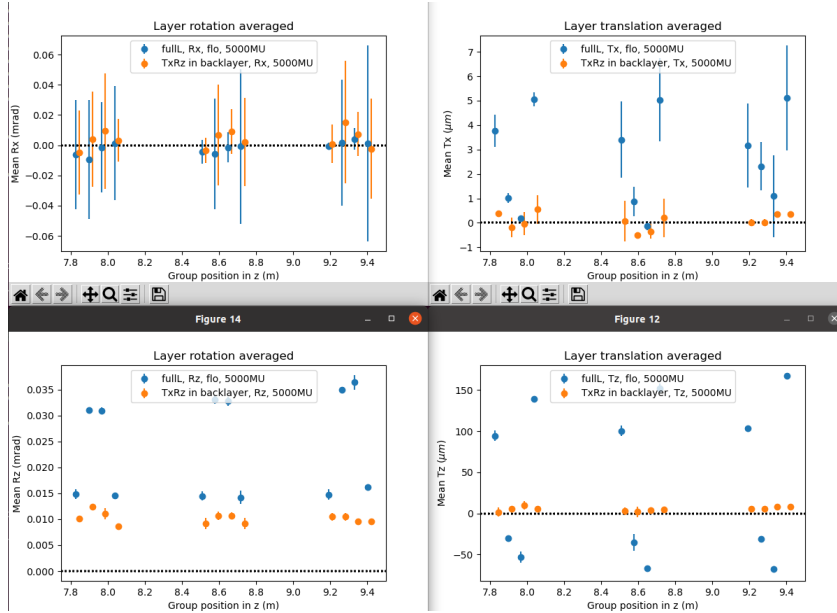


Abbildung 4.10: dofs Tx Rz and backlayer constraints.

TODO: redo the plots for 4.10 and 4.11 and don't use florian but instead use a different config5 to compare with!

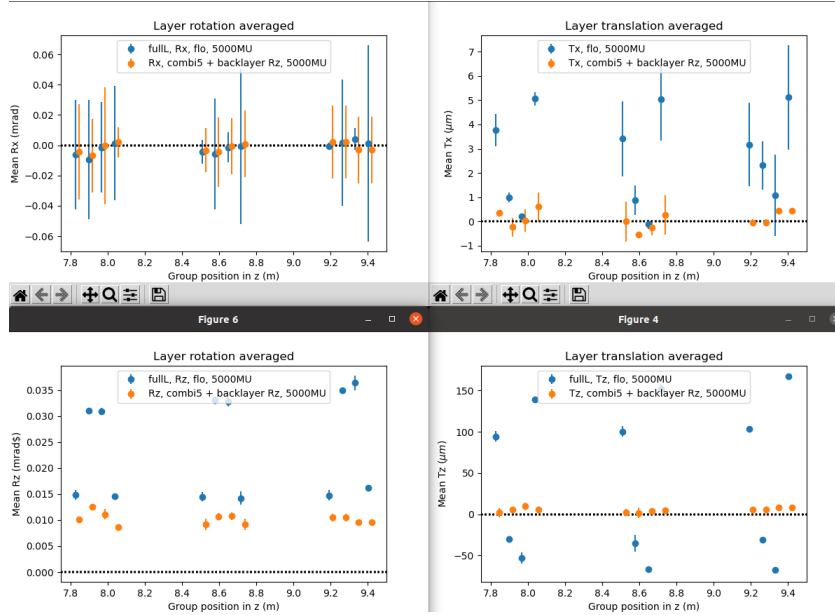


Abbildung 4.11: combi 5 with Rz backlayer constraint.

4.3 chi2 tests and weak modes

In this section, χ^2 are performed in order to study the "goodness" of the alignment since the better the χ^2 after the alignment the better. The second aspect i want to cover is the impact of potential weak modes also known as "correlated alignment parameters". There are several weak modes that could occur namely *global translation*, *shearing* and *curvature bias*. weak modes are unaffected by the χ^2 since the residuals do not change. The effect weak modes have on the alignment are biases regarding track parameters and late convergences. There are different solutions that can be utilized to reduce the effect from weakmodes such as

- using other configurations like magnet off or mass plots for off-axis events
- utilizing other survey data sets
- using kinematic and vertex constraints

for figure 4.19 redo the plot with correct labels and legend !!

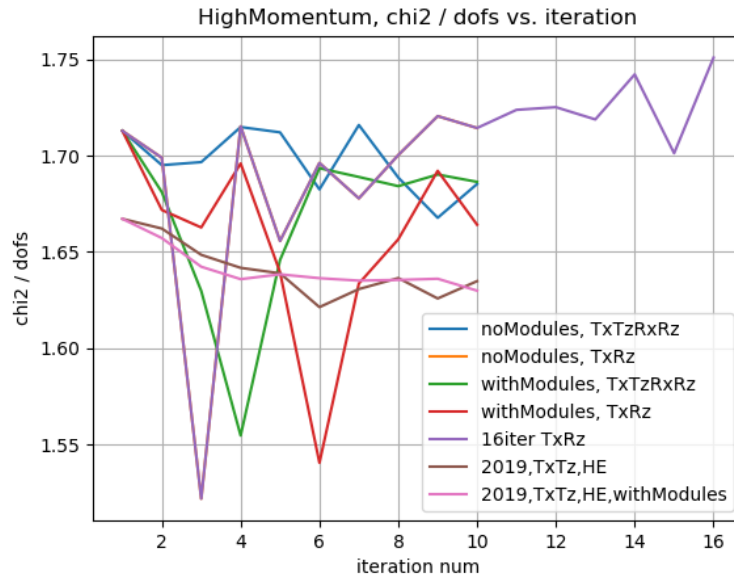


Abbildung 4.12: χ^2 -test versus iteration number of different degrees of freedom, alignables and data samples.

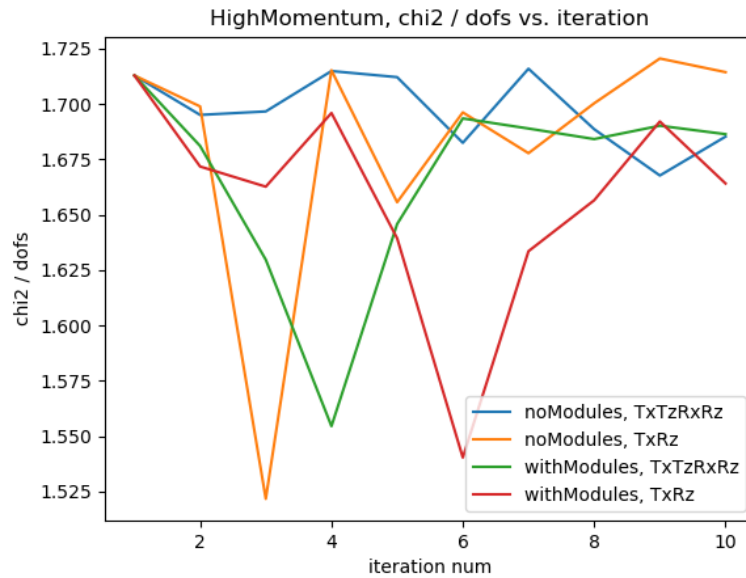


Abbildung 4.13: χ^2 -test versus iteration number of different degrees of freedom, alignables and data samples but fewer (redo with grid).

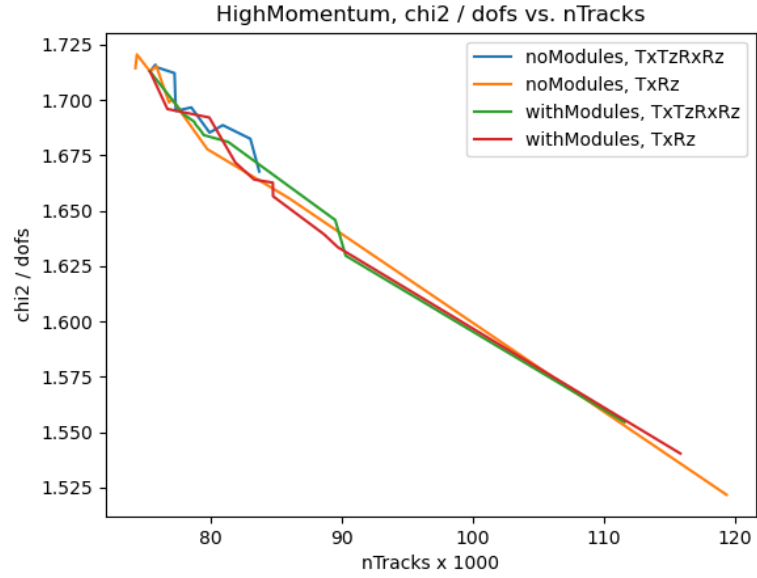


Abbildung 4.14: χ^2 -test versus number of tracks of different degrees of freedom, alignables and data samples but fewer (redo with grid).

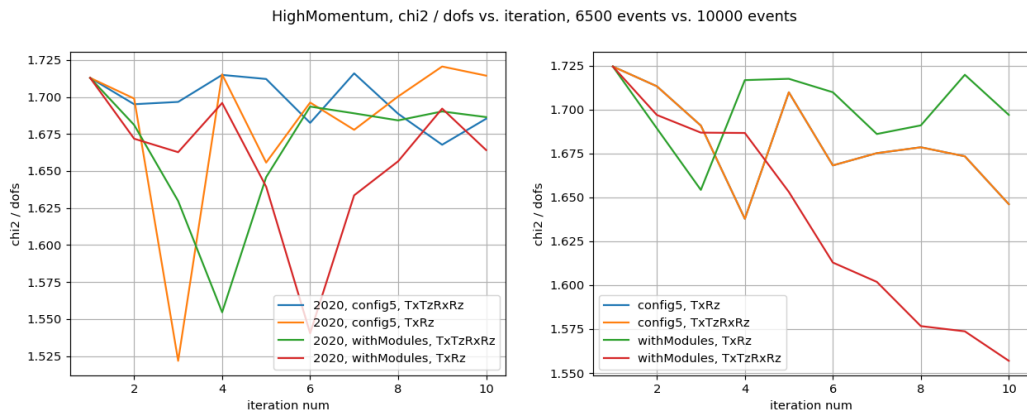


Abbildung 4.15: chi2 versus iteration count normal(?).

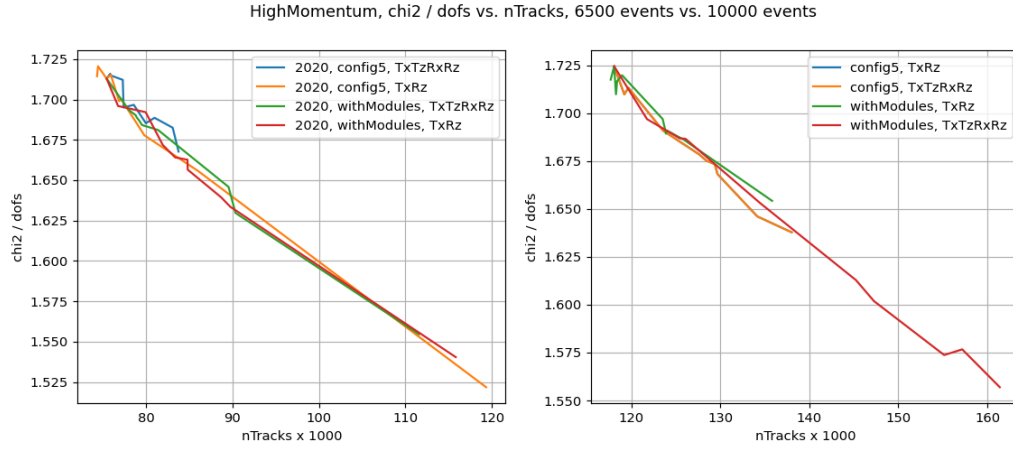


Abbildung 4.16: χ^2 versus number of tracks normal.

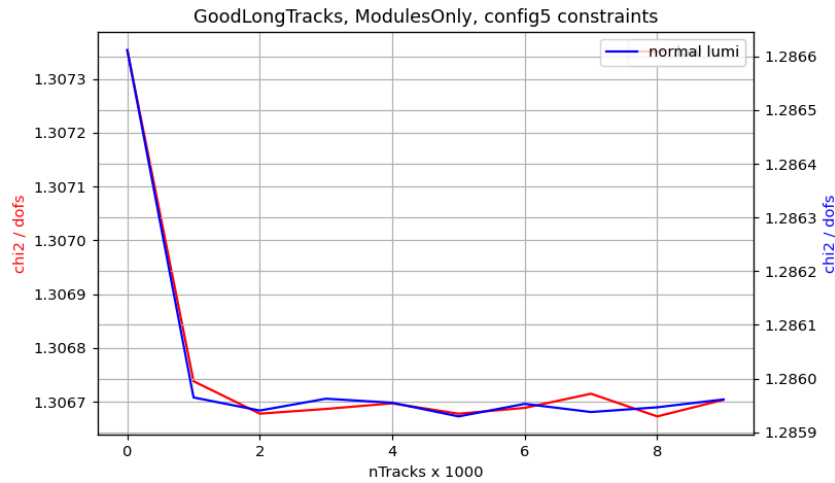


Abbildung 4.17: compare different luminosities and plot χ^2 versus iteration number as a measurement for weak modes and alignment.

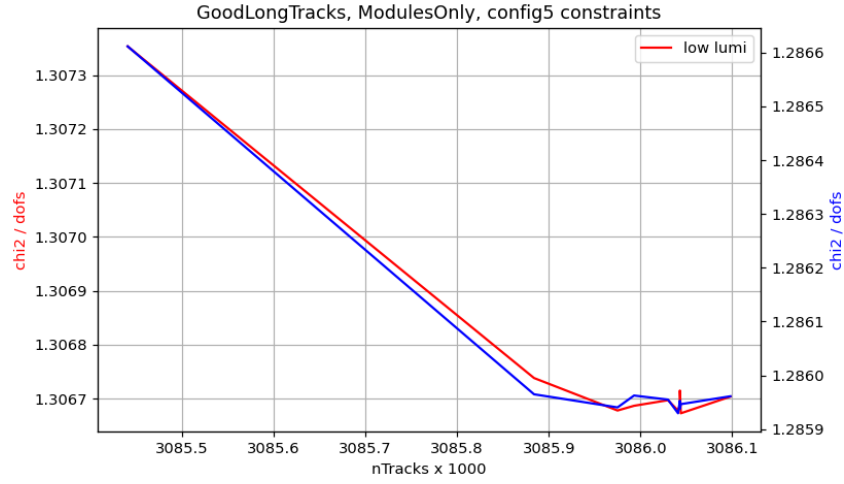


Abbildung 4.18: compare different luminosities and plot chi2 versus number of tracks as a measurement for weakmodes and alignment.

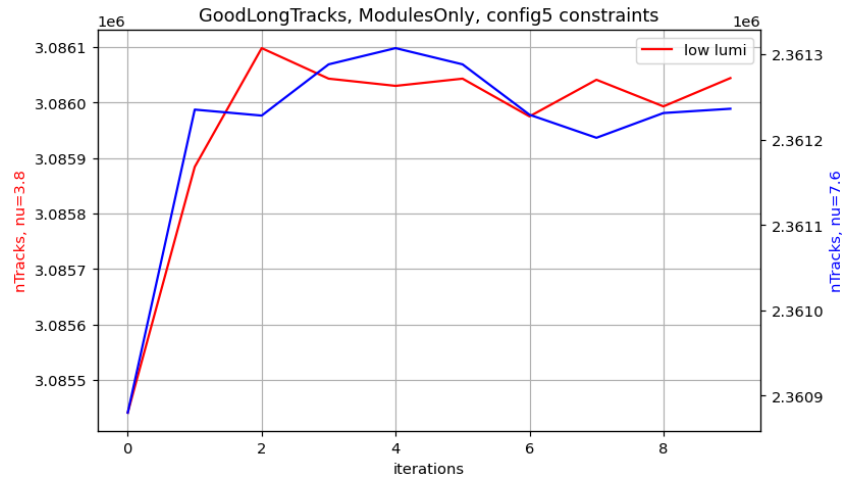


Abbildung 4.19: compare different luminosities and plot number of tracks versus iteration number as a measurement for weakmodes and alignment.

4.4 impact of the cluster bias

As mentioned earlier the clusterbias most certainly causes the shift in the rotation around z for each layer so it does not reach 0. To test that a momentary fix was found and implemented. The workaround was to add a scaling to the value ... (look in laptop) by 0,95.

Figure 4.20 shows the impact of the cluster bias hack regarding the rotation around z .

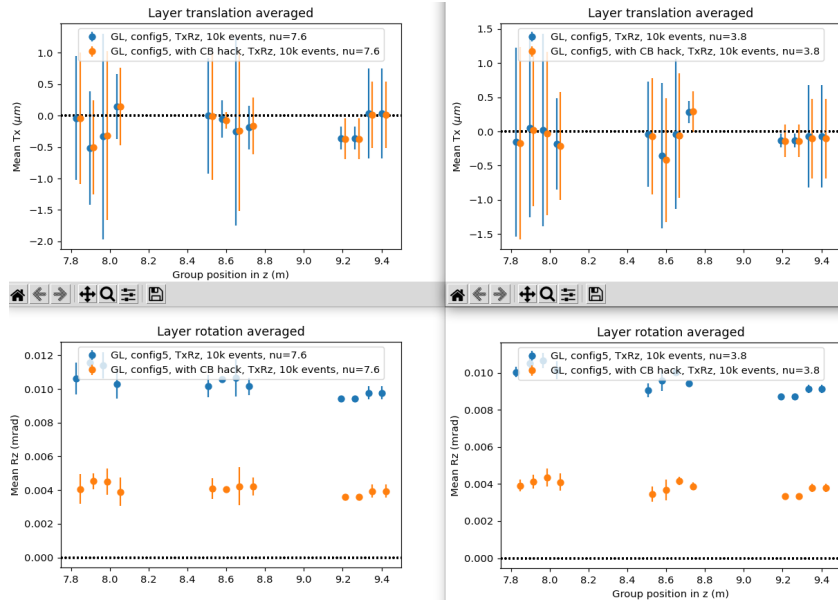


Abbildung 4.20: because of the clusterbias hack the difference between a measurement with the hack we implemented active and without is shown.

As we expected, the amount of rotation was reduced to about 0,004 mrad from the previous 0,01 mrad which is more than a factor of 2 improvement. We also know, that the fix for the cluster bias will not be the only source for the shift and we need further analysis to find the other sources.

Now that we know, that the cluster bias can be taken care of we take a closer look at samples of different luminosities since the LHC will not be operated at the maximum luminosity from the start, there is also the ramp up phase where the luminosity will be lower so that is what will be discussed in the following part.

Since we want to know what the shifts in rotation and translation will look like when the cluster bias is fixed we will keep it active for the next studies. Figure 4.21 shows

the difference between a sample with ramp-up luminosity and a sample with the luminosity during the measurement phase. We see, that the layer separation is much more prominent in station 1 and 3 for the higher luminosity sample but slightly better behaved in station 2 when looking at x-translation. Regarding the z-rotation, the lower luminosity sample as slightly lower rotational shifts. The difference is so minute that it can be safely disregarded. (not sure about that)

With that, we tested if there is a noticable difference in the $\frac{\chi^2}{\text{dof}}$ and the result is shown in figure 4.22. The scale is a little bit confusion so i will redo this plot for better readability.

Now, since the alignment works quite good with the current configuration we tested how translation misalignment effects the convergence by looking at the χ^2 , portrayed in figure 4.23. For this figure eight different samples of 100 μm module translation misalignment over all translatory degrees of freedom. The idea behind using different samples is to reduce errors from biased samples. The plot shows the total χ^2 over degrees of freedom plotted against the number of iterations. We see no visible difference regarding the total χ^2 between the samples which is good. Also, the total χ^2 decreases with and increasing number of iterations during the alignment.

We do want the least amount of constraints in the system so we also tested the consequences of removing constraints from "config5". In general, removing any constraint improves the χ^2

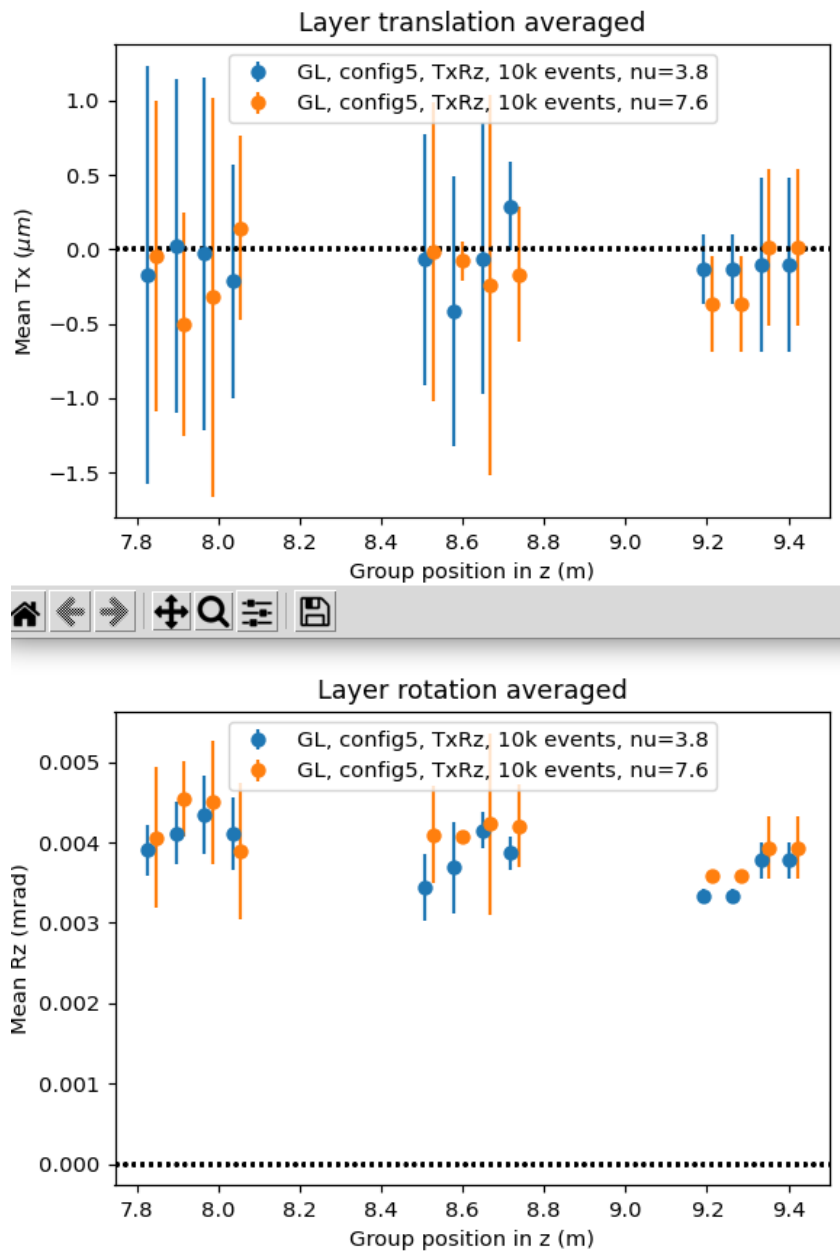


Abbildung 4.21: show difference between low and normal luminosity with clusterbias hack active.

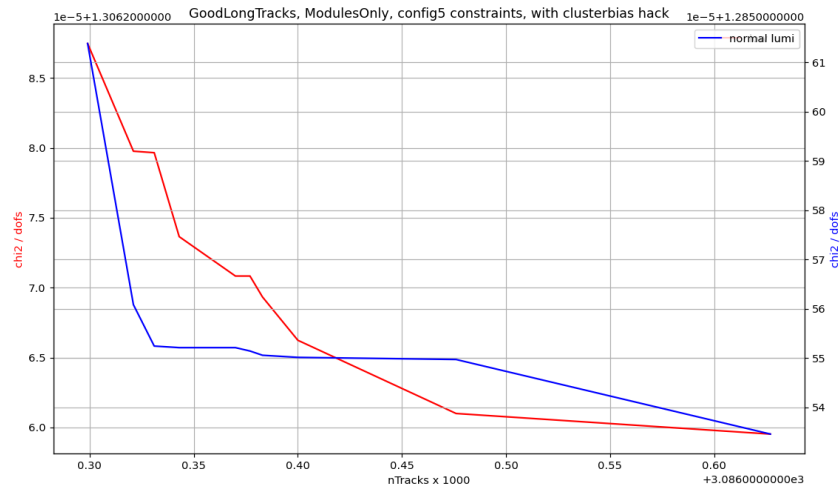


Abbildung 4.22: GoodLong tracks for module alignment and config 5 active. also the clusterbias hack is active comparing low and normal luminosity.

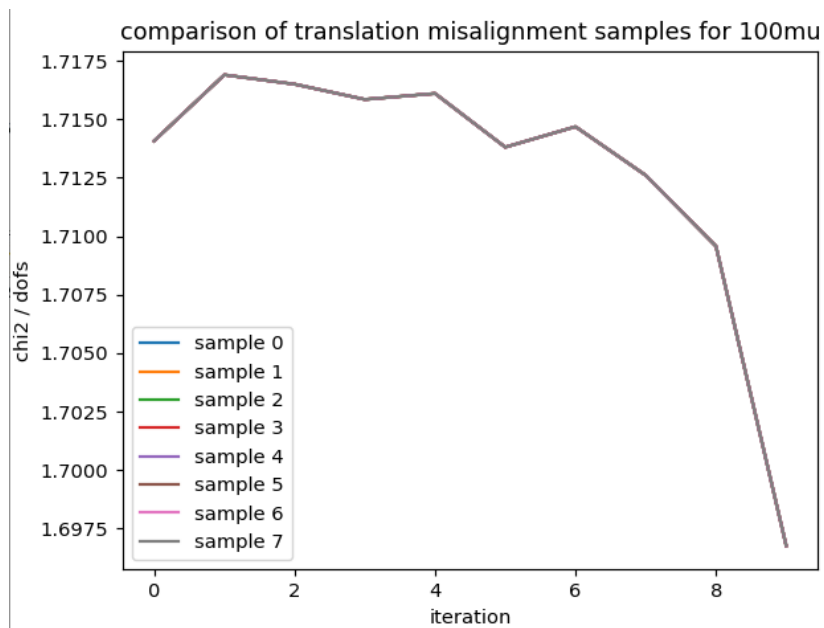


Abbildung 4.23: 100mu translation misalignment comparison for different misalignment samples.

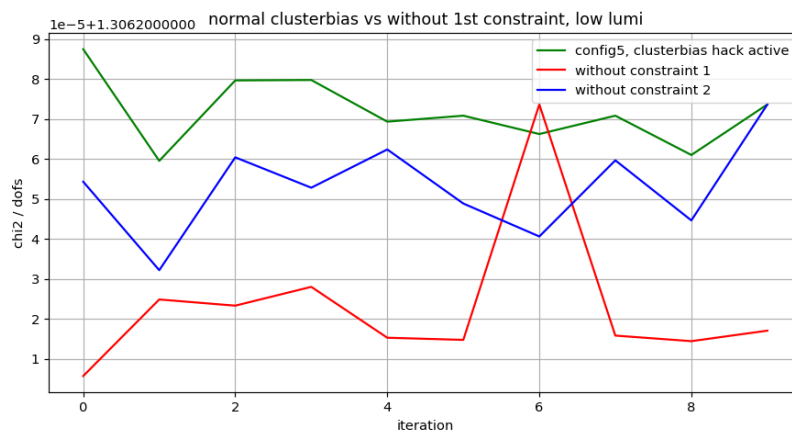


Abbildung 4.24: impact of removing constraints from exisiting studies regarding chi2.

5 Continuing Work

6 Future Work

instead of only doing normal(low) luminosity tests do it for the other luminosity as well (jan 24th)

7 Conclusion and Outlook

Literatur

- [1] *A diagram showing the complete structure of the LHC facility at CERN.* URL: https://www.researchgate.net/figure/A-diagram-showing-the-complete-structure-of-the-LHC-facility-at-CERN-There-are-the-4_fig8_348806406 (besucht am 09.03.2022).
- [2] *LHC Machine.* URL: https://cds.cern.ch/record/1129806/files/jinst8_08_s08001.pdf (besucht am 09.03.2022).
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- [5] *The invariant Rauch-Tung-Striebel Smoother.* URL: <http://ras.papercept.net/images/temp/IR0S/files/2526.pdf> (besucht am 24.03.2022).
- [6] *The LHCb Detector at the LHC.* URL: https://cds.cern.ch/record/1129809/files/jinst8_08_s08005.pdf (besucht am 09.03.2022).
- [7] J Van Tilburg. „Track simulation and reconstruction in LHCb“. Presented on 01 Sep 2005. 2005. URL: <https://cds.cern.ch/record/885750>.

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Eidesstattliche Versicherung

Ich versichere hiermit an Eides statt, dass ich die vorliegende Abschlussarbeit mit dem Titel „Alignment studies for the LHCb SciFi Detector“ selbstständig und ohne unzulässige fremde Hilfe erbracht habe. Ich habe keine anderen als die angegebenen Quellen und Hilfsmittel benutzt, sowie wörtliche und sinngemäße Zitate kenntlich gemacht. Die Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.

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