Muon Alignment in ATLAS and CMS

Detector Understanding with First LHC Data
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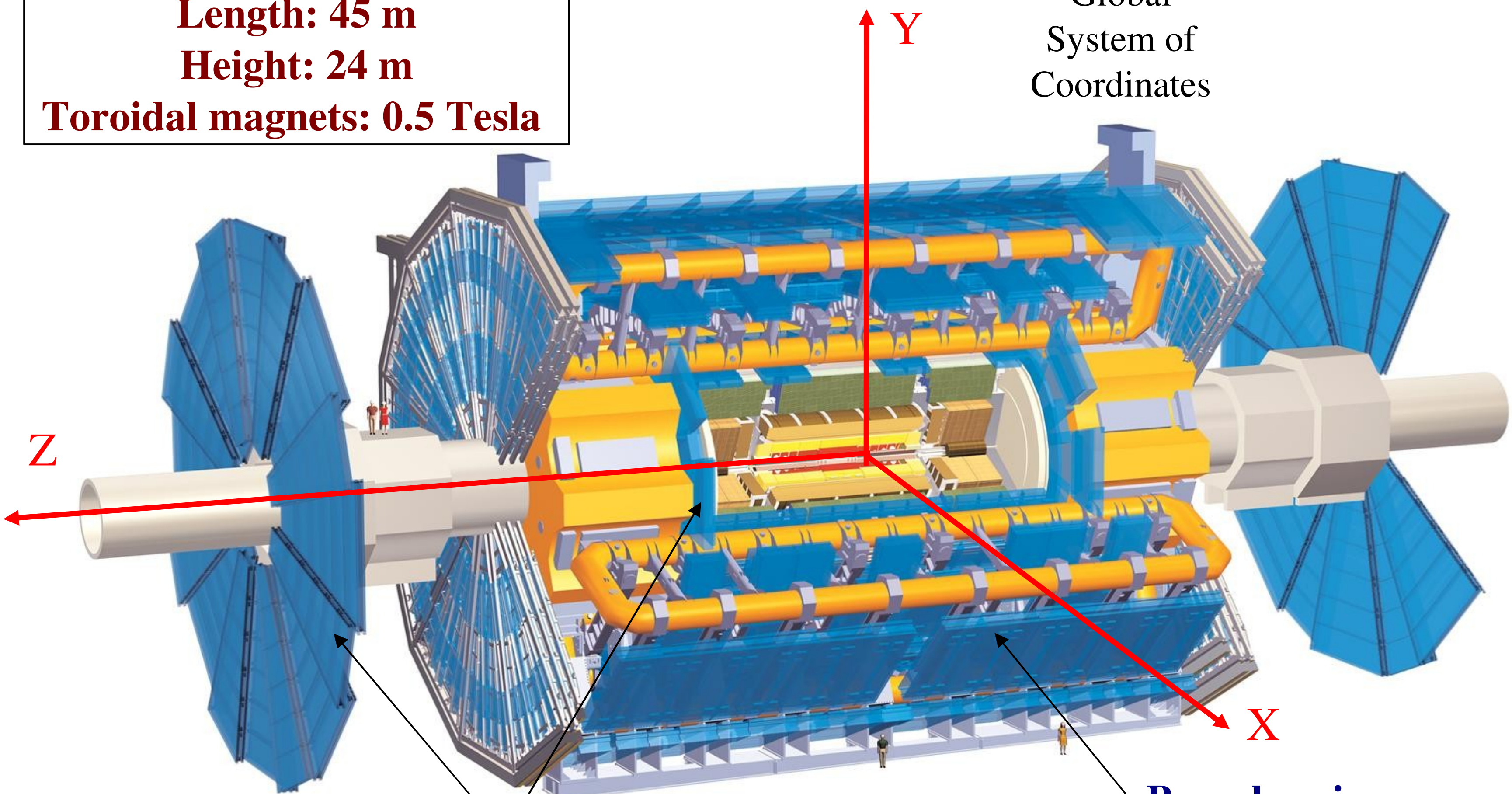
Introduction

- The aim of this talk is to show:
  - why the alignment of the muon spectrometers of ATLAS and CMS is so important and how it affects the reconstruction performance (specially in the first data)
  - which are the techniques used to align them (with some discussion on the weak and strong points)
  - which is the state of the art and what can be expected for the LHC start-up

The ATLAS Muon Spectrometer

Length: 45 m
Height: 24 m
Toroidal magnets: 0.5 Tesla

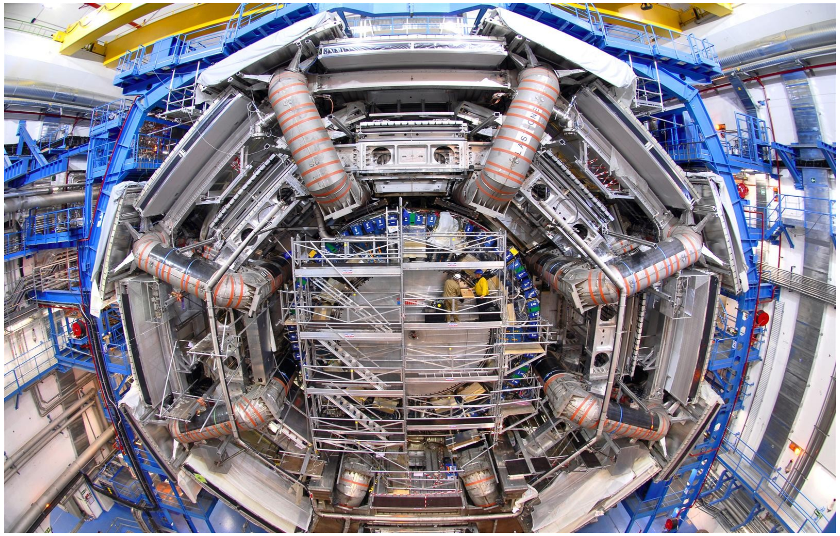
Global System of Coordinates



Endcap region:
Drift Tube Chambers + Cathode Strip Chambers + Resistive Plate Chambers

Barrel region:
Monitored Drift Tube Chambers + Resistive Plate Chambers

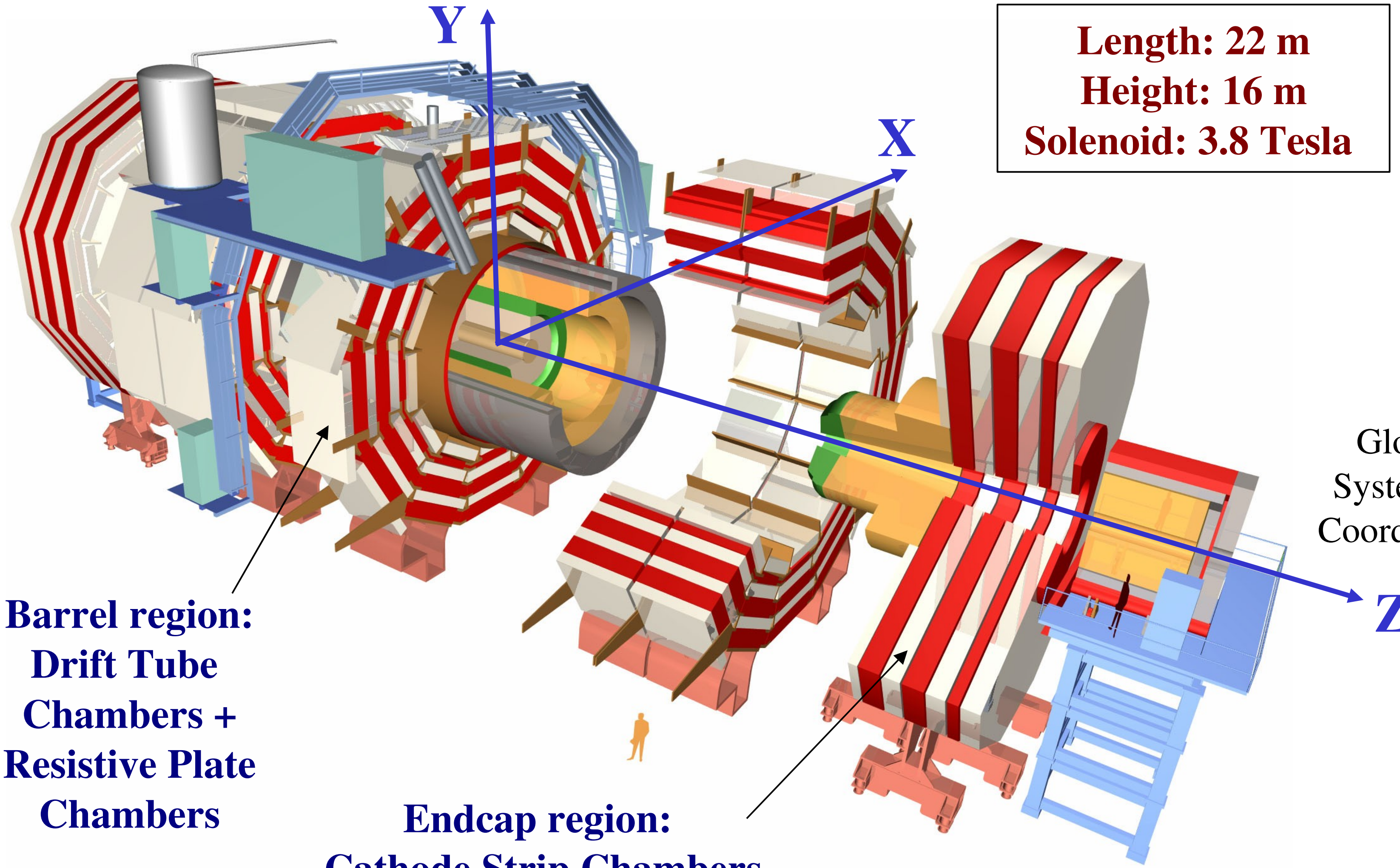
The ATLAS Muon Spectrometer



- MDT Chambers intercalated in the toroidal magnets
- There are 3 layers of chambers
- 16 phi sectors (8 short, 8 long)
- Spatial resolution of MDT chambers ~ 50 microns

- MDT and CSC chambers attached to the 4 endcap disks
- A total of 16 phi sectors (8 short, 8 long)
- Spatial resolution of MDT chambers ~ 50 microns, CSC ~ 40 microns

The CMS Muon Spectrometer



Length: 22 m
Height: 16 m
Solenoid: 3.8 Tesla

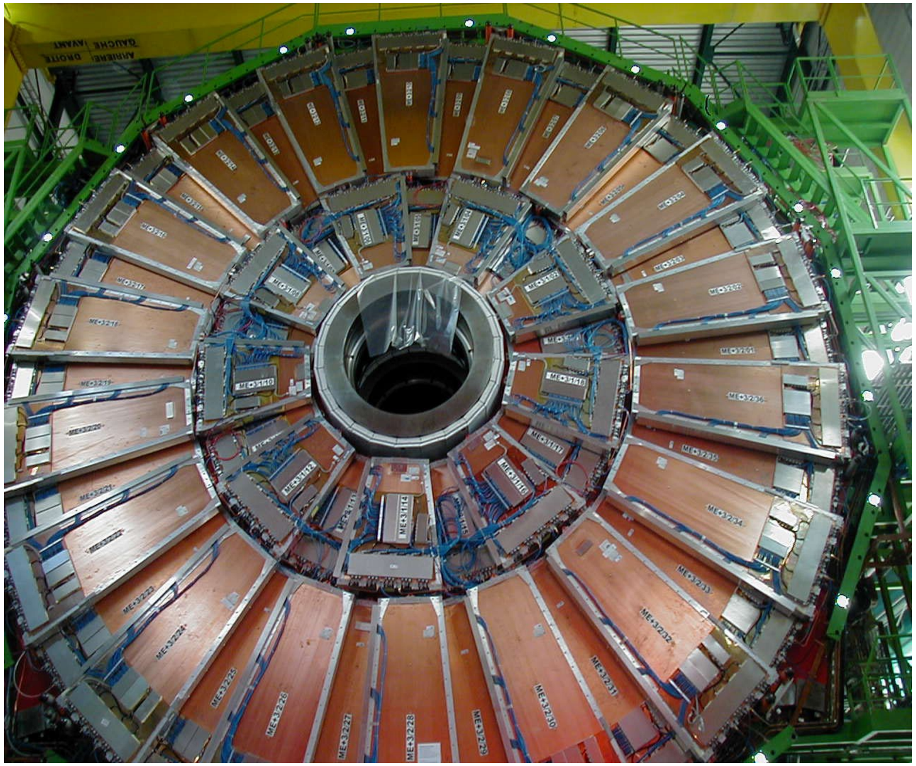
Global System of Coordinates

Barrel region: Drift Tube Chambers + Resistive Plate Chambers

Endcap region: Cathode Strip Chambers + Resistive Plate Chambers

The CMS Muon Spectrometer

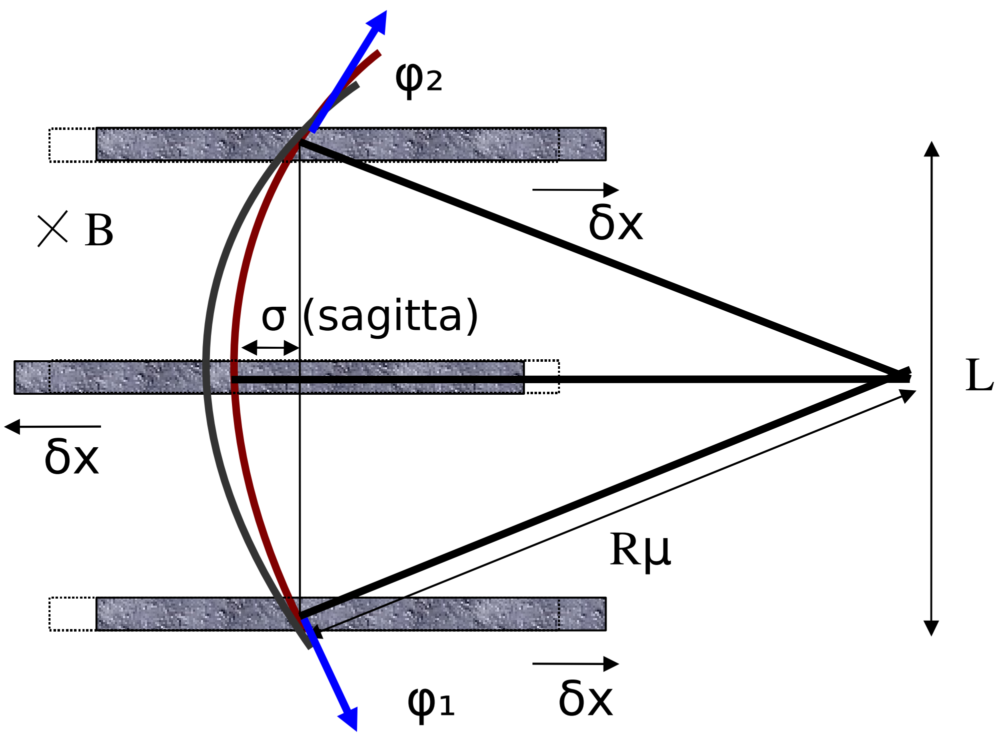
- **DT Chambers are embedded in the return yoke**
- **There are 5 wheels, with 4 layers or stations and 12 phi sectors**
- **Spatial resolution of DT chambers ~ 100-150 microns**



- **CSC Chambers are attached to the endcap disks**
- **There are 4 disks or stations, with 2 rings (3 in the fist station), and 18 phi sectors**
- **Spatial resolution of CSC chambers ~ 100 microns**

The alignment challenge (I)

- **Tracking detectors measure the position in the space of the particles.**
- **The momentum of a charged particle is related to the sagitta (maximum deviation from the straight line), and to the difference in the direction.**



$$P_T(GeV) = 0.3BR_\mu = \frac{0.3BL^2}{8\sigma}$$

$$P_T(GeV) = 0.3BR_\mu = \frac{0.3BL}{\delta(\varphi 2 - \varphi 1)}$$

$$\frac{\delta\sigma}{\sigma} = \frac{\delta P_T}{P_T} \qquad \frac{\delta(\varphi 2 - \varphi 1)}{\delta\varphi} = \frac{\delta P_T}{P_T}$$

Let's imagine a muon spectrometer with B=1 Tesla, and L = 3 m (not too far from ATLAS and CMS) detecting a 500 GeV muon

$$\sigma = 650\ \mu m$$

$$\delta(\varphi 2 - \varphi 1) = 1.8\ mrad$$

If δx is ~ 200 microns

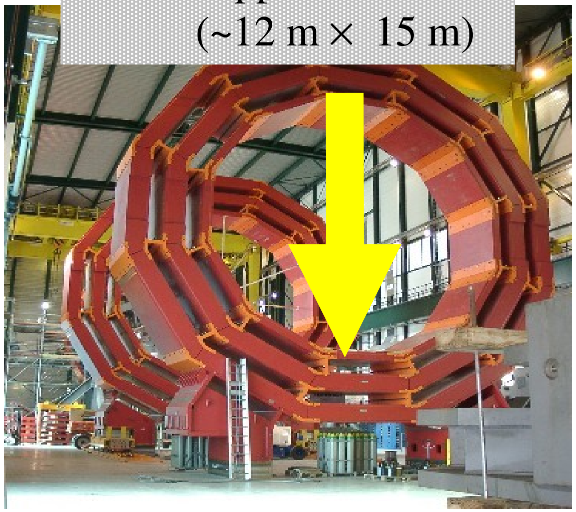
$$\frac{\delta\sigma}{\sigma} = \frac{\delta P_T}{P_T} = 60\ percent$$

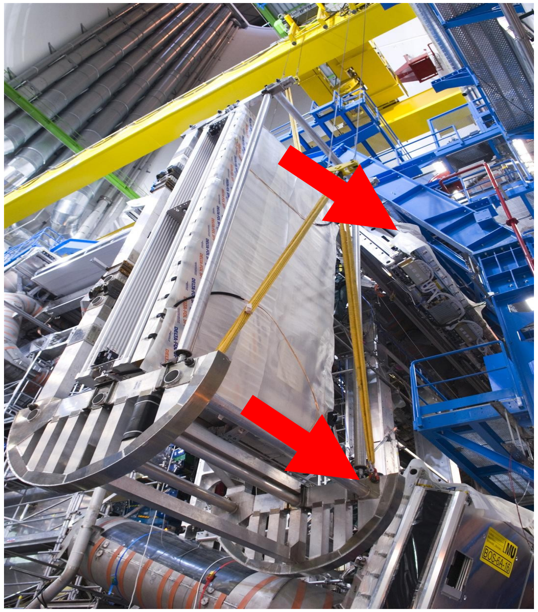
The alignment challenge (II)

- **Mechanical structures are not rigid. Misalignments are expected.**
  - **Gravity (detectors are very heavy)**
  - **Magnetic Field (the field is so strong that could provoke movements and deformations)**
  - **Temperature effects, operation effects**
  - **Construction/assembly tolerances**

The muon spectrometers of ATLAS and CMS must be aligned to the level of ~50 microns and ~200 microns to exploit their full Physics potential

Barrel support structure (~12 m × 15 m)





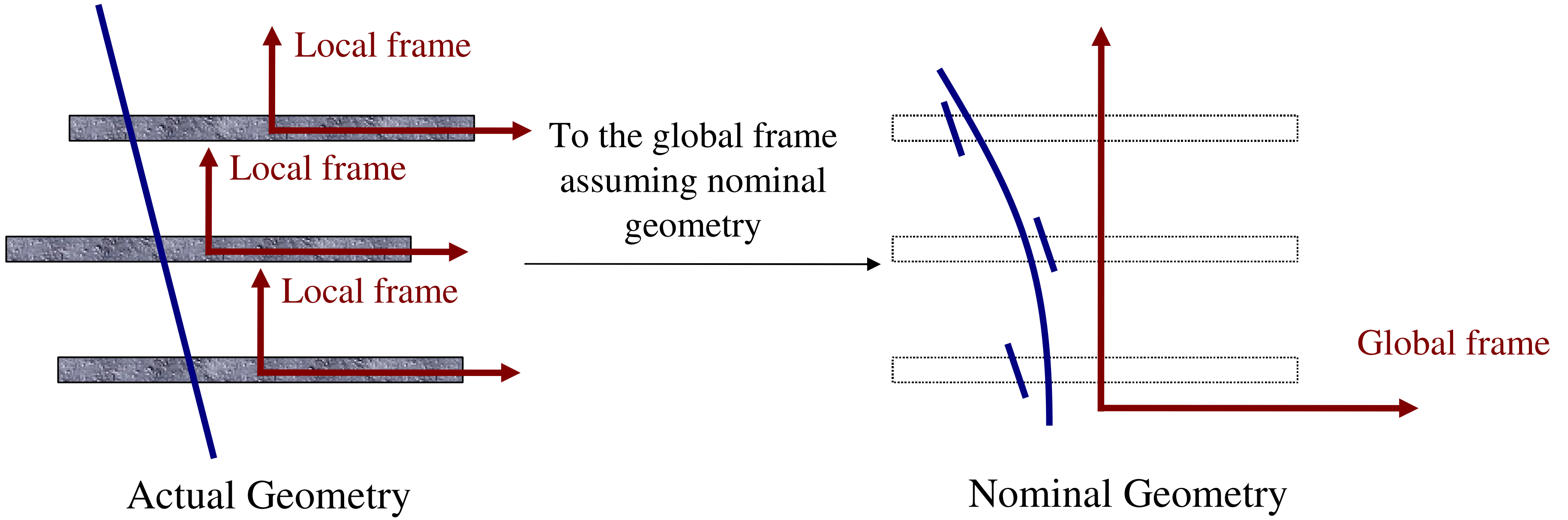
Correcting for misalignments

- **Tracking detector are composed by a large amount of subdetectors**
- **Each detecting element defines a local frame in which it makes the measurement**
- **In order to reconstruct a full track it is needed to put all the different measurements in the same system of reference**
- **Misalignments affect to this conversion**

The conversion from local to global is done as follows

$$x_{global} = R x_{local} + \delta$$

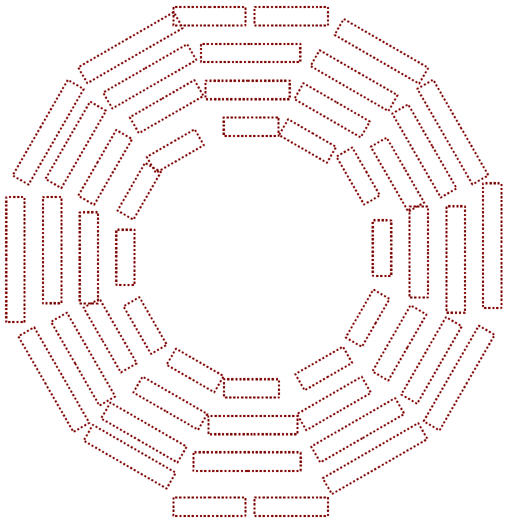
where R is a rotation matrix and δ a displacement.
The target of the alignment is to find the actual R and δ



Understanding the effect of misalignment

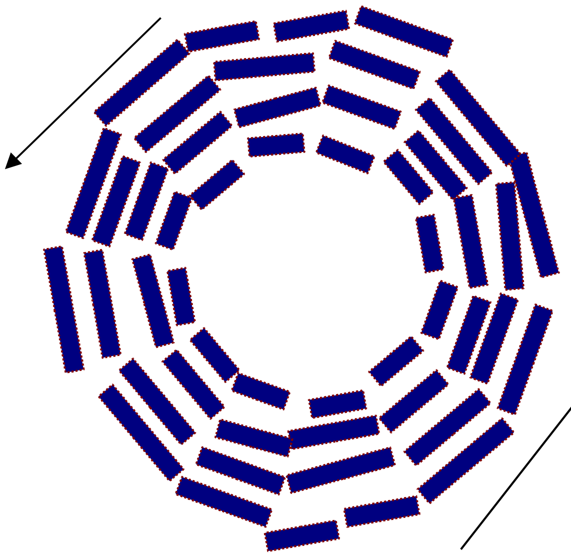
- **In order to study the effect and consequences of a misaligned detector Monte Carlo studies are performed**
- **Generated samples are reconstructed in a fake, misaligned geometry called scenario (instead of adding corrections to the geometry, misalignments are added)**
- **Scenarios try to reproduce the level of expected misalignment**
  - **Chambers are randomly smeared according to the alignment precision**
  - **Known systematic effects can be emphasized**

Nominal geometry



Smearing + rotation
(example)

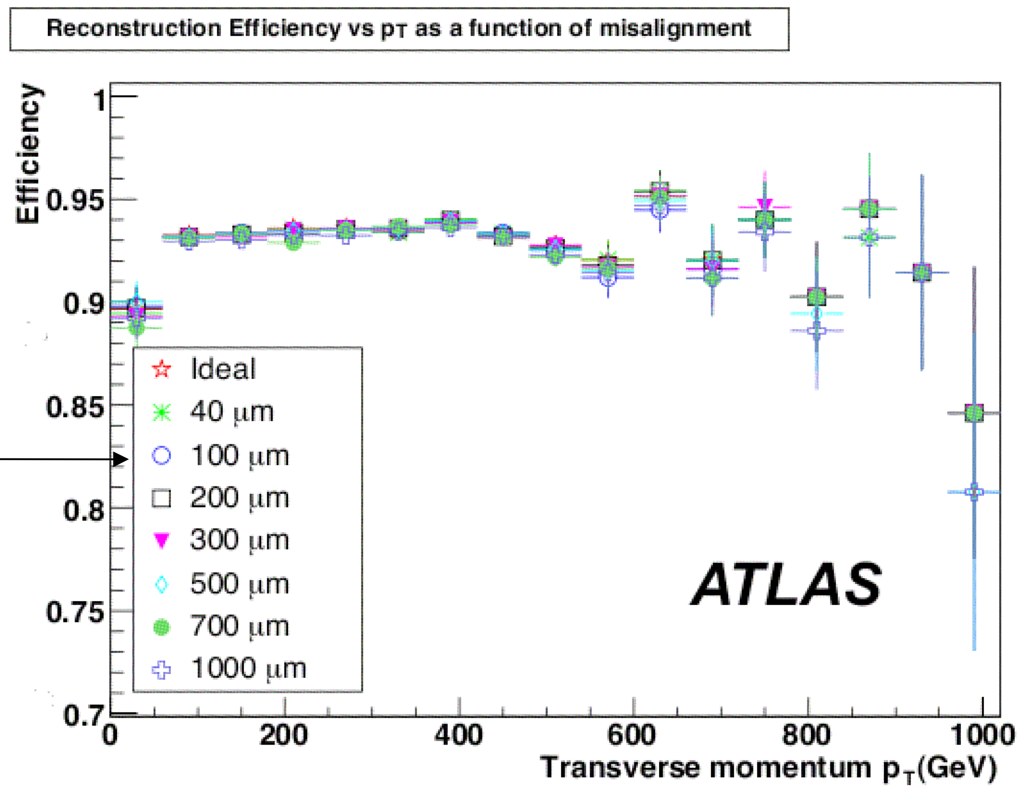
Scenario



Impact of misalignments on the reconstruction

- **The efficiency of the reconstruction is not seriously affected by small misalignments**
  - **As long as the misalignments are not huge, the hits are still being associated to the track and hence the track is reconstructed**

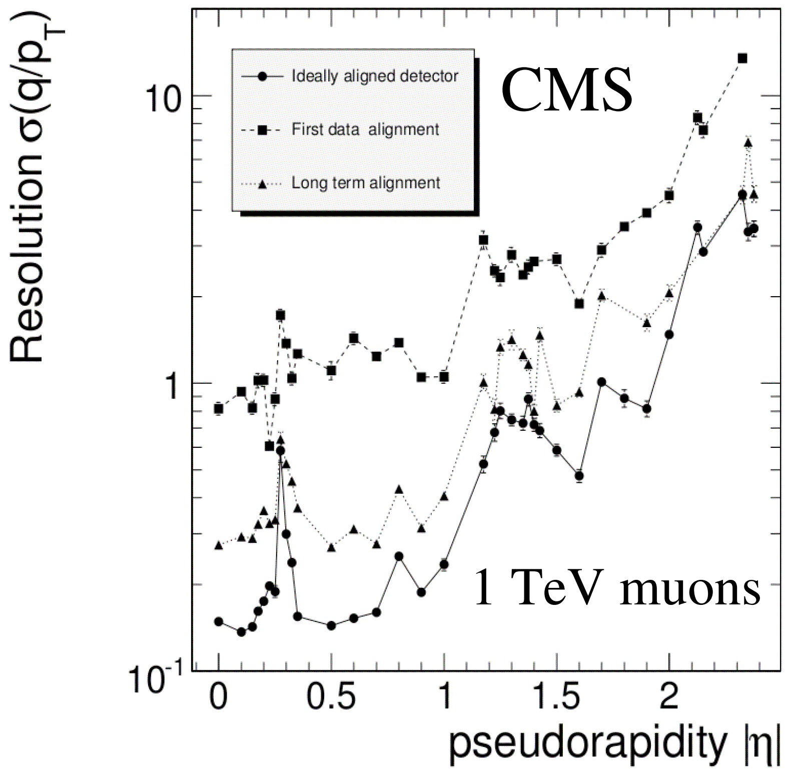
Misalignment scenarios: the detector is smeared with this amplitude

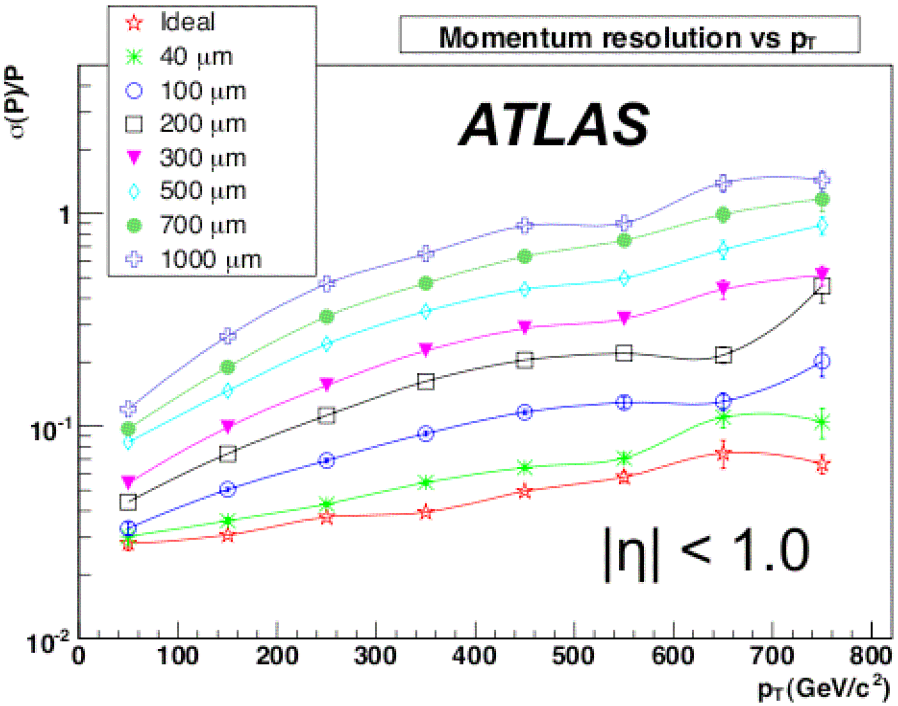


Similar behaviour in CMS

Impact of misalignments on reconstruction

- **Misalignments affect the momentum measurement and therefore the momentum resolution**



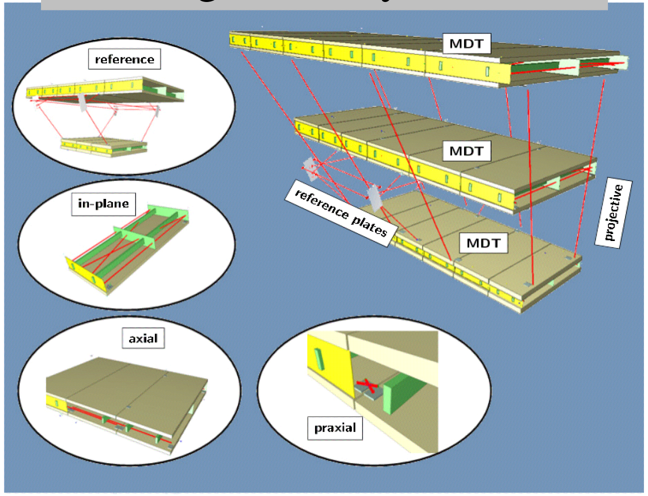


Momentum resolution degrades with the magnitude of the misalignments

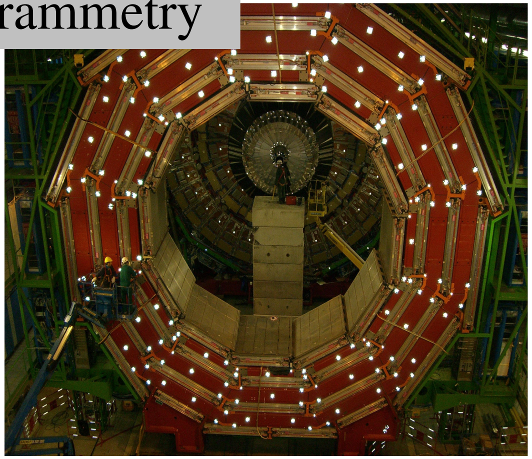
Alignment information

- There are mainly three different source of alignment information

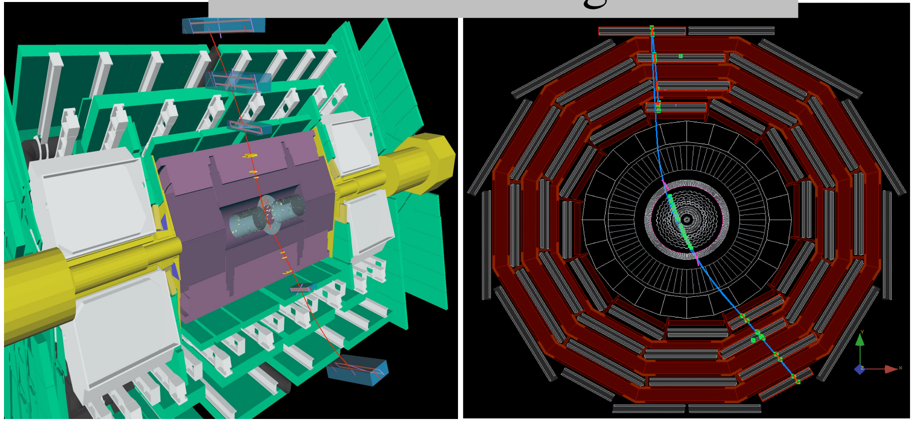
Optical-Hardware Alignment Systems



Photogrammetry



Track-Based Alignment



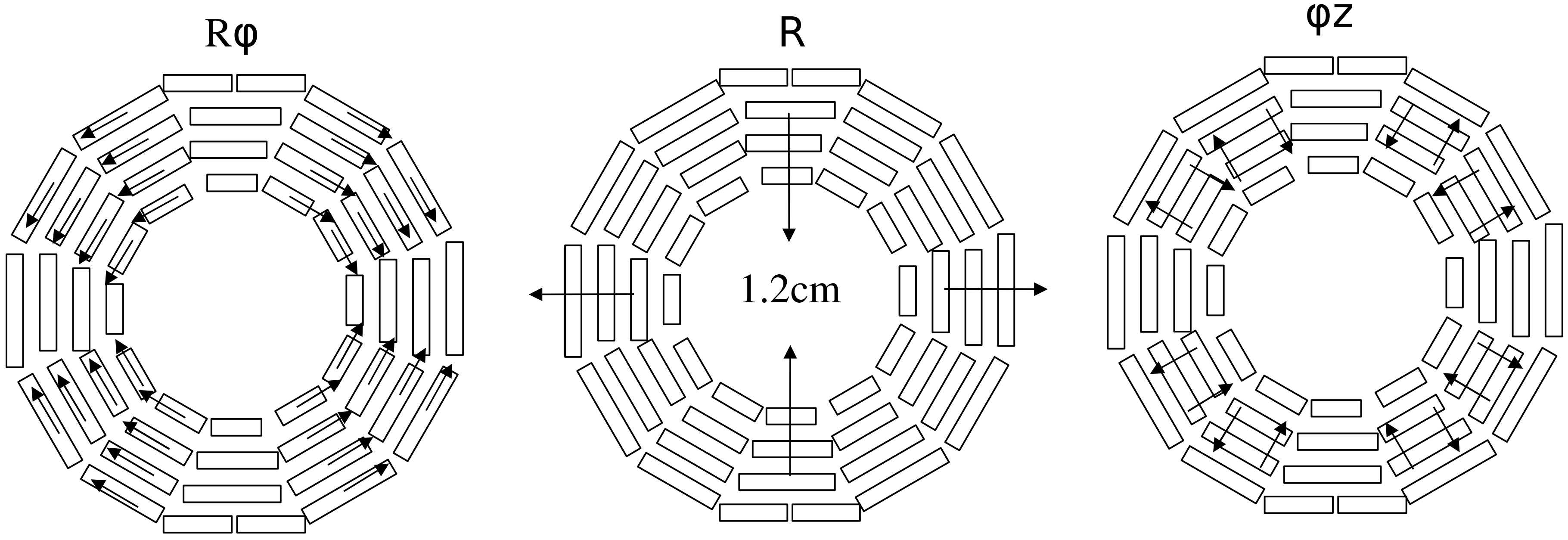
Photogrammetry

- Bright targets are distributed over the detector
- Pictures are taken from different locations to find their position
- Some advantages:
  - Independent from track measurements
- Some drawbacks:
  - It can be only applied in some specific situations (usually during shutdown periods)
  - It's not able to reach the detecting elements themselves but just external references

Photogrammetry is used also to calibrate the hardware alignment systems

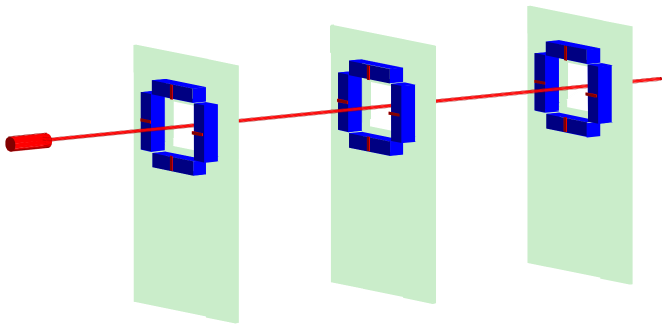
Photogrammetry.Example in CMS

- **Example of the analysis of the photogrammetry measurements in the DT chambers of CMS**
- **Relevant movements in Rφ, R and φz indicating a gravitational sag. The wheels compress vertically and expand horizontally.**



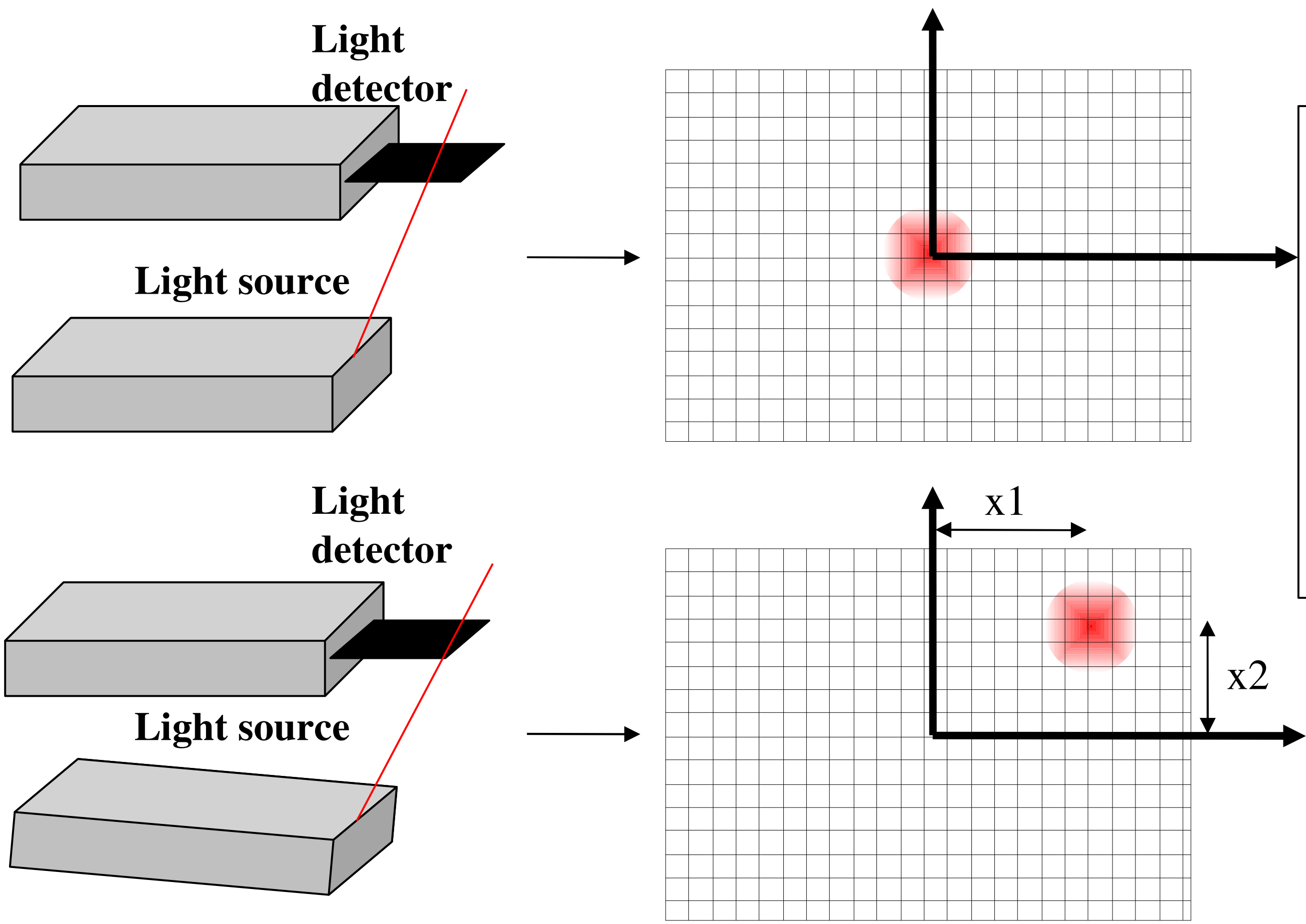
The Hardware-Optical Alignment Systems (I)

- **A collection of laser lines, light detectors, temperature sensors, and distance and tilt meters, disposed in a redundant scheme allowing the measurement of misalignments (see following transparencies)**
- **Some advantages:**
  - **Independent from track measurements**
  - **Fast response, almost quasi-online monitoring**
- **Some drawbacks:**
  - **It's not able to reach the detecting elements themselves but some external references**
  - **Hard calibration of the components**



Relative Mode
Optical Systems are able to measure differences between the detector at time t1, and the detector at time t2

Absolute Mode
They can also provide absolute alignment information. A very good calibration of the alignment components is needed

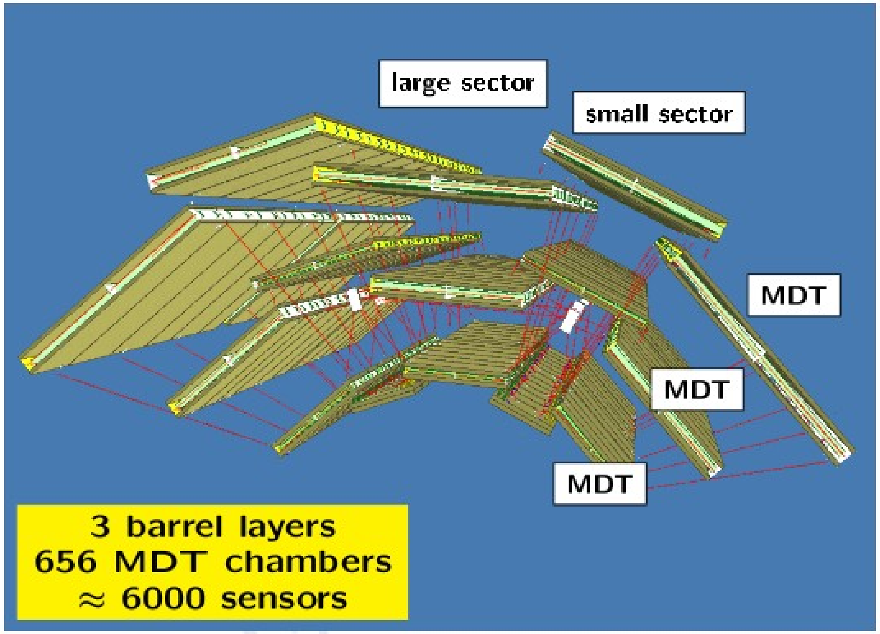


f(δ) is the model, which depends on the topology of the system and the alignment parameters

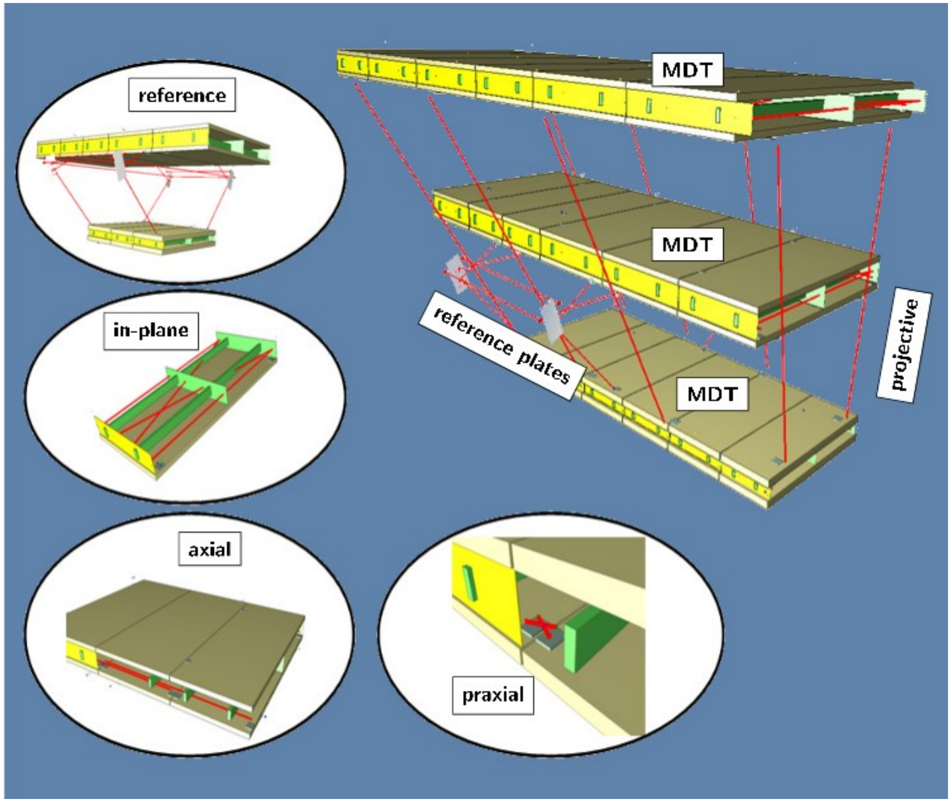
$$\sum_{ij} \frac{\left(X_{ij}^{calculated} - X_{ij}^{measured} - f(\delta)\right)^2}{\sigma_{ij}}$$

- **Residuals are minimized as a function of the alignment parameters, in a combined chi2 which has into account all the different correlations**

The ATLAS Hardware Alignment System: Barrel

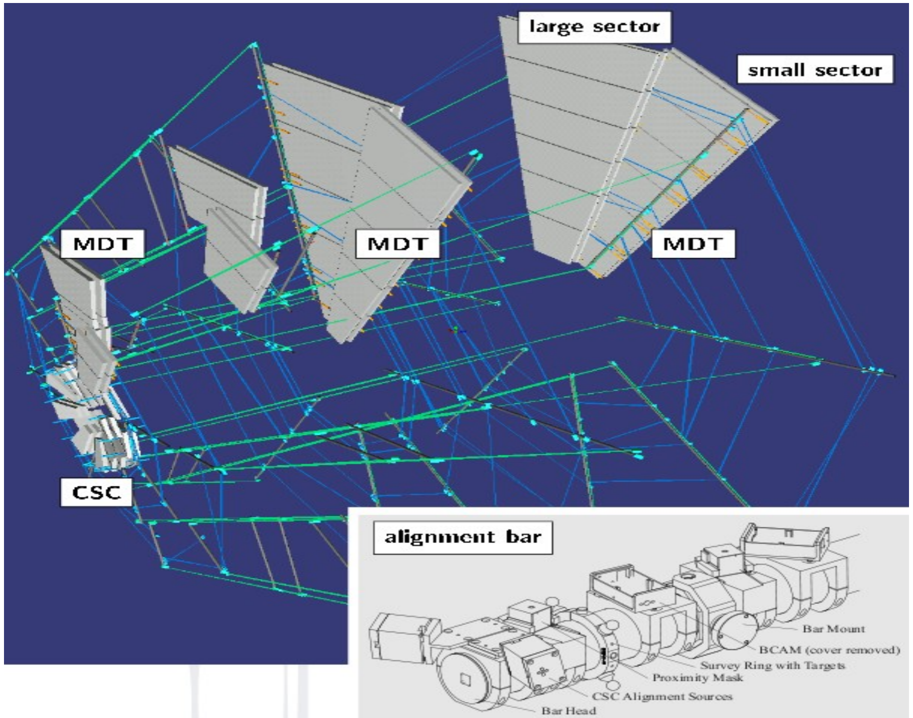


- Internal alignment of the barrel region
- Laser lines and light detectors near the corners of the chambers

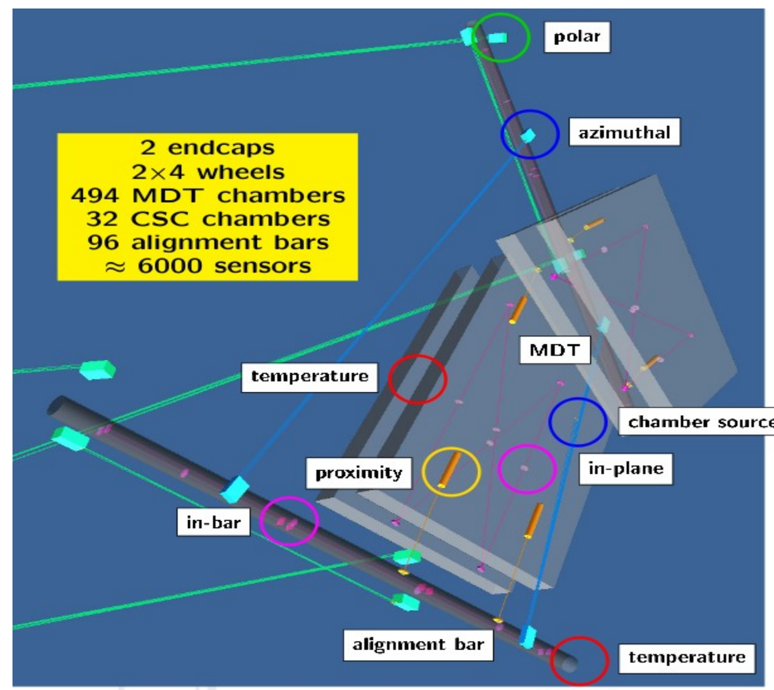


- Projective lines: alignment between layers
- Axial lines: alignment within a layer
- Reference lines: inner layers and sectors
- In plan lines: deformations
- Temperature: expansions

The ATLAS Hardware Alignment System: Endcap



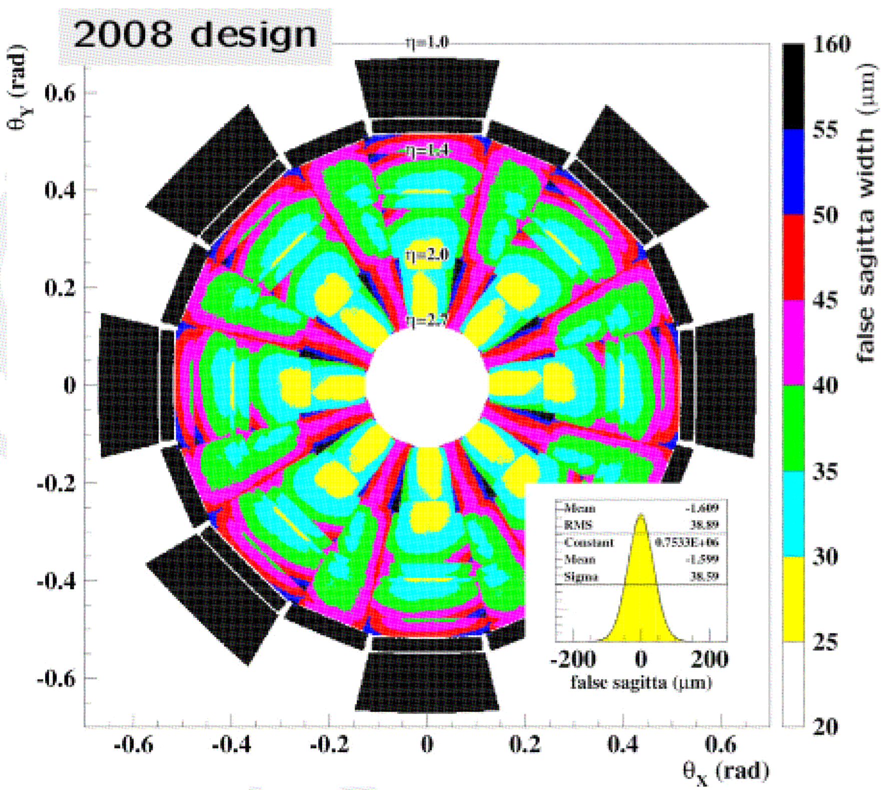
- Internal alignment of the endcap region
- Instrumented alignment bars deploy a laser network

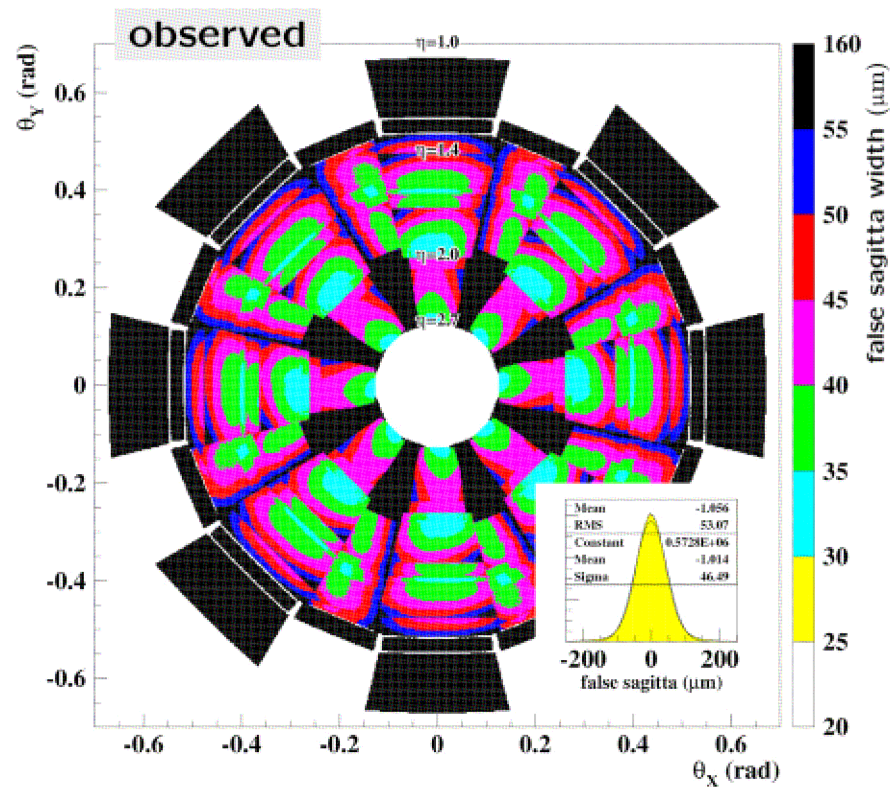


- Polar lines: alignment to other wheels
- Azimuthal: alignment of chambers in the wheel
- In plane: Deformations
- Temperature: Expansions

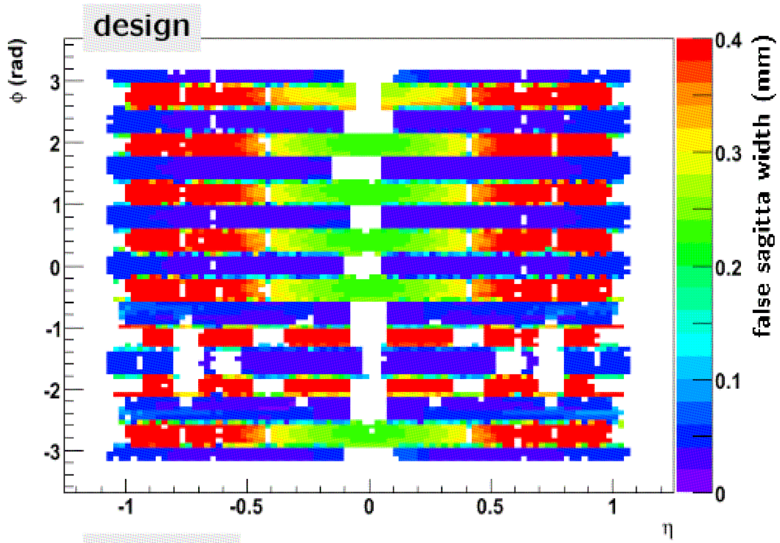
The ATLAS Hardware Alignment System: Results (I)

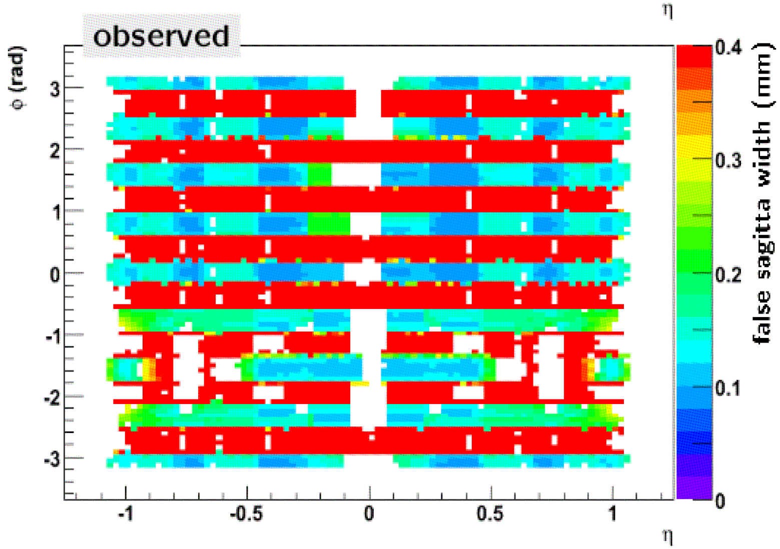
- **Straight tracks (magnetic field off) are used to calculate the remaining false sagitta**
- **The endcap was designed to have 40 microns of sagitta accuracy**
- **The achieved resolution is 45 microns except for small CSC chambers at high eta**





The ATLAS Hardware Alignment System: Results (II)

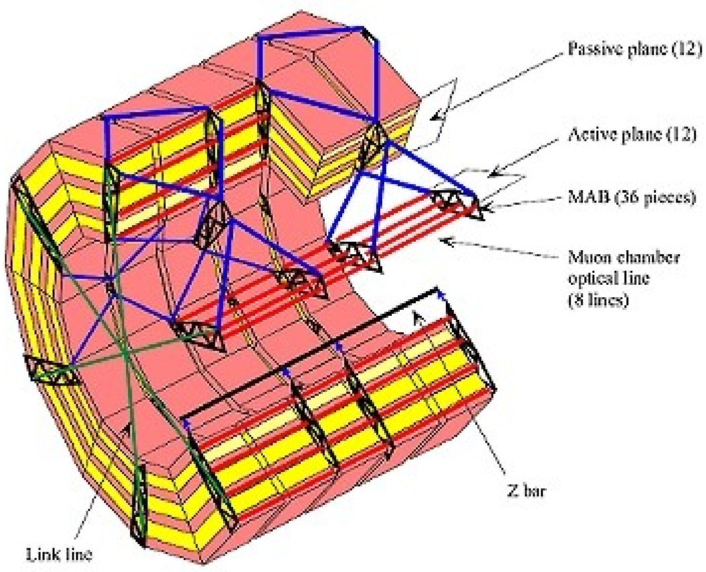


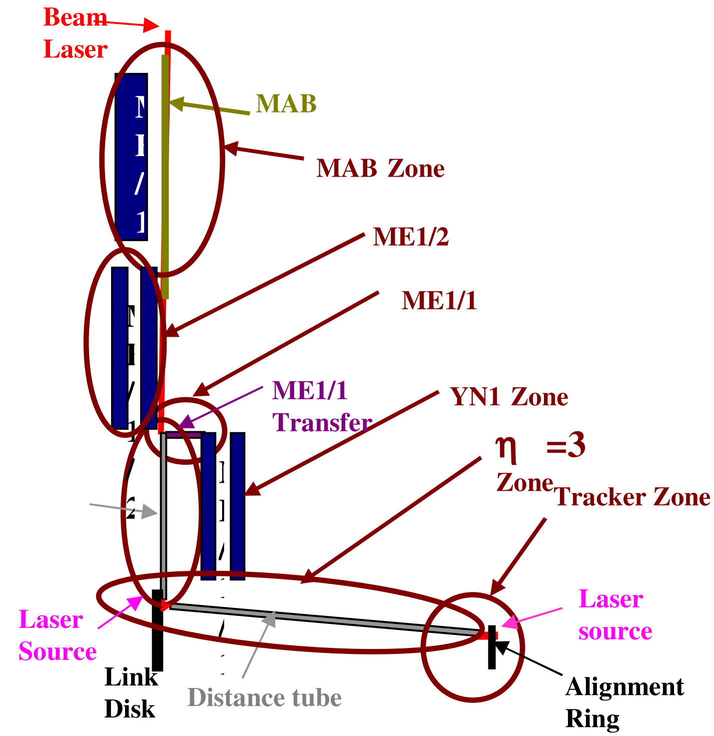


- Straight tracks (magnetic field off) are used to calculate the remaining false sagitta
- The barrel was designed 30/300 microns sagitta accuracy for large/small sectors
- The observed accuracy is 200/1000 microns for large/small sectors
- Track-based alignment is needed to provide initial positions of the chambers

The CMS Hardware Alignment System: Barrel & Link

- Barrel System: Internal alignment of the drift tube chambers
- Active planes: optical lines monitoring the chamber position
- Passive planes: optical lines monitoring active planes

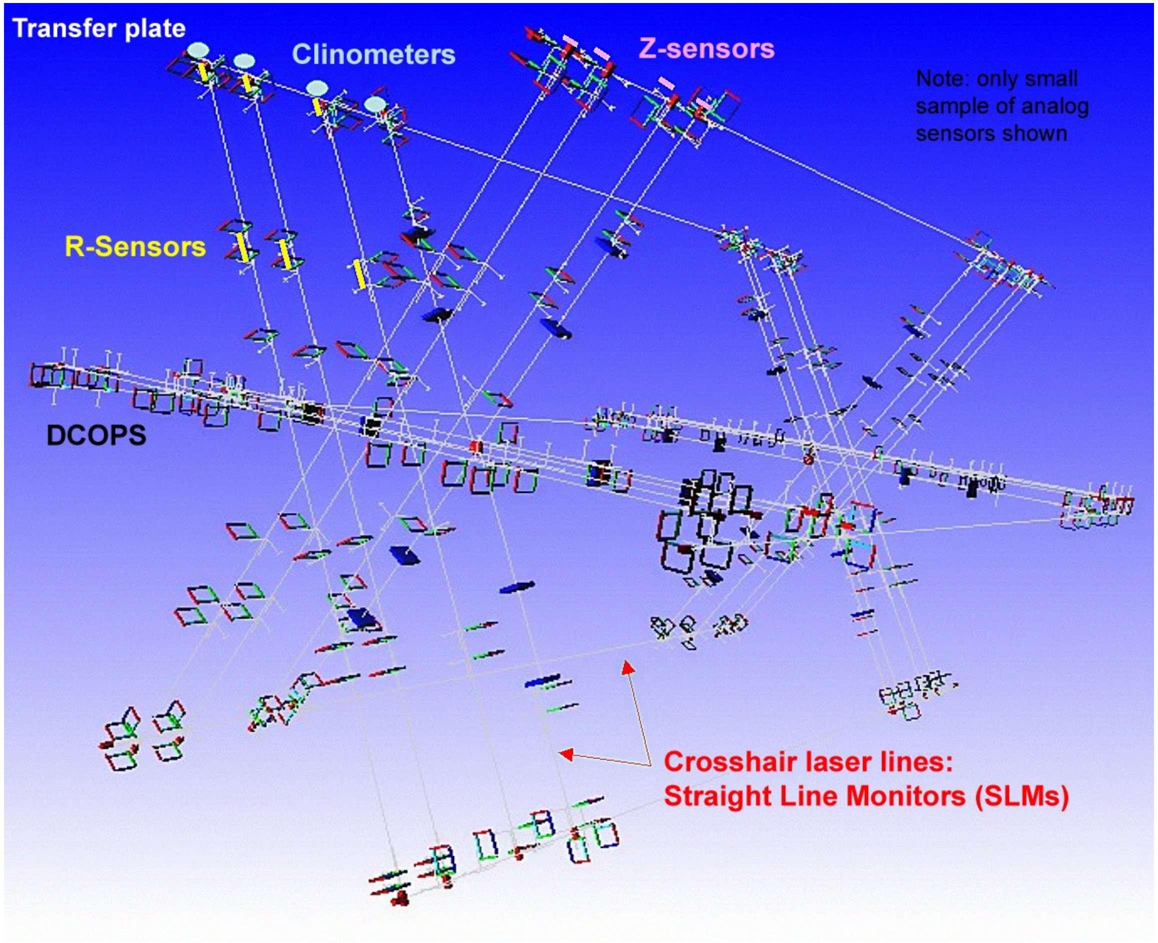




- Link system: relative alignment of barrel, endcap and central tracker
- Tracker-Endcap lines: relative alignment tracker and endcap
- Endcap-Barrel lines: relative alignment endcap barrel
- ME1/1 lines: alignment of ME1/1 chambers

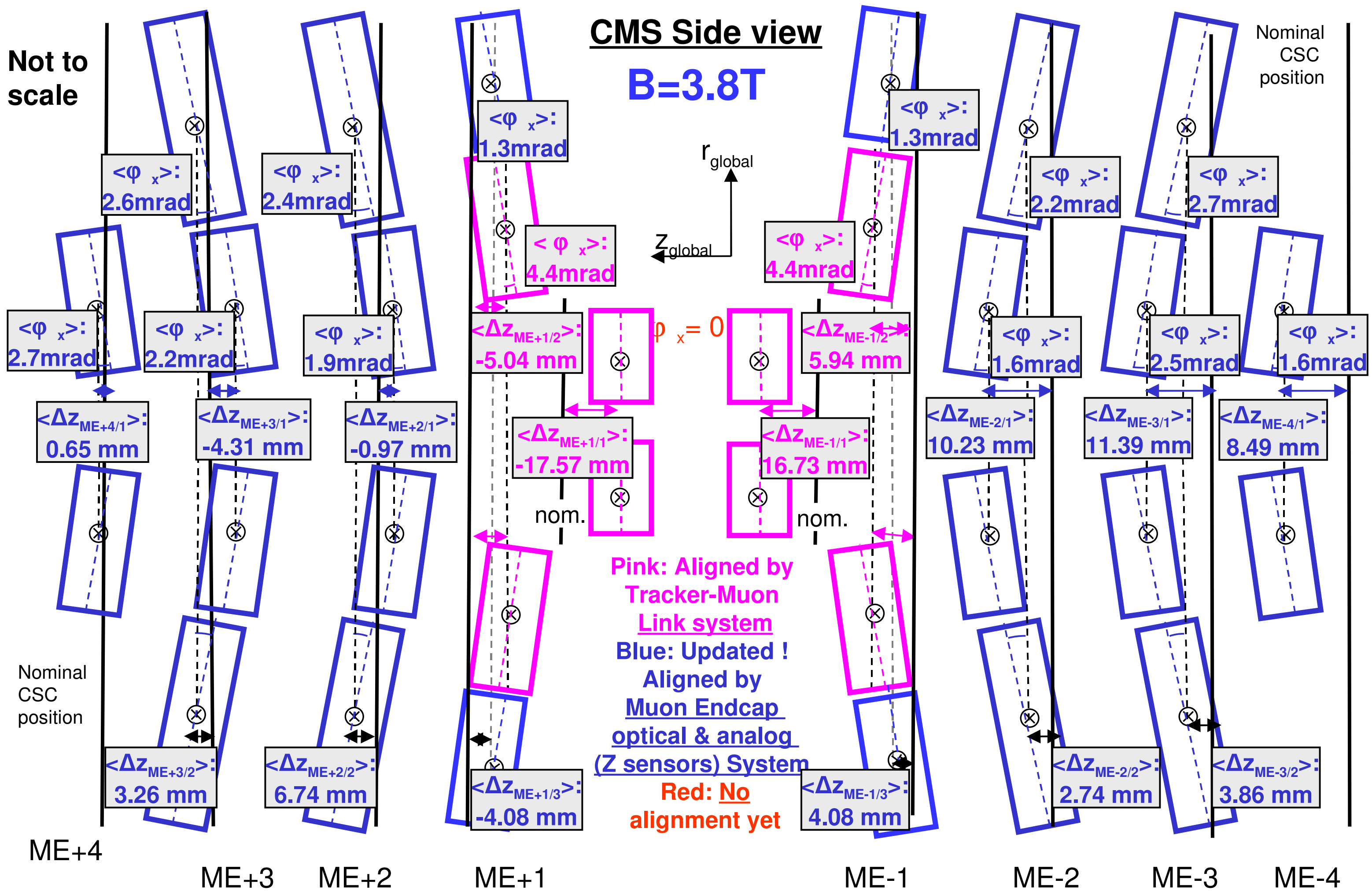
The CMS Hardware Alignment System: Endcap

- Relative alignment Cathode Strip Chambers with respect to each other



- **Straight Line Monitors: chambers within one station**
- **Z sensors: relative z distance between endcap muon stations**
- **Transfer lines: Relative X, Y position of the muon endcap stations**

The CMS Hardware Alignment System: Results

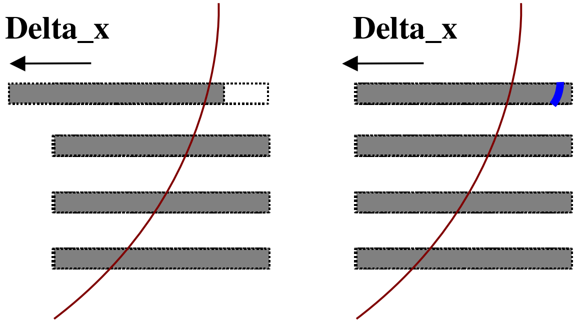


Precision better than 1mm

- Reconstruction complete in the endcap. Compression due to the magnetic field.
  - the endcap adopts the shape of a lens

Track-Based Alignment

- The idea is to use the redundancy in the track parameter determination to infer alignment information
- Some advantages:
  - Intrinsically deals with the actual detecting elements
  - Very precise as long as enough tracks are collected
- Some drawbacks:
  - Sensible to all the systematics affecting the tracking
  - Require accumulation of enough statistics



Example: The reconstruction is done only with the first three layers. The track is then extrapolated to the forth and compared with the actual measurement (residual).

Intrinsic mode
Alignment of some structures using only track information from themselves.
Some examples: Millepede algorithm, the HIP algorithm, alignment using Kalman Filter techniques

Reference mode
Alignment of some structure using track information from other structure.
(Relative alignment of one structure with respect to other)

Track-Based Alignment: Systematics (I)

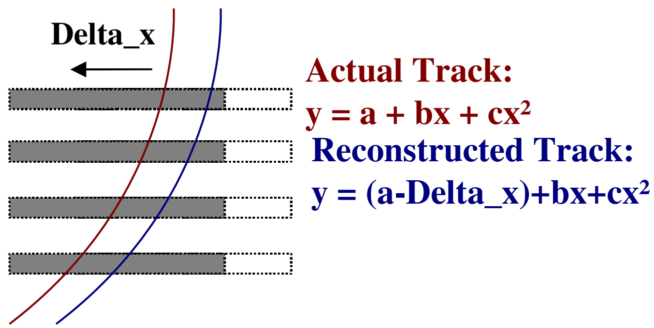
- **Track based alignment algorithms are affected by tracking systematics**
- **Everything which produces a deviation of the reconstructed track with respect to the actual track will bias the track based alignment**
  - **Uncertainties in the magnetic field**
    - **The effect reduces as Pt increases**
    - **Particles and antiparticles compensate the effect**
  - **Uncertainties in the material description**
    - **The effect reduces as Pt increases (Energy Loss Bethe-Block formula)**
  - **Multiple scattering**
    - **The effect reduces as Pt increases (Coulomb Scattering formula)**
  - **Internal calibrations of subdetectors**

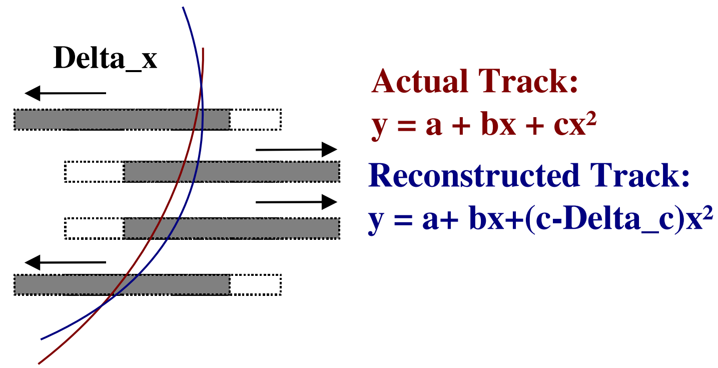
$$\delta\sigma = \frac{0.3L^2}{8P_T}\delta B$$

Many of the effects are small as long as the Pt is high enough, however the luminosity of high momentum muons is of course lower (approximately a decreasing potential law for cosmics, and a decreasing exponential for pp collisions).

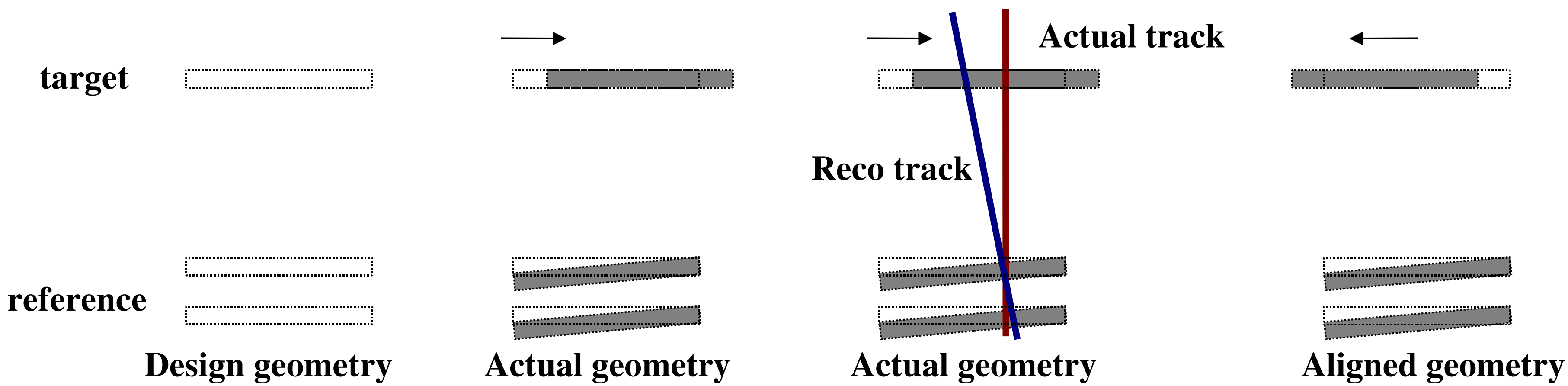
Track-Based Alignment: Systematics (II)

- Standalone alignment algorithms are blind to some specific configurations of misalignments, absorbed in the track parameters. These are called weak modes.



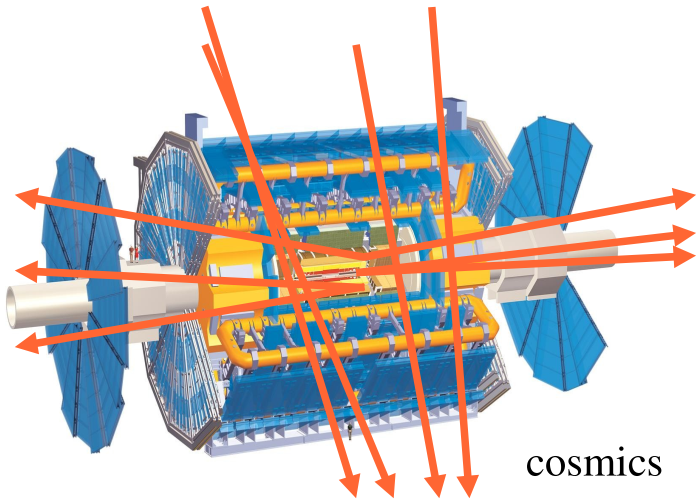


- One strong systematic in the by-reference algorithms is the propagation of misalignments in the reference system to the target system

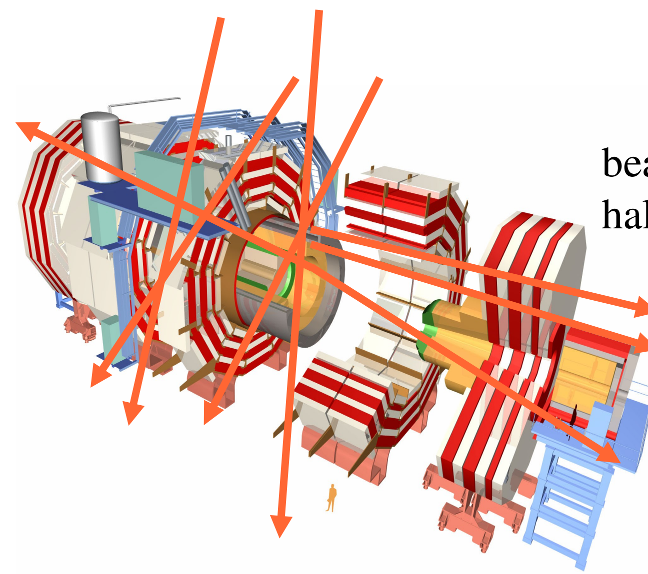


Track-Based Alignment in ATLAS & CMS: overview

- **Cosmic and beam halo muons provided the opportunity to test the track based alignment algorithms in the muon spectrometer of ATLAS & CMS**
- **However the topology of these muons is not able to give a uniform illumination of the chambers**
  - **For example: cosmic muons are mainly orthogonal to the ground ($\cos^2(\theta)$ distribution), and therefore very few muons cross the sides of the detectors**
- **Many different algorithms are applied depending on:**
  - **Kind of data sample: cosmic, beam-halo**
  - **Part of the muon spectrometer**
  - **Kind of alignment: by reference, intrinsic**
- **In the following transparencies a compilation of results is shown**



cosmics



beam halo

Track-Based Alignment in ATLAS

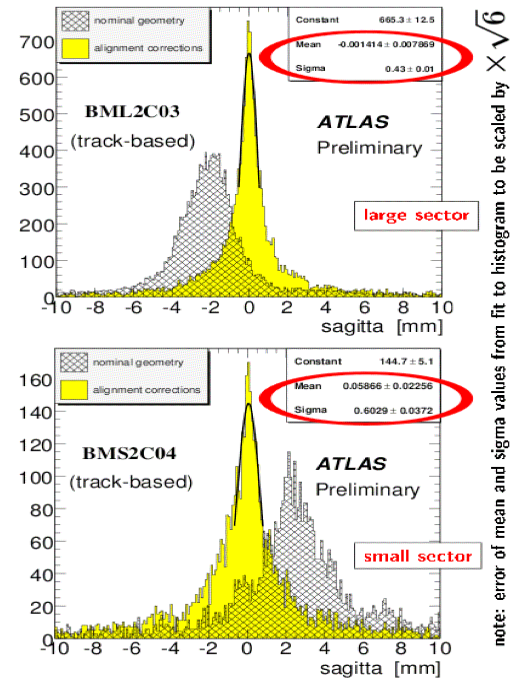
- **An implementation of the so called Millepede method is developed**
- **The input from this method are the residuals: the difference between the reconstructed track in the muon system and the measurements of the chambers**
- **Residuals are minimized against the track and alignment parameters in a combined fit**

$$\vec{x}(\vec{p}+\overrightarrow{\Delta p},\vec{\delta})\approx\vec{x}(\vec{p},0)+J_p\overrightarrow{\Delta p}+J_\delta\vec{\delta} \longrightarrow \vec{R}\approx J_p\overrightarrow{\Delta p}+J_\delta\vec{\delta}$$

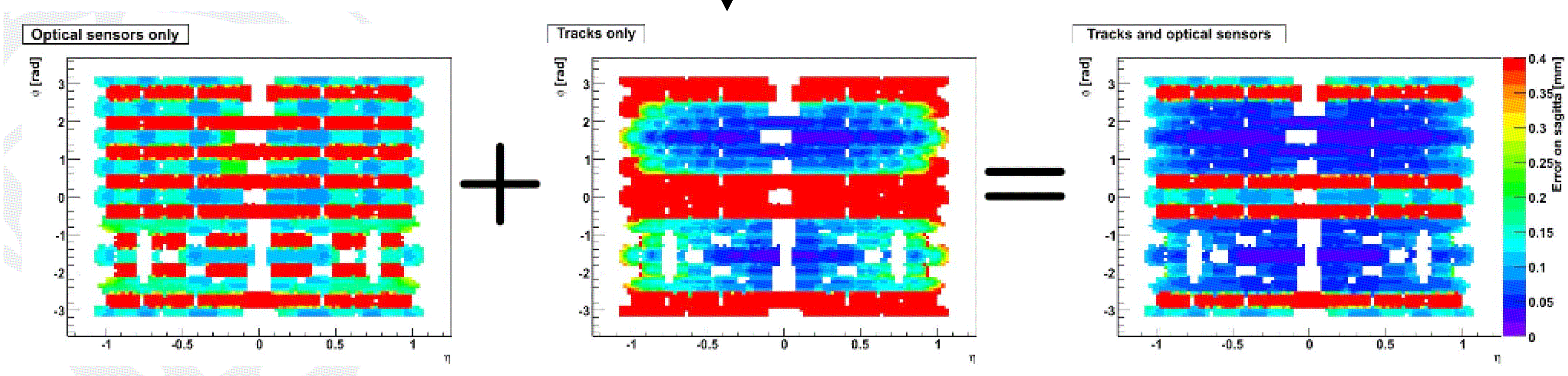
The measurements in the chambers are a function of the real momentum of the particle and the misalignments

Residuals are a function of the error in the momentum estimation and the misalignments

- **After the alignment the sagitta using straight tracks is of the order of 30/50 microns for large/small sectors at the top and the bottom**

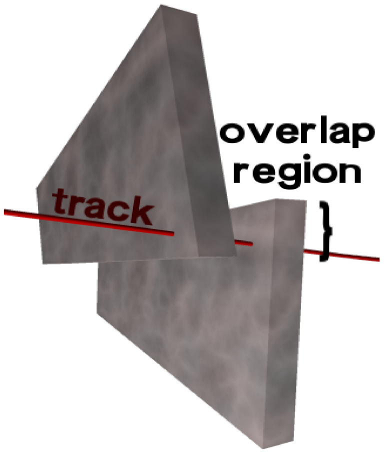


- **Finally using cosmic muons: (Before LHC run)**
  - **Good alignment for top and bottom sector**
  - **While large side sectors only 200 microns (from optical) and small side sectors at 1mm**

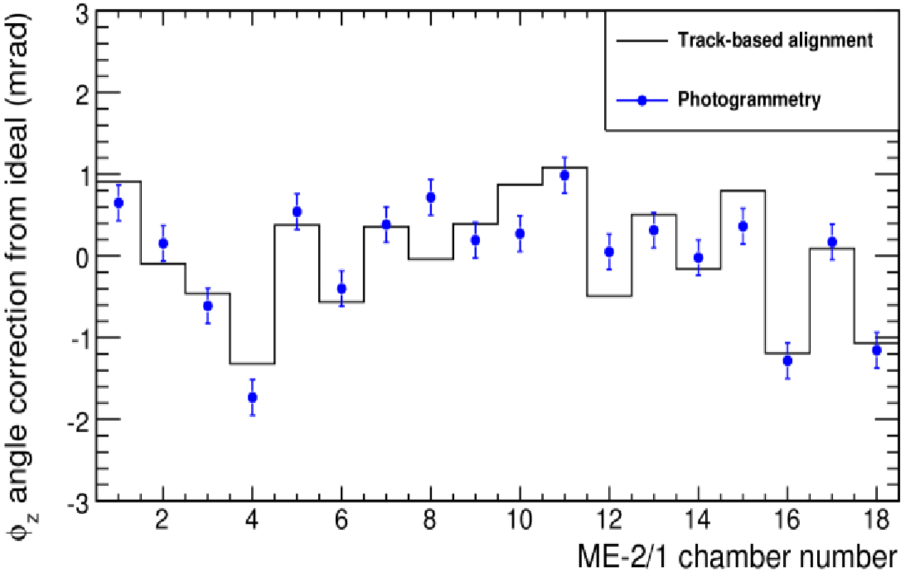


Track-Based Alignment: CMS Ring alignment in the endcaps

- **CSC chambers in CMS are designed with a small overlap region**
- **Misalignments between chambers can be calculated imposing coherency in the segments in both chambers**
- **As every chamber has two neigbours, at the end closure conditions are required to get the final calculation**
- **The achieved precision is of the order of 300 um**

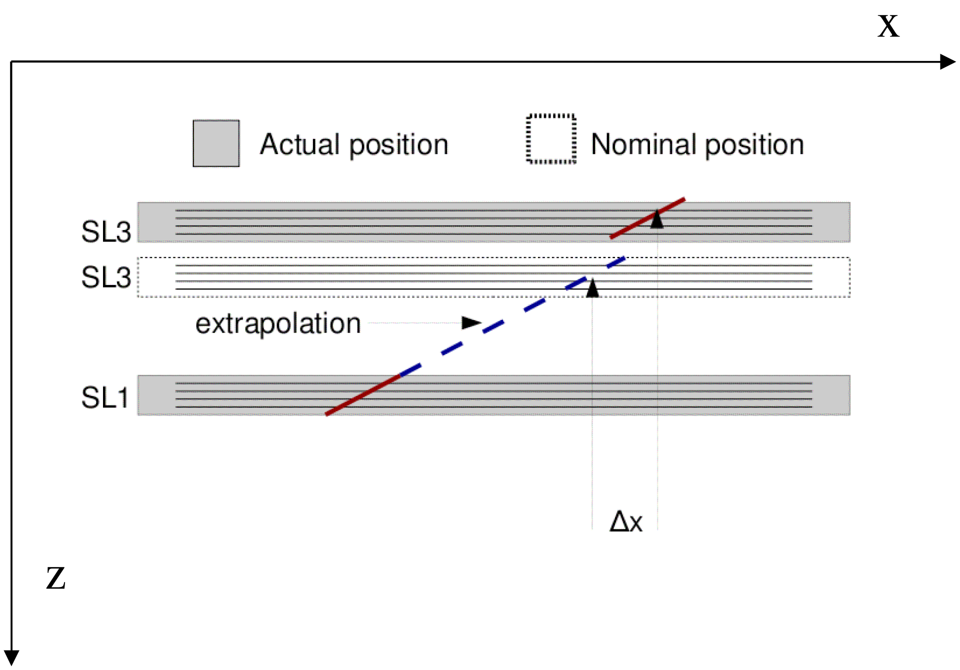


Comparison of photogrammetry and track-based results



Track-Based Alignment: CMS DT internal alignment

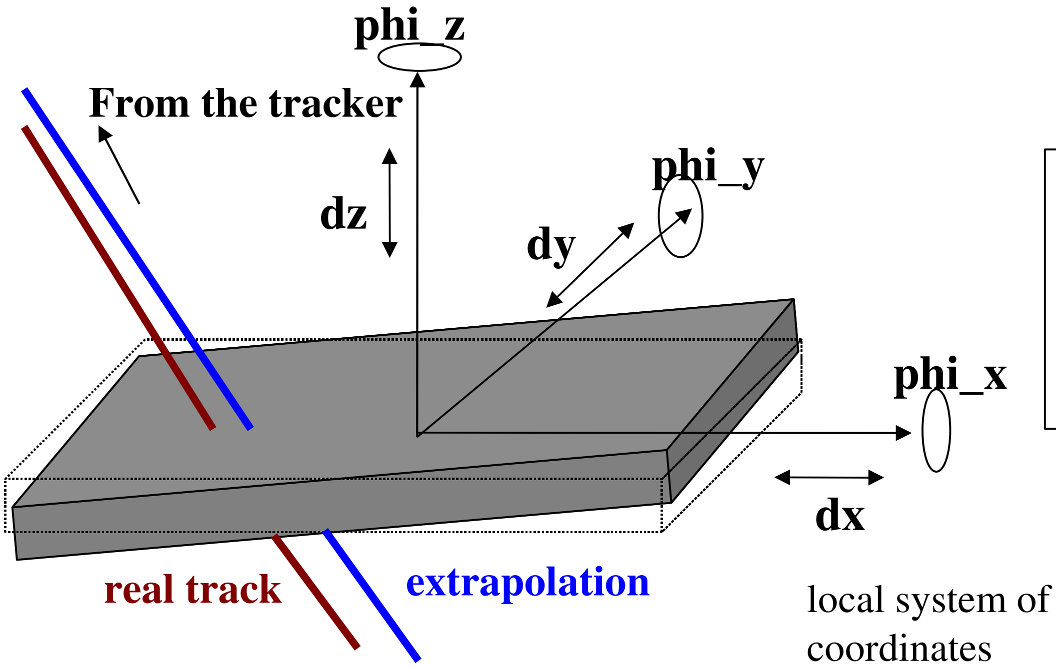
- **The internal structure of the Drift Tube chambers is aligned**
  - **DT chambers in CMS are composed by 3 superlayers, each containing 4 planes of wires**
- **The segment is calculated in one of the superlayers and extrapolated to the other, the residual is defined as the difference between the segment and the extrapolation**
- **Residuals are minimized against the δx, δz and φy vertical and horizontal displacements between superlayers and the rotation in the y direction**



The agreement between the track-based alignment and the photogrammetry is 580 microns in the δz which suffers the largest misalignments

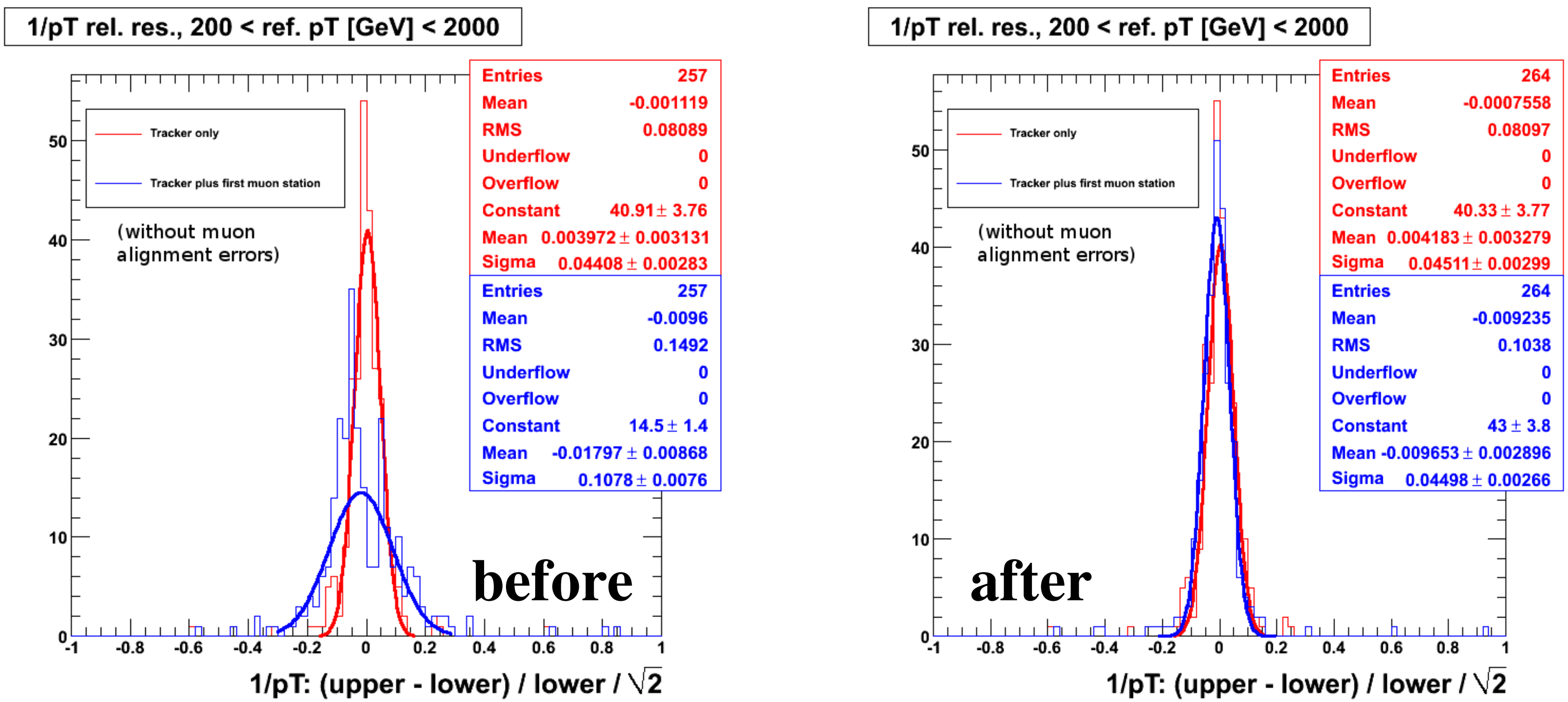
Track-Based Alignment: CMS DT global alignment

- **Drift tube chambers are aligned with respect to the central silicon tracker using cosmic muons**
- **The residuals are defined as the difference between the measured segment and the extrapolation from the tracker**
- **A global fit is performed to find the 6 alignment parameters that minimize the residual distributions**
- **Because of the topology of the tracks, it can be only applied to the central wheels**



A CMS drift tube chamber is able to measure the position and direction of the track in the rphi and z plane. So, there are 4 residuals Δx, $\Delta dx/dz$, Δy, $\Delta dy/dz$

Track-Based Alignment: CMS DT results



- **The Pt resolution is calculated using split tracks: the same track is reconstructed as two, one in the bottom part and one in the top**
- **Before introducing the alignment of the drift tubes the tracker-only track resolution (in red) is much better than the combination of tracker and the first muon station**
- **After introducing the alignment, both are comparable**

Conclusions

- **The alignment of the muon spectrometers plays a very important role in the quality and correctness of the measurement of the muon momentum**
- **For this reason the muon spectrometers of ATLAS and CMS have a very strong alignment program based on optical alignment systems and the extensive use of alignment with tracks techniques**
- **During the last commissioning runs, both systems have been tested very successfully producing the first alignments and starting to converge to the design specifications**
- **These alignments offer improved tracking for the 2009 start-up**