



Experiences with the Muon Alignment Systems of the Compact Muon Solenoid Detector

Experimental Detector Systems

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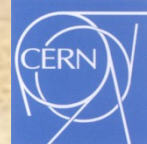
(ATOMKI, Debrecen; CERN)

on behalf of CMS experiment

TIPP 2011 - 2nd Technology and Instrumentation in Particle Physics, Chicago, 9-14 June 2011

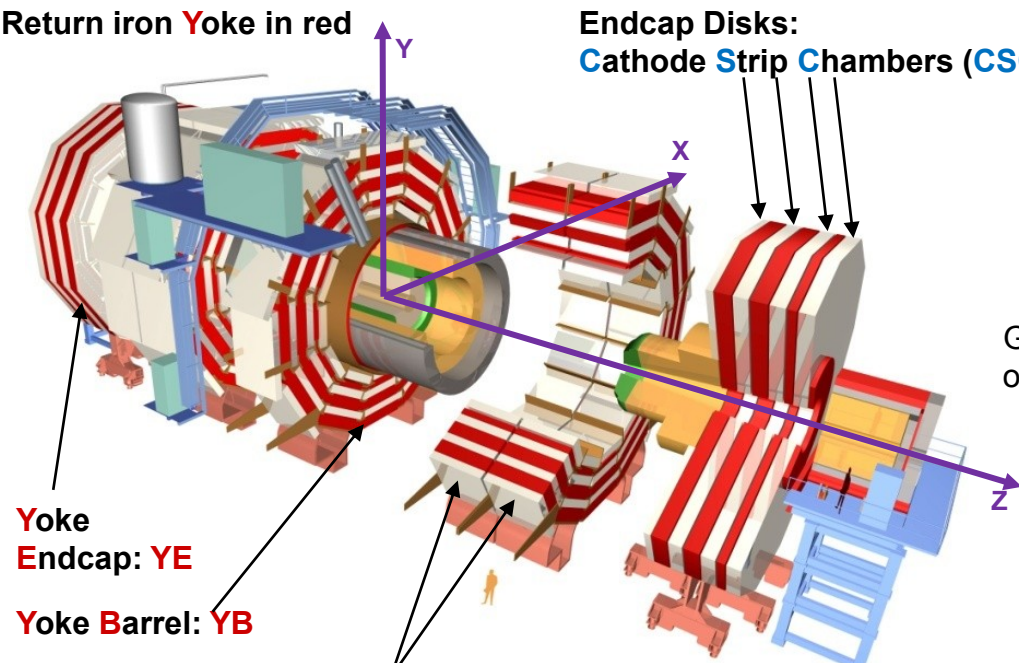


Outline



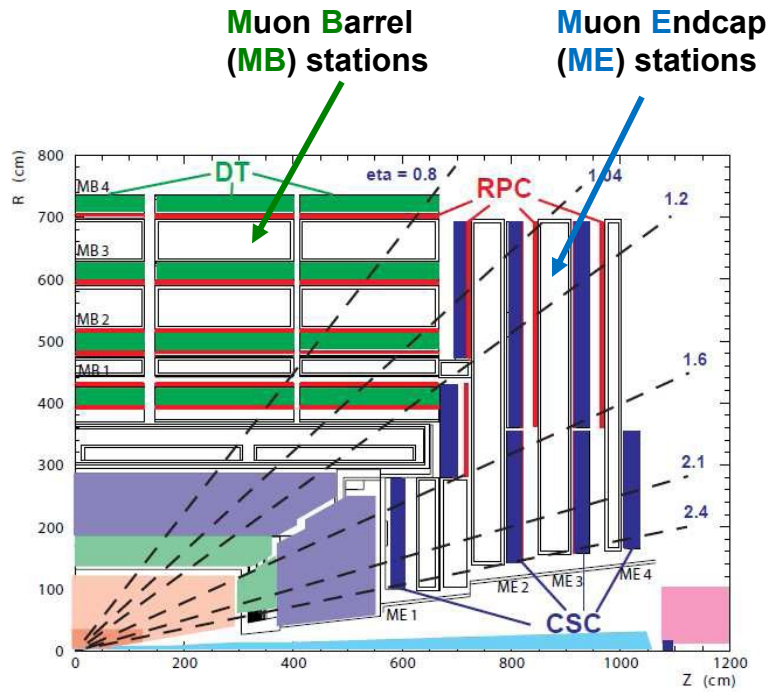
- CMS Muon System
- Motivation / Challenge
- CMS Muon Alignment Systems
 - Barrel
 - Endcap
 - Link
 - Calibration/Installation/Commissioning and Operation
 - Track-based Alignment
- Offline data analysis
 - Barrel
 - Endcap
- Impact on Physics
- Twist lesson
- Conclusion and Outlook

Length: 21 meter
Height: 15 meter
Solenoid: 3.8 Tesla



Barrel: 4 DT stations in 5 iron wheels and 12 (3) or 14 (1) phi-sectors: 250 chambers

2 Endcaps: 4 CSC stations mounted on 3 iron disks and 18 (3) or 36 (5) phi-sectors: 468 chambers



- Huge magnetic field (3.8T)
 - Magnetic forces ($\sim 10\text{K}$ tons) displace, rotate and deform yoke elements by several mm
- Yoke elements are HEAVY
 - Distortions due to gravity observed at the level of several mm
- Yoke wheels/disks are movable
 - Position reproducibility for such large & heavy structures expected at the mm level at best
- Thermal instability effects might contribute at the sub-mm level
- **Muon Alignment system must track these effects after CMS is closed and magnet is On**
 - Tight spatial confinement
 - Tolerance to large (3.8T) magnetic fields
 - Tolerance to large radiation exposure

CMS MUON ALIGNMENT SYSTEMS

- Alignment of 250 Drift Tube chamber w.r.t each other
- Redundant network of optical connections built from cheap LEDs and Video cameras
 - 10000 LEDs mounted on DTs read by ~600 cameras on 36 MABs (Module of the Alignment of Barrel)
 - Each MAB has one Board computer (read-out, control)
 - Rigid carbon fiber structures attached to Barrel Yoke YB±2 MABs contain Link & Endcap components
 - Z-bars equipped with LEDs and read by active MABs provide better Z-resolution
- Calibration of single elements was needed before installation

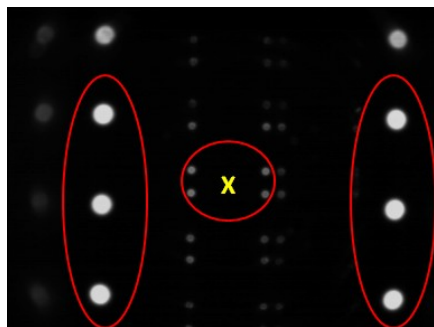
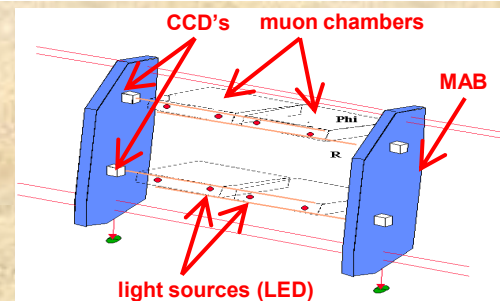
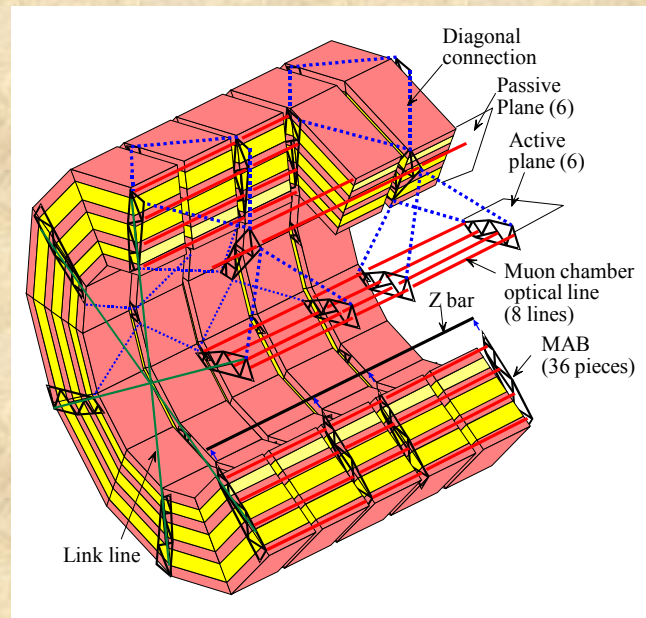
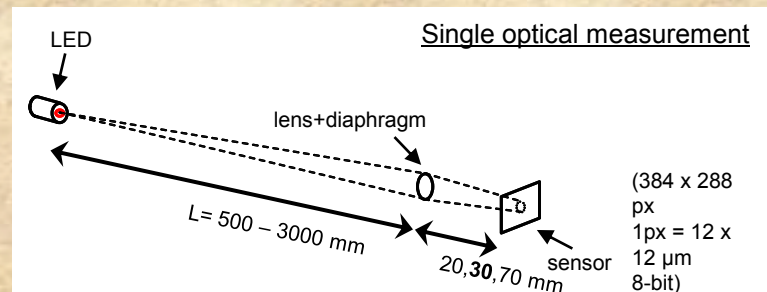
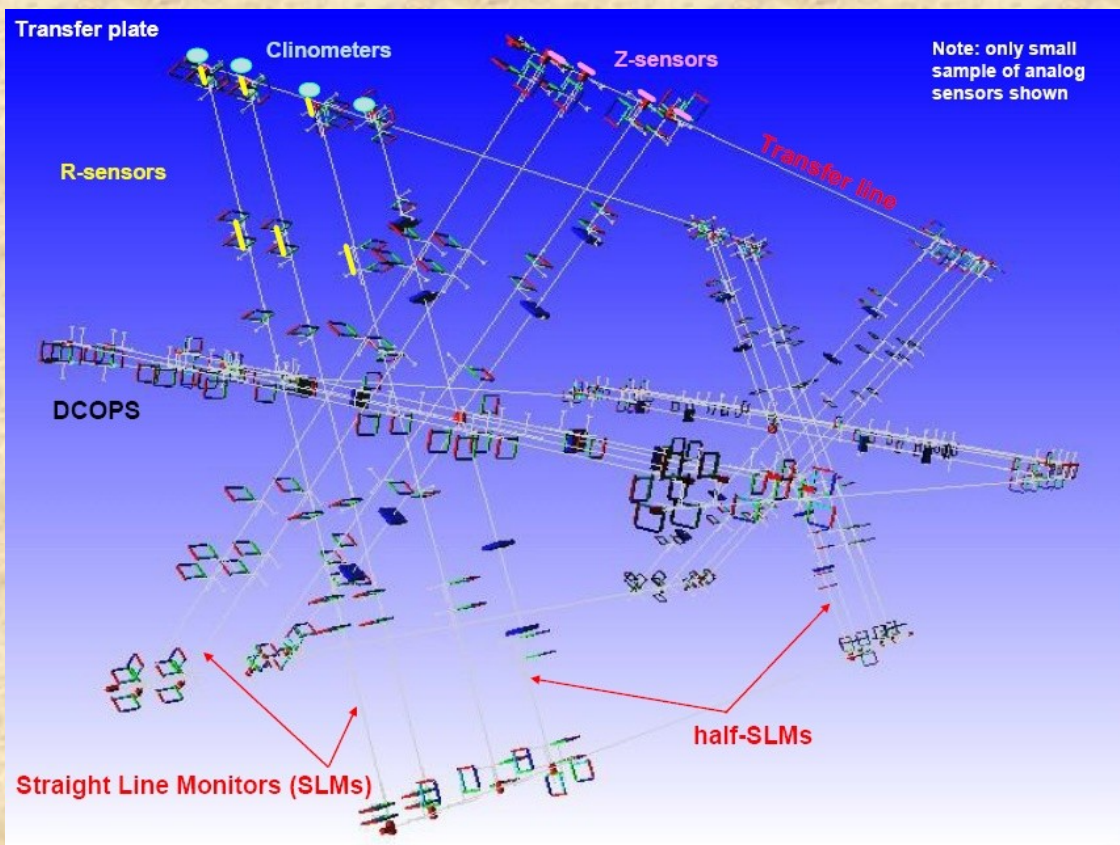


Image taken of forks installed on a chamber. Larger dots belong to the closer fork, while smaller dots are spots of the farther fork. The real spots can be seen inside the red markers. The others spots are reflections from the Alignment passage



Endcap Alignment

- Relative alignment Cathode Strip Chambers (CSC) w.r.t. each other. Measure the bending and the relative Z position of the YEs w.r.t. each other
- Network of optical connections complemented by clinometers, axial and radial distance meters.



Straight Line Monitors (SLM):

- 3 per Muon Endcap (ME) station
- Laser lines read by Digital CCU Optical Position Sensors (DCOPS)

Z-sensors

- Relative z distance between ME stations

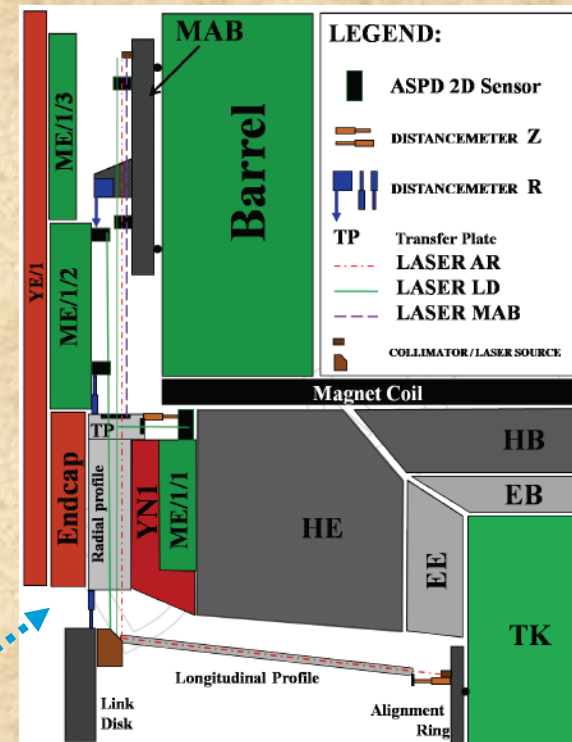
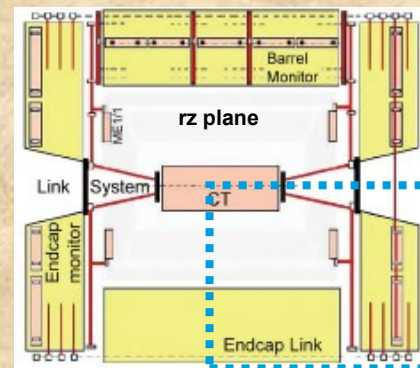
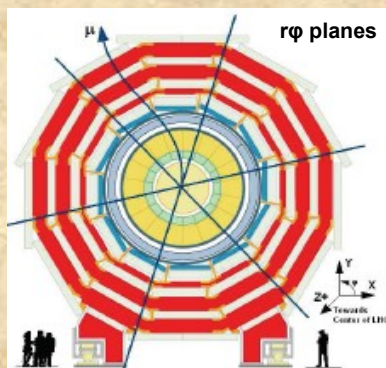
Transfer lines

- SLM cross z, measure relative x,y displacements between ME stations

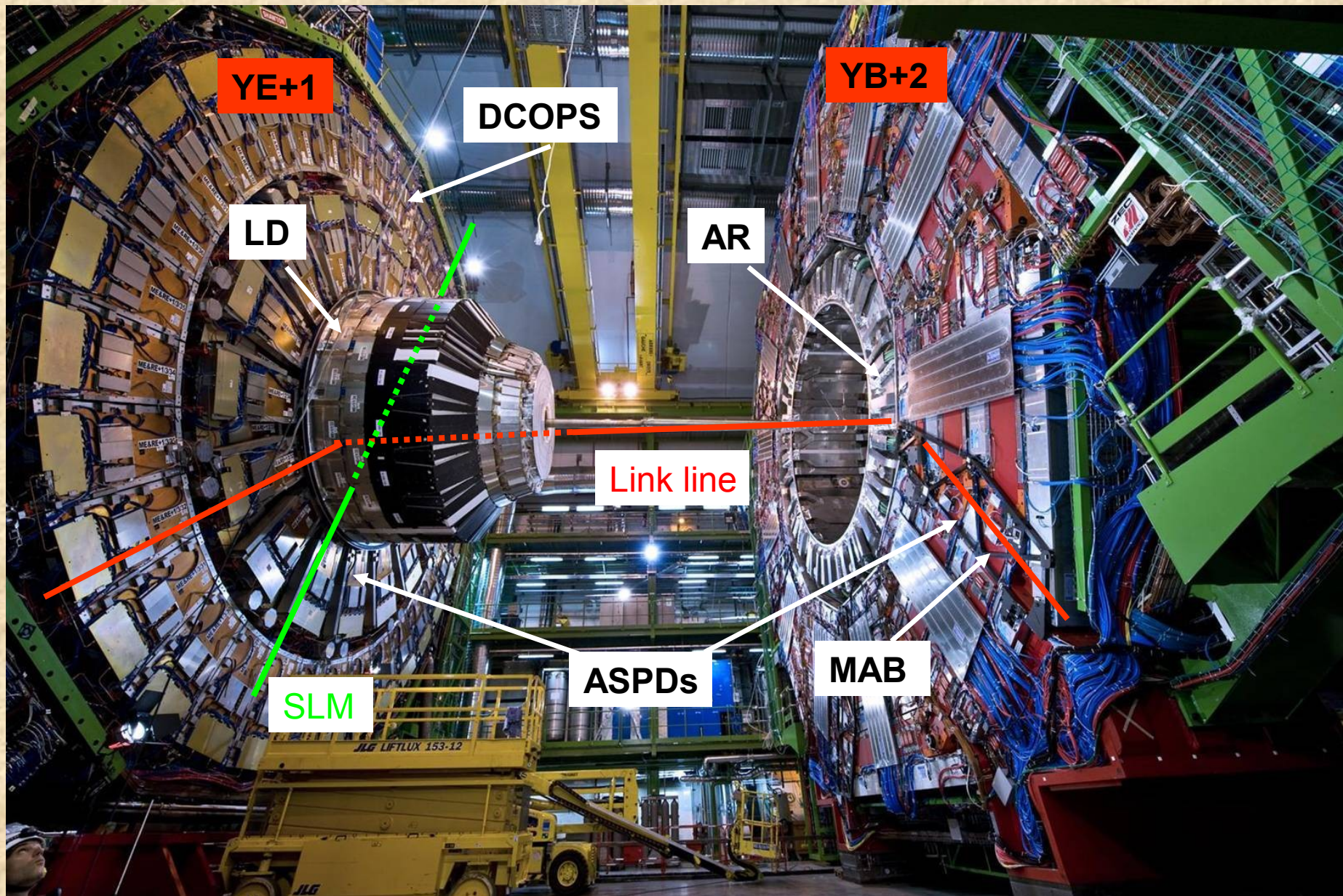
Each SLM measures only 4 CSC, therefore the Endcap System measures only about the 1/6 of all CSC

Link Alignment

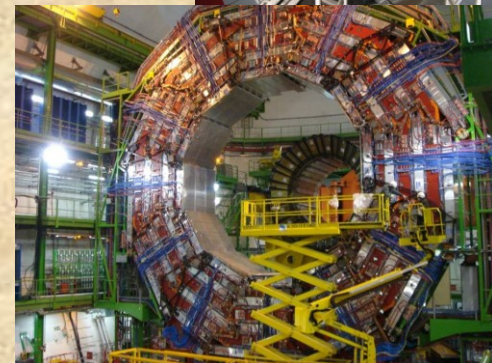
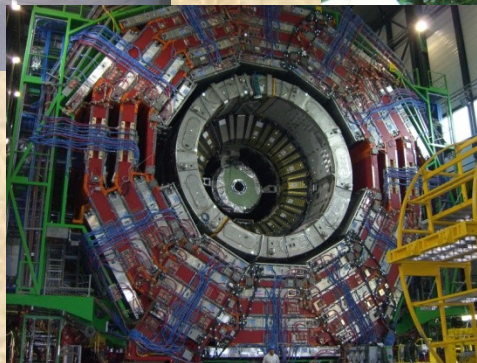
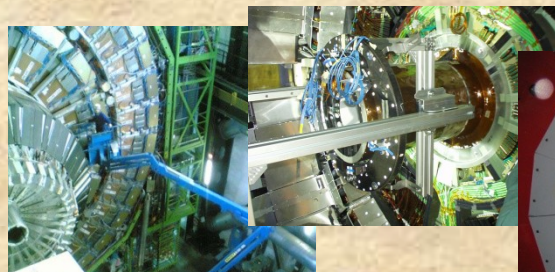
- Simultaneous Monitoring and Alignment of **DTs** and **CSCs** in a **common** frame of reference related to the tracker through a network of optical connections
- Lasers sources housed in rigid structures:
 - Alignment **Rings (AR)** attached to the tracker
 - Link **Disks (LD)** at **Yoke Endcaps YE \pm 1**
 - Module of the Alignment of **Barrel (MAB)**
- Read by optical 2D sensors,
- **Amorphous Silicon-strip Position Detectors (ASPD)**
 - On **Muon Endcap ME \pm 1** chambers and on **MABs** on **Yoke Barrel YB \pm 2**
- Complemented by clinometers and axial and radial distance meters
- Organized into **three $r\phi$ planes** staggered 60° in ϕ (to match YB 12-fold geometry)
- Each plane consists of four independent quadrants for a total of **12 Link quadrants** (6 on each z_{CMS} side)



CMS Muon Alignment System

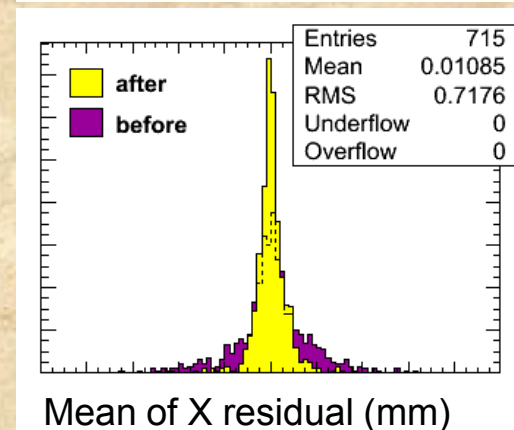
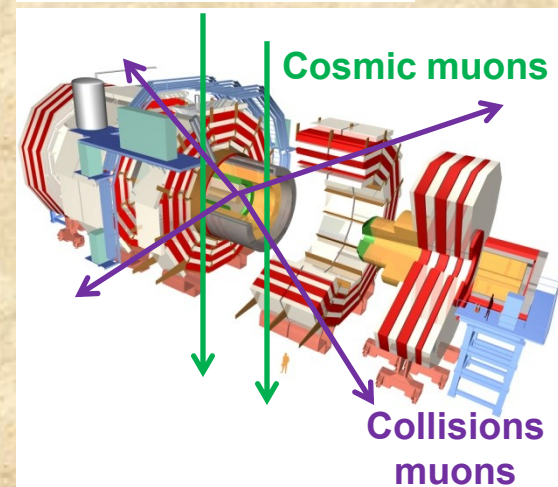
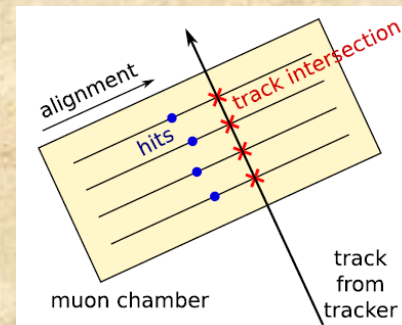


- Calibration of elements started after 2002
 - Light source holders calibration
 - DT chamber calibration
 - Sensor and Camera calibrations
 - MAB calibrations
 - Alignment Ring and Link Disk calibrations
- Installation and Commissioning – Started at 2003
 - Magnet test (partial alignment systems) – 2006
 - Full system – 2008
 - Challenges during installation:
 - Small space for the cables and MABs
 - Clean the light blocking objects (cables, pipes, covers)
 - LDs and ARs are very near to the Beam Pipe (Beam Pipe is unique and fragile)
 - Devices trapped between the wheels → If CMS closed, no access to devices



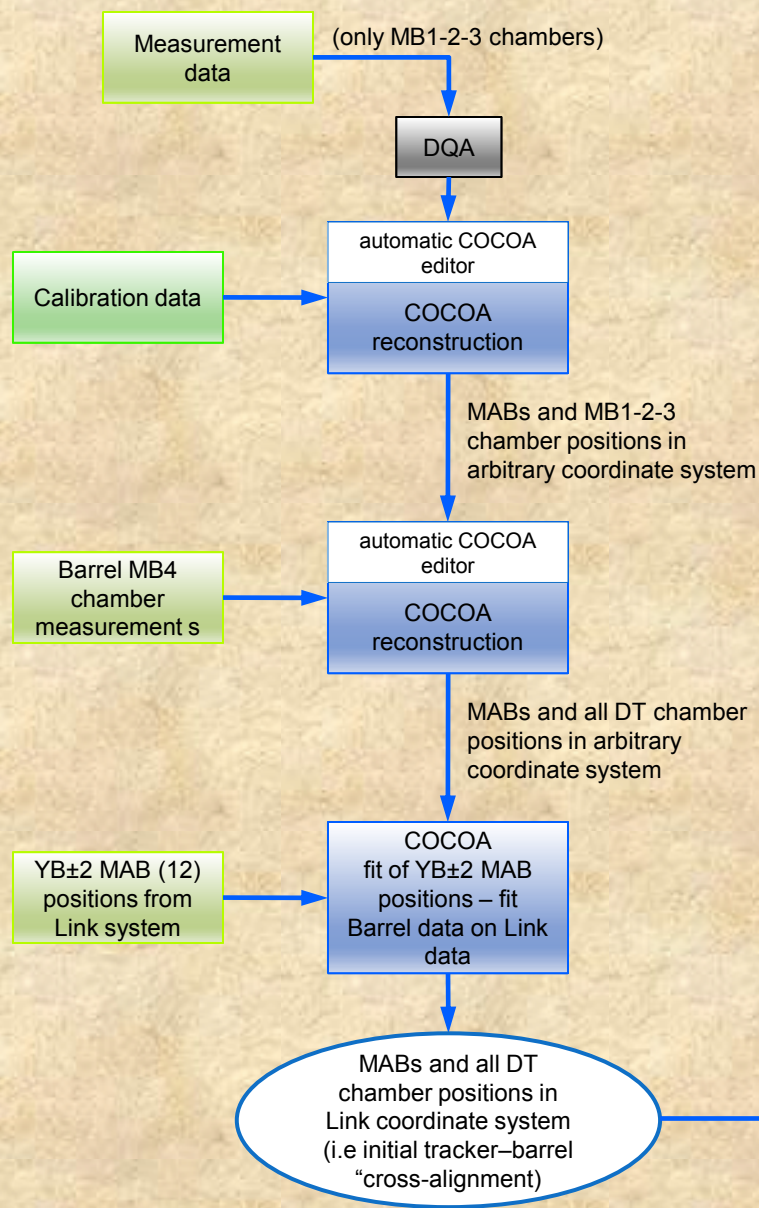
- Operation
 - Full measurement cycle
 - Barrel Alignment: ~ 2hours
 - Link Alignment: ~30mins
 - Endcap Alignment: ~15mins
- } Full time granularity of the system driven by Barrel
- Control Systems of Muon Alignment System
 - Operation of the system has been integrated to the CMS Detector Control System (DCS)
 - The three Alignment systems have separate control panel and common LV control panel

- Track-based (TB) Alignment — precise measurement of muon chambers positions with respect to the tracker
 - Relies on precise reconstruction of muon tracks in inner silicon tracker
 - Tracks from the “reference” tracker are freely propagated to the “target” muon system
 - The differences between propagated trajectory and muon chamber data (residuals) are calculated in each chamber and used for corrections
 - Measured positions are used to improve accuracy of high-energy muon reconstruction
 - Data: 2010 cosmic and collisions



OFFLINE DATA ANALYSIS

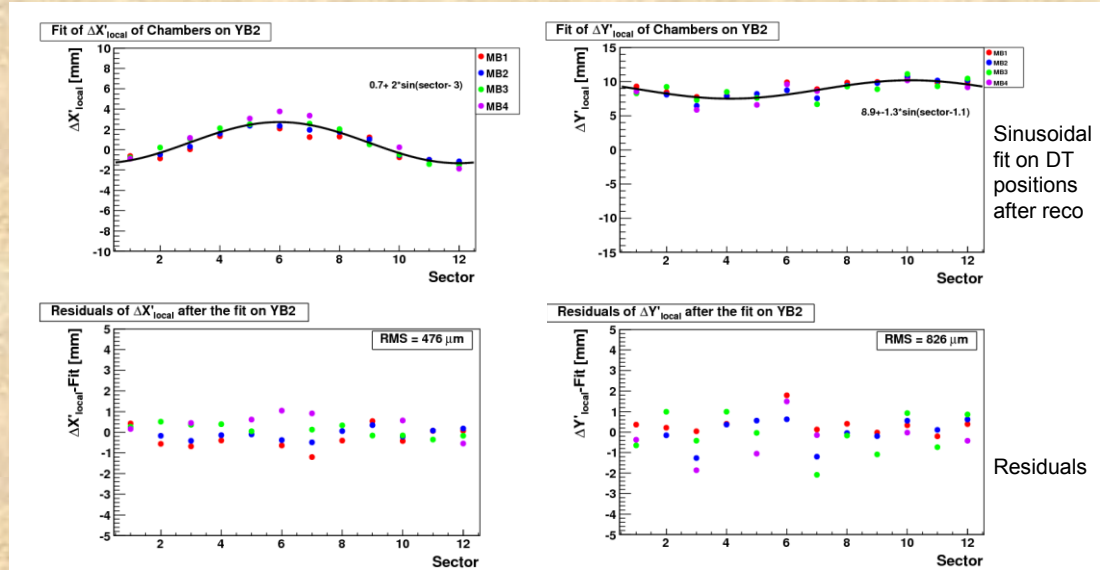
An example for reconstruction: Barrel



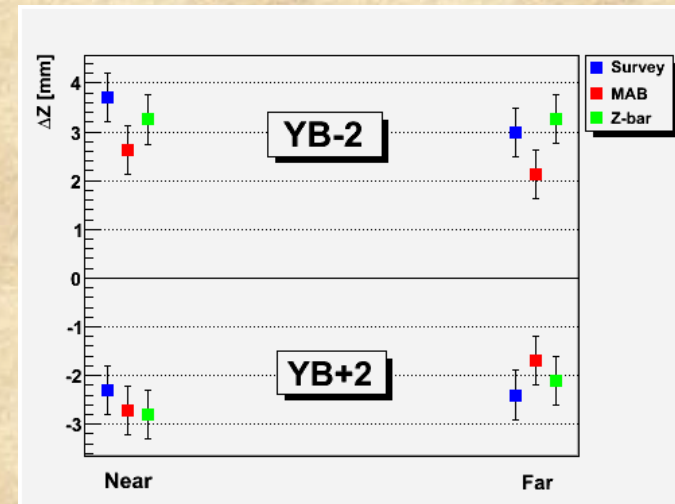
- COCOA: CMS Object-oriented Code for Optical Alignment; Geometrical reconstruction program based on iterative non-linear χ^2 fit
- DQA: Data Quality Assurance
 - checks raw measurement data and exclude bad measurements. For example fast pattern check to exclude reflection
 - **without it system wouldn't tolerate bad measurements!**
- During the first step MB1-2-3 stations define the barrel.
- Station 4 DTs are added in a second step. Reason:
 - computational problem significantly simpler and reco runs much faster
 - knowledge of camera positions on MABs for outer station is less precise than internal barrel, therefore the structure is essentially not affected by excluding station 4
- Overwhelming part of these steps are automatized (specially the measured and calibration data collection from Database) and we plan to make the reconstruction fully automatic

- **Comparison with Photogrammetry**
 - Magnetic field 0T
 - Handle on wheel movements and rotations
 - Relatively large disagreement is expected
 - photogrammetry - open detector
 - alignment - close detector

Barrel Wheel	$\Delta\phi$ RMS [μm]	z RMS [μm]
YB+2	480	830
YB+1	430	1260
YB0	710	990
YB-1	440	820
YB-2	630	850



- **Comparison of mutually independent Z measurement of Barrel wheels (YB±2)**
 - Measurement by Survey group at 0T and 3.8T (2011 Jan & Feb).
 - Measurement of Barrel Alignment System at 0T and 3.8T
 - Z-bar data
 - Reconstructed MAB positions
 - Errors of the different measurements:
 - Survey: ± 0.5 mm
 - MABs : $\pm 800 \times \sqrt{2} / \sqrt{6} \sim \pm 0.5$ mm
 - Z-bar : $\sim \pm 0.5$ mm



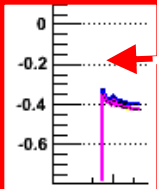
Z-bars and MABs are very much compatible with Survey

Detector behavior under B field: compression, stability and reproducibility

Movements of the Z-bar LEDs vs #run in the Z direction

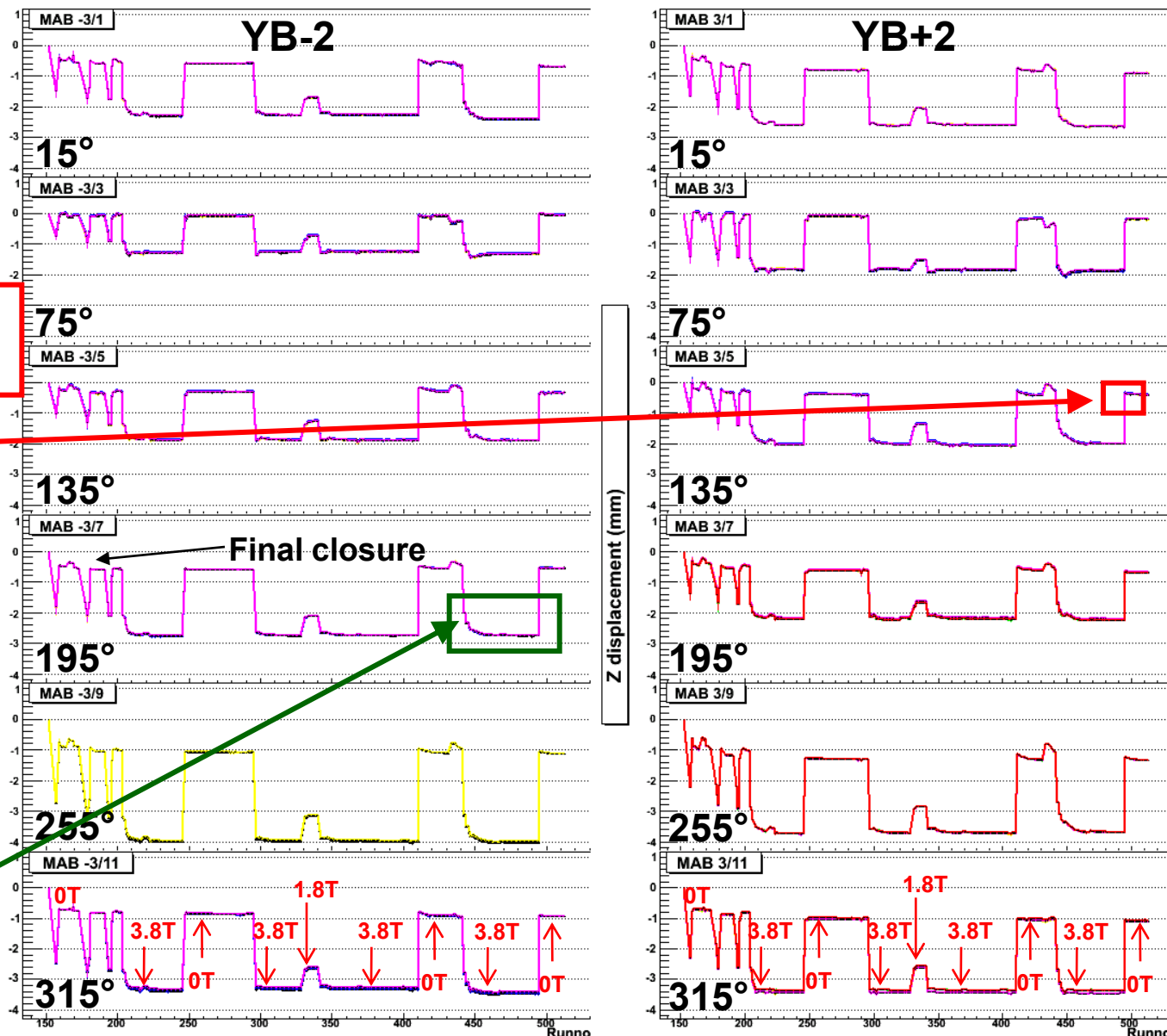
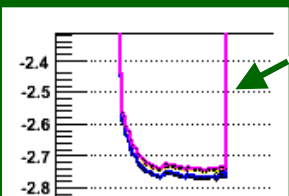
Final closure of Barrel @ 2T

relaxation effect @ beginning of 0T (~8-10h)

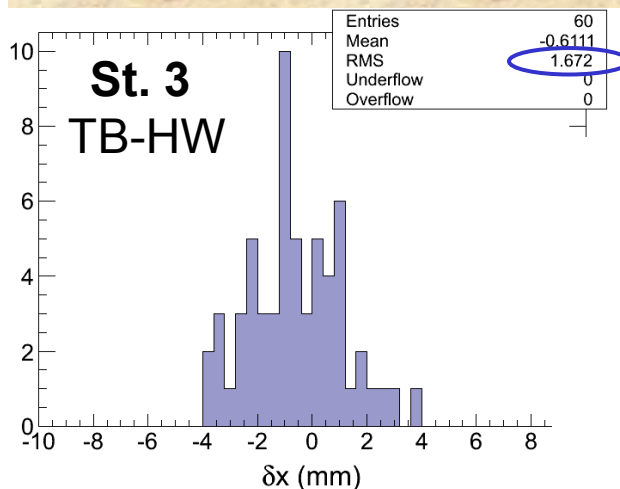
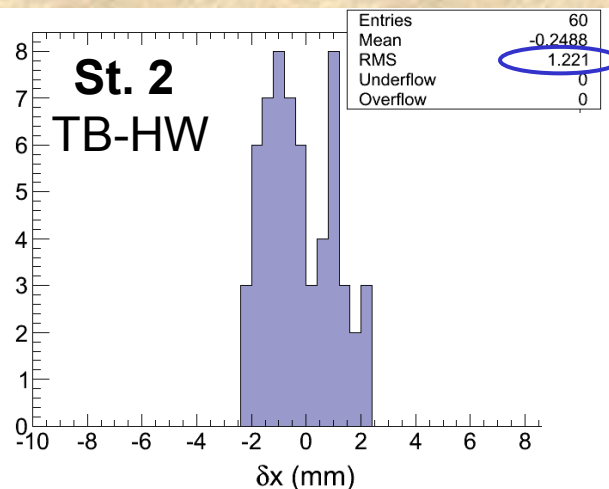
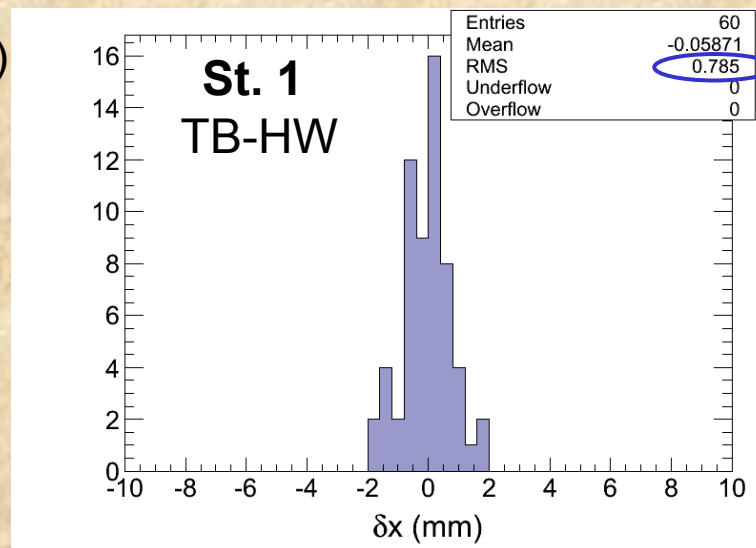


3.8 T reproducibility: ~< 100 microns

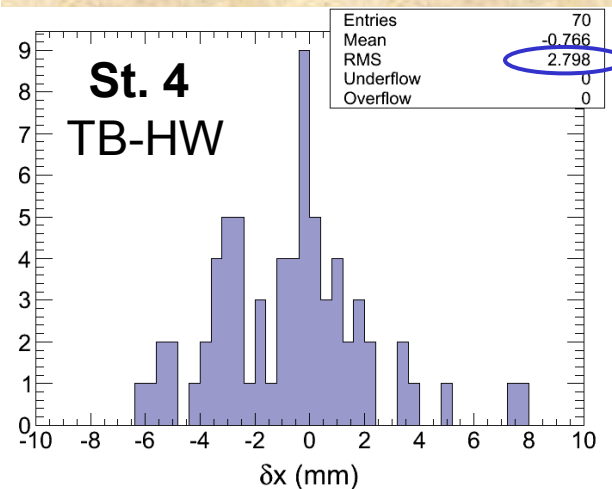
switching-on effect!!!
max 200 microns
1 day long



- Comparison of Track-based (TB) and Hardware (HW) alignment in CMS Barrel
 - tracks from collisions (35pb^{-1} , 2010 data)
 - 3.8T magnetic field
 - muons p_T in range from 20GeV to 200GeV
 - RMSs consistent with expectations: grows with radius to beam pipe
- $\sim 1\text{mm}$ for inner stations and $\sim 2\text{mm}$ for outer station



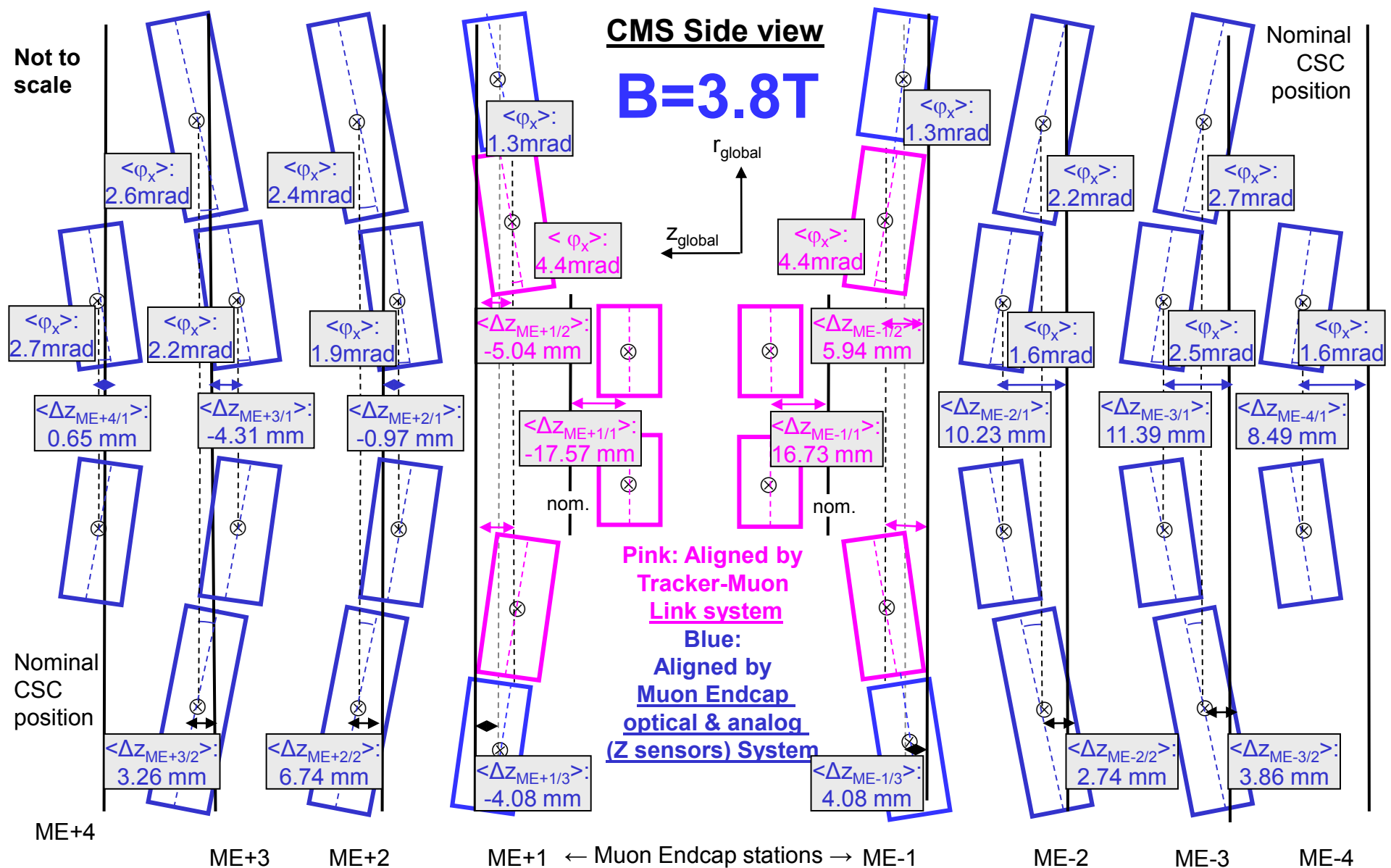
RMSs consistent with expectations



- Endcap Alignment using information from 4 different sources:
 1. Hardware alignment → Bending, rotations and Z position of the YEs at 0T and 3.8T
 - Combined information from Endcap and Link Alignment
 2. Photogrammetry → Internal ring alignment at 0T (CSCs alignment w.r.t. each other)
 3. Beam-halo muons → Internal ring alignment at 3.8T (CSCs alignment w.r.t. each other)
 4. Muons from pp collisions
 - CSC Overlap Alignment at 3.8T (CSCs alignment w.r.t. each other)
 - Align CSC rings w.r.t the Tracker at 3.8T

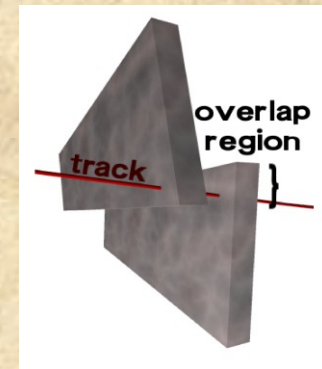
- Some of these sources measure the same alignment parameters in different ways, providing cross-checks between the different systems, while others do not. To combine information, alignment corrections were applied in a well-defined sequence, such that each step benefited from the previous. Potentially interdependent corrections were iterated to obtain a mutually consistent solution.

Bending of YEs in magnetic field



1. Overlap alignment

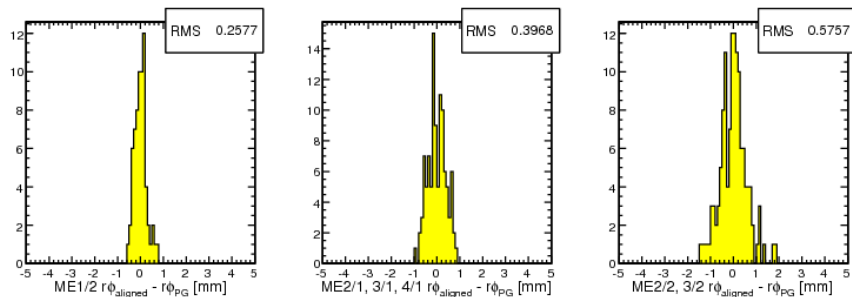
- CSC chambers in CMS are designed with a small overlap region
- Misalignments between chambers can be calculated imposing coherency in the segments in both chambers
- As every chamber has two neighbors, at the end are required to get the final calculation
- The algorithm uses muons from Beam-halo and from pp collisions



2. Ring placement alignment

- To complete the endcap alignment, the internally aligned rings must be aligned relative to one another and the tracker.

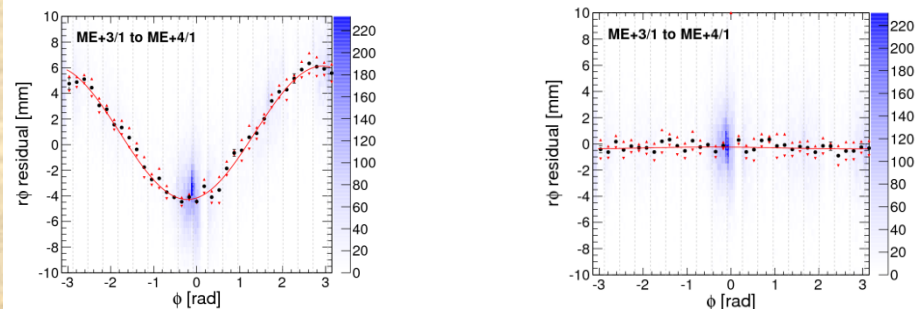
1



Chamber positions after internal-ring alignment compared with photogrammetry, split by ring. (ME1/1 chambers were not measured by the photogrammetry.)

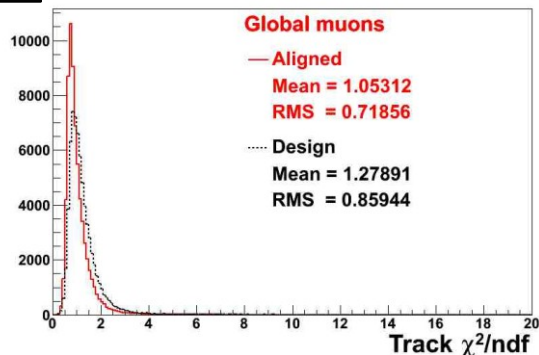
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Before alignment

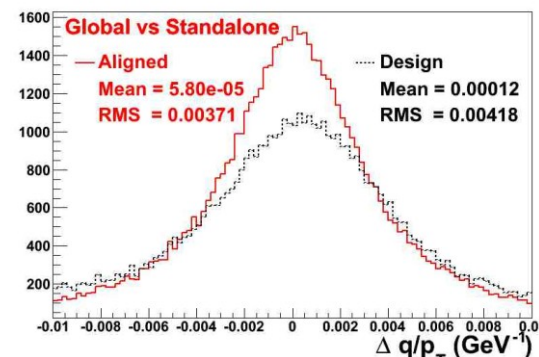


IMPACT ON PHYSICS

1

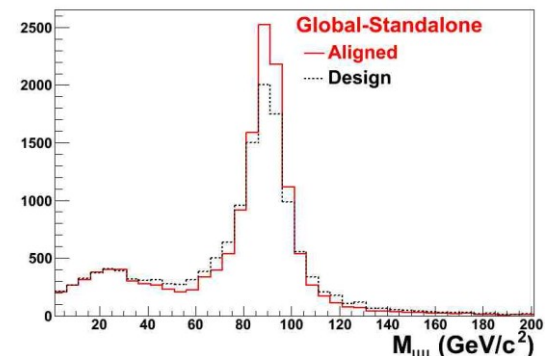


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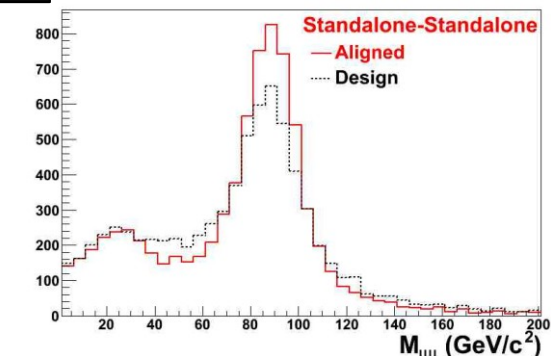


- Study the effect of Muon Alignment on muon tracks
- Low momentum muon tracks (below 200 GeV/c) from pp collisions collected during 2010
- 1: χ^2 for global tracks
- 2: difference in q/p_T muons reconstructed as global and as stand alone
- 3 & 4: μ - μ mass resolution in the Z^0 region.

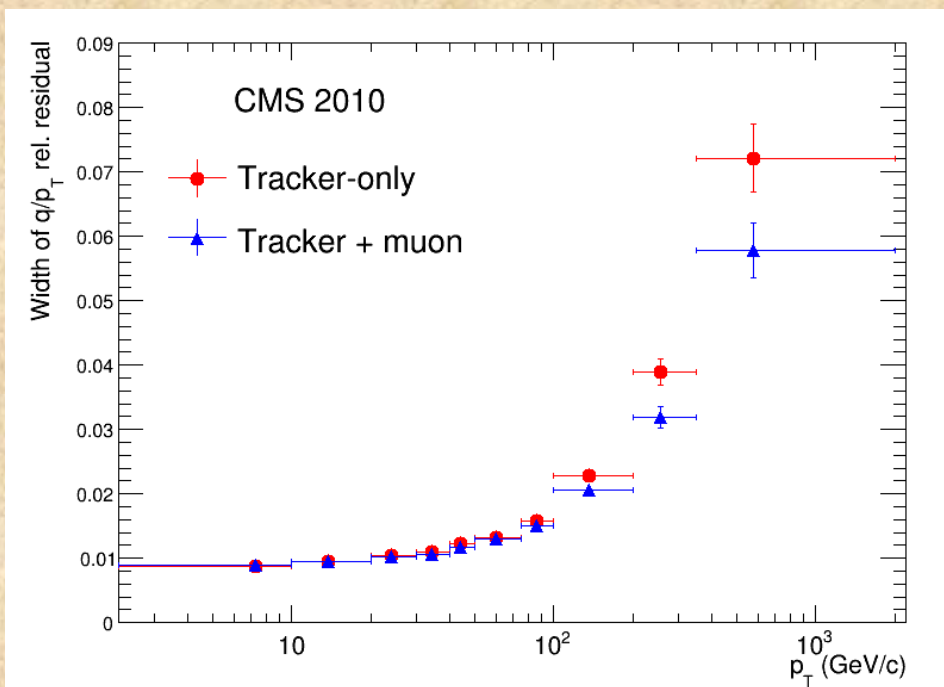
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4



- In order to study the effect of the alignment on highly energetic muons, **cosmic ray muons** must be used. Currently there are very few high momentum muon tracks (above 200 GeV/c) from pp collisions.
- Gaussian width of the difference in q/p_T between top and bottom reconstructed cosmics using design and aligned muon chamber positions compared to Tracker-only reconstruction.

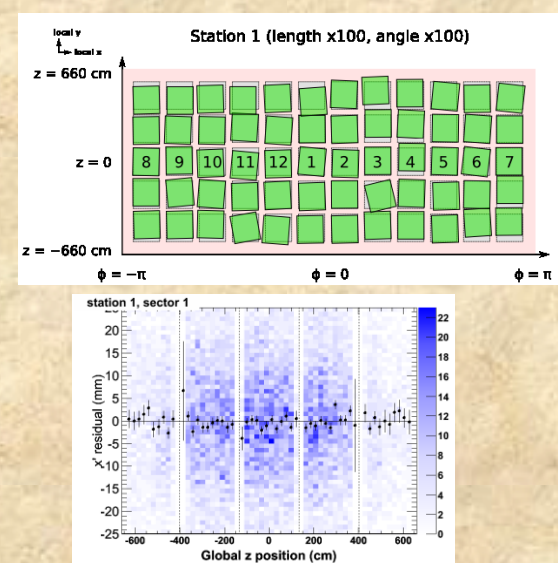
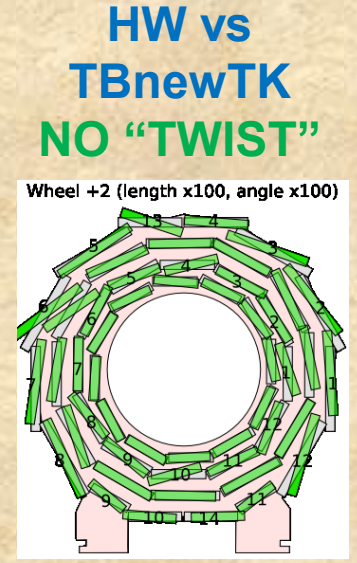
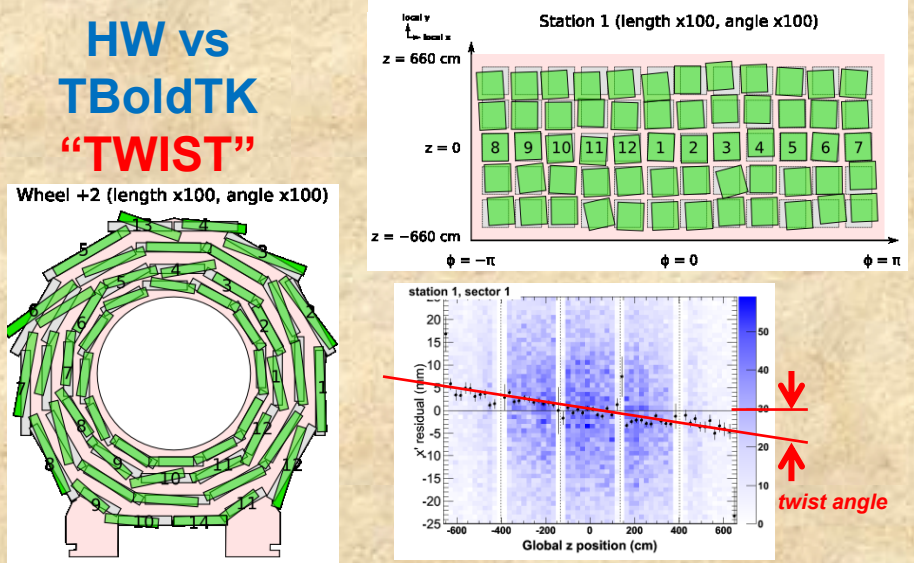


Aligned muon system improves tracker-only p_T measurement above 100 GeV/c

TWIST LESSON (AND UPGRADE)

“Twist” - Track-based vs HW barrel – a lesson to learn

- 2010 – a relative "twist" is observed in the barrel in track-based muon alignment with respect to hardware muon alignment.
 - Overall 4-5 mm end-to-end effect in Z and $r\phi$
 - Many studies has been done in order to find the reason.
 - Results of these studies: the three hw alignment system consist with each other and with the survey measurements at 0T. However, on 3.8T photogrammetry measurement was impossible to perform.
- 2011 Feb – a new "twist free" tracker alignment produced by Tracker DPG
- 2011 Feb 20 – the twist is **gone** with latest track-based muon alignment with the “no twist” tracker. Muon $p_T = 15 - 200$ GeV, multiple refit of global muons.
- Comparisons of track-based and hardware muon alignments can be a handle for detecting possible **tracker deformations or weak modes**
- **Independent measurement on the HW is needed, when detector is closed → Special hw upgrade planned.**



Conclusion

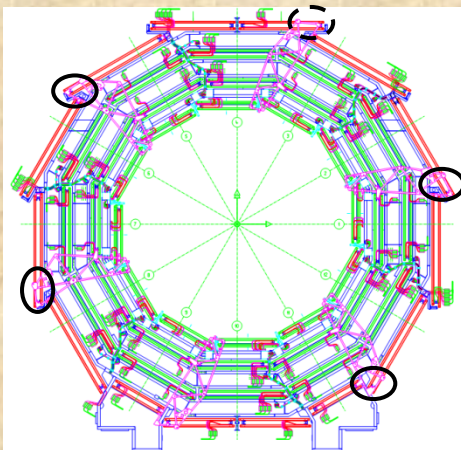
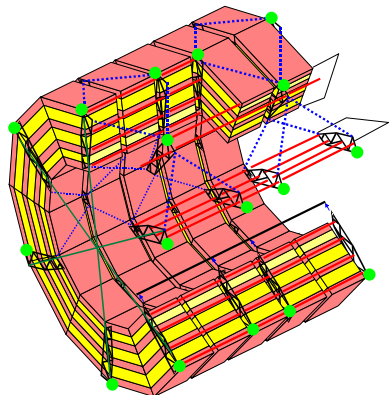
- The three hardware alignment systems have good agreement with each other and with the survey measurements.
- Agreement between independent hardware and track-based alignment is consistent with current track-based statistical precision
- Alignment impact on physics data:
 - improved track reconstruction (χ^2), improved μ - μ mass reconstruction for low p_T muons
 - improved momentum resolution for muons above 100 GeV/c
 - improvement over Tracker-only reconstruction

Plans

- work ongoing on detector alignment with Stand Alone Muons (SA)
- work ongoing on detailed error (APE) determination of chambers
- upgrade of Hardware Barrel Alignment System during the long shut-down (2013)

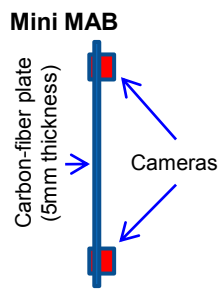
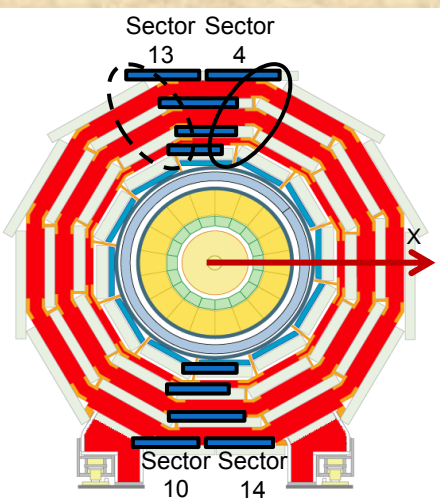


BACKUP

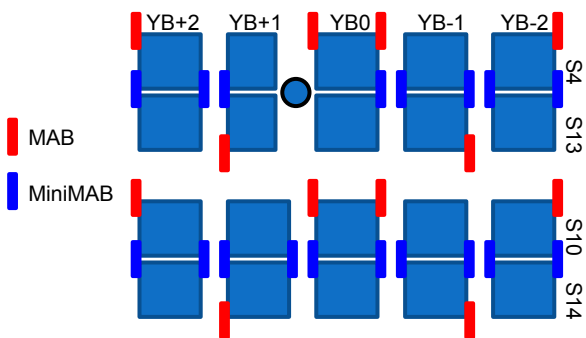


Additional photogrammetry targets on MABs

- Motivation: **We need a direct external measurement possibility.**
- What to do? Install additional photogrammetry target to MABs, they can be observed by survey, when the detector is already closed and field is on.



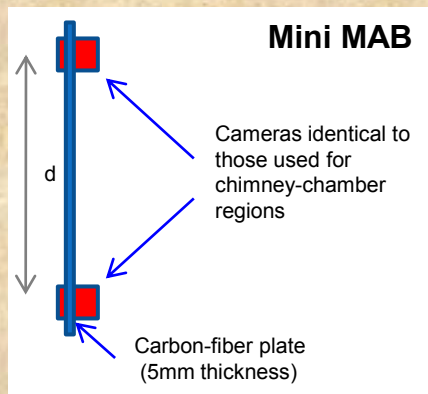
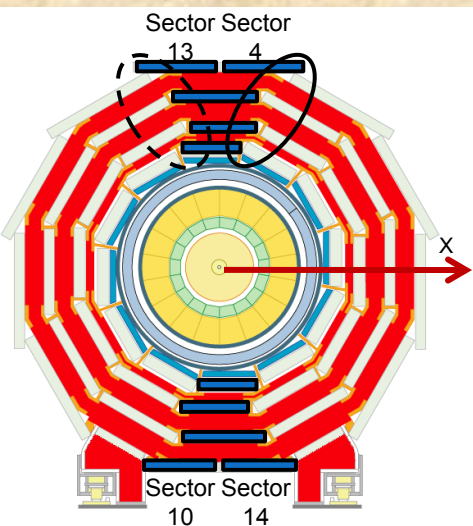
Proposed MiniMAB arrangement:



Reinforcement of meas in Sector 13 & 14

- The reconstruction error for rotZ of MB4 twin chambers are higher than the other MB4 chambers.
Reason: those chambers can be seen only from one side
- Solution: install “Mini MAB” to those chambers. Very similar to the MAB, but it houses only 2 camera.
- With the Mini MABs the alignment precision for these chambers will be better.
For example: rotZ error for YB+2, sector 13 changes from 0.13 mrad to 0.046 mrad

Upgrade plans – Reinforcement of measurements in Sector 13 & 14



- The reconstruction error for rotZ of MB4 twin chambers are higher than the other MB4 chambers. Reason: those chambers can be seen only from one side
- Solution: install “Mini MAB” to those chambers. Very similar to the MAB, but it houses only 2 camera.
- The proposed positions are seen on the drawing below. Due to several reasons (blocking electronic and cooling cables) it is impossible to put Mini MAB to every twin chamber.
- Results of simulation calculation of errors are on the tables. The position calculations shows the worst case, where the chamber can be seen though two other chamber.
- With the Mini MABs the alignment precision for these chambers will be better.

Results of simulation

Position error for YB0_sect14:

	w/out MM micrometer	with MMs micrometer
phi	27.4	7.5
R	1423.8	135.2
Z	1511.2	70.1

Position error for YB0_sect13:

	w/out MM micrometer	with MMs micrometer
phi	27.4	20.4
R	1423.8	166.2
Z	1511.2	90.1

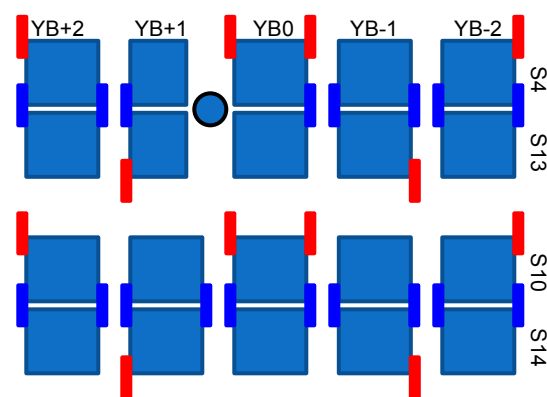
rot_Z error:

Wheel	Sect 14		Sect 10	
	w/out MM mrad	with MMs mrad	w/out MM mrad	with MMs mrad
2	0.13	0.046	0.11	0.046
1	0.11	0.046	0.14	0.046
0	0.48	0.045	0.48	0.045
-1	0.11	0.046	0.14	0.046
-2	0.13	0.046	0.11	0.046

rot_Z error:

Wheel	Sect 13		Sect 4	
	w/out MM mrad	with MMs mrad	w/out MM mrad	with MMs mrad
2	0.13	0.046	0.11	0.046
1	0.11	0.058	0.14	0.058
0	0.48	0.056	0.48	0.055
-1	0.11	0.046	0.14	0.046
-2	0.13	0.046	0.11	0.046

Proposed MiniMAB arrangement:



Parts of Barrel Alignment System

Light source



LED

12000 pieces



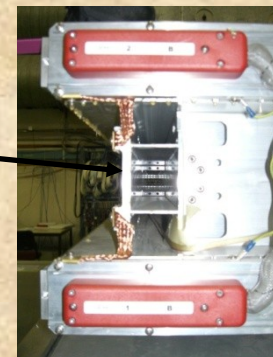
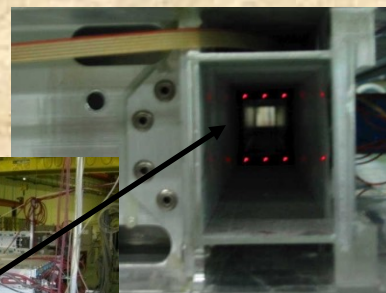
Fork

1200 pieces

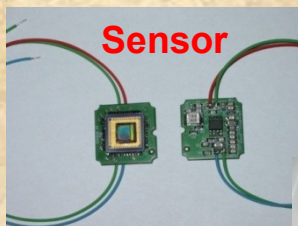


Drift Tube

267 pieces



Camera



Sensor



Camera

~600 pieces



MAB

36 pieces

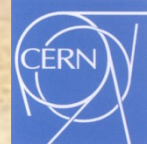


BoardPC

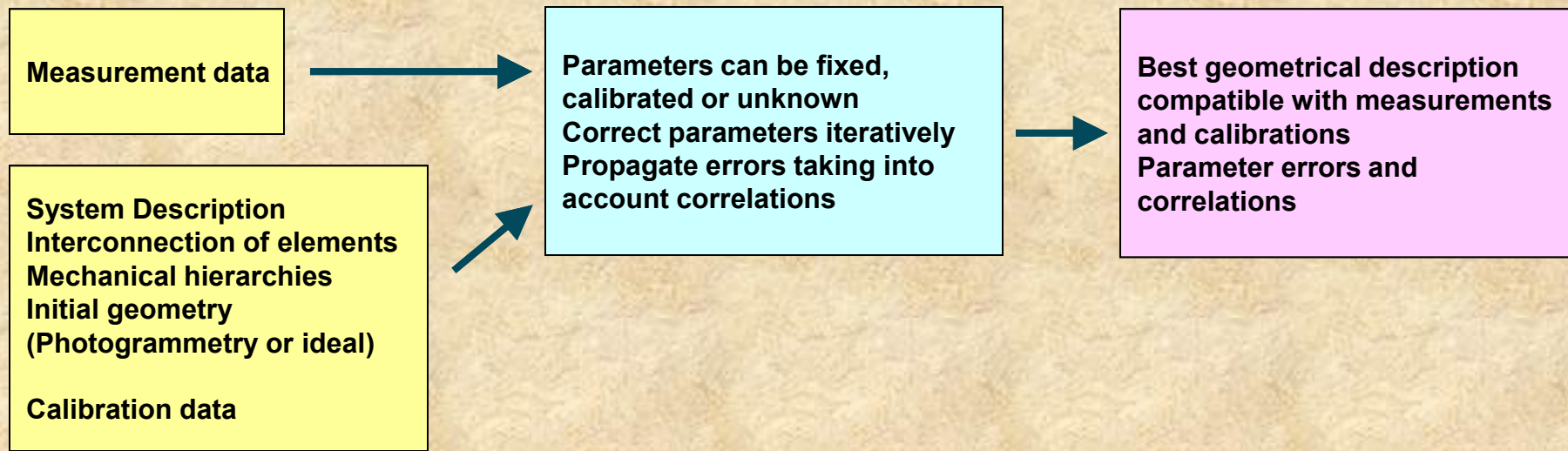
Including spare pieces



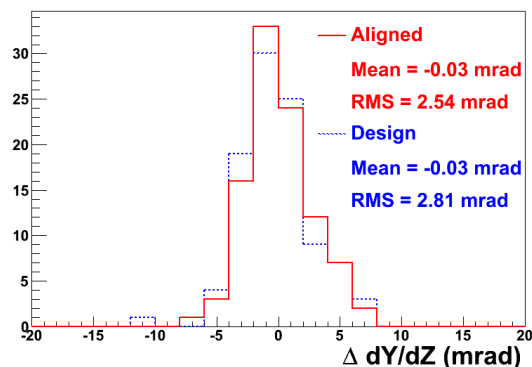
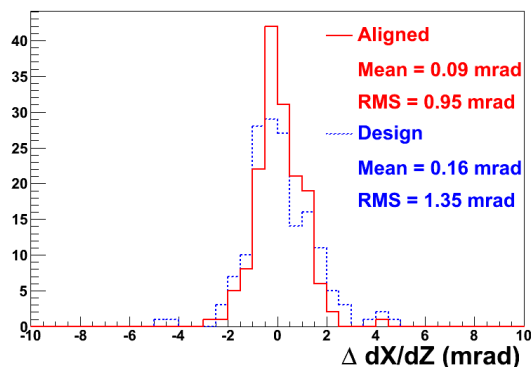
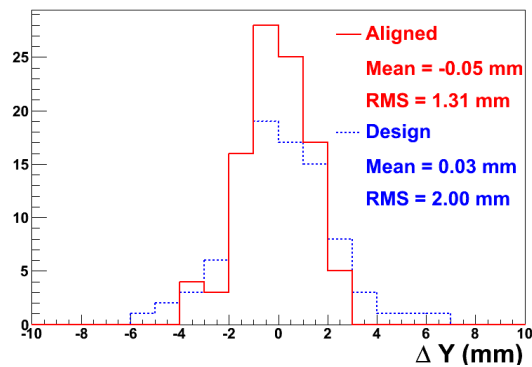
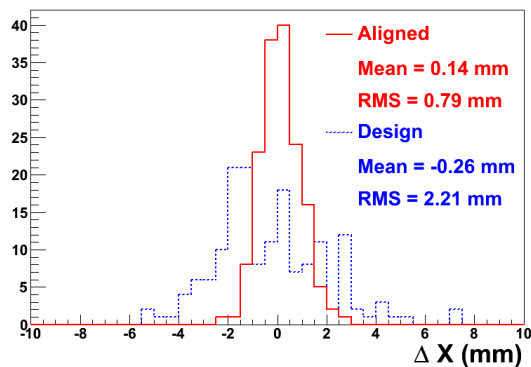
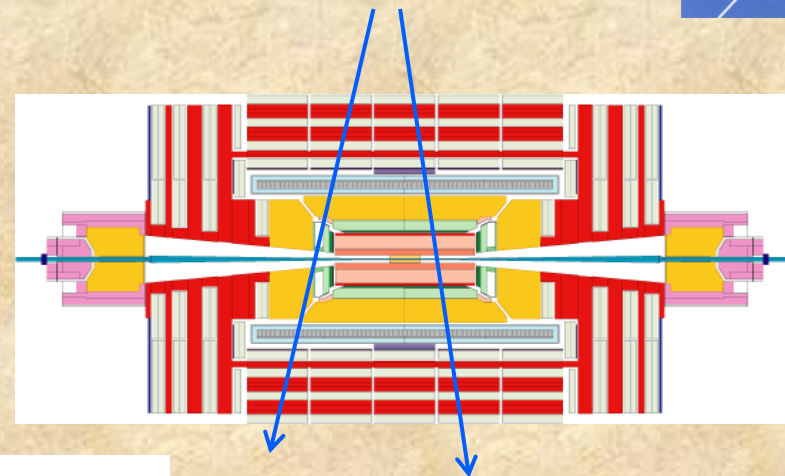
Offline geometry reconstruction



- CMS Object-oriented Code for Optical Alignment (COCO A)
- Designed for the study and use of the CMS Optical Position Monitor System.
- Geometrical reconstruction based on iterative non-linear χ^2 fit

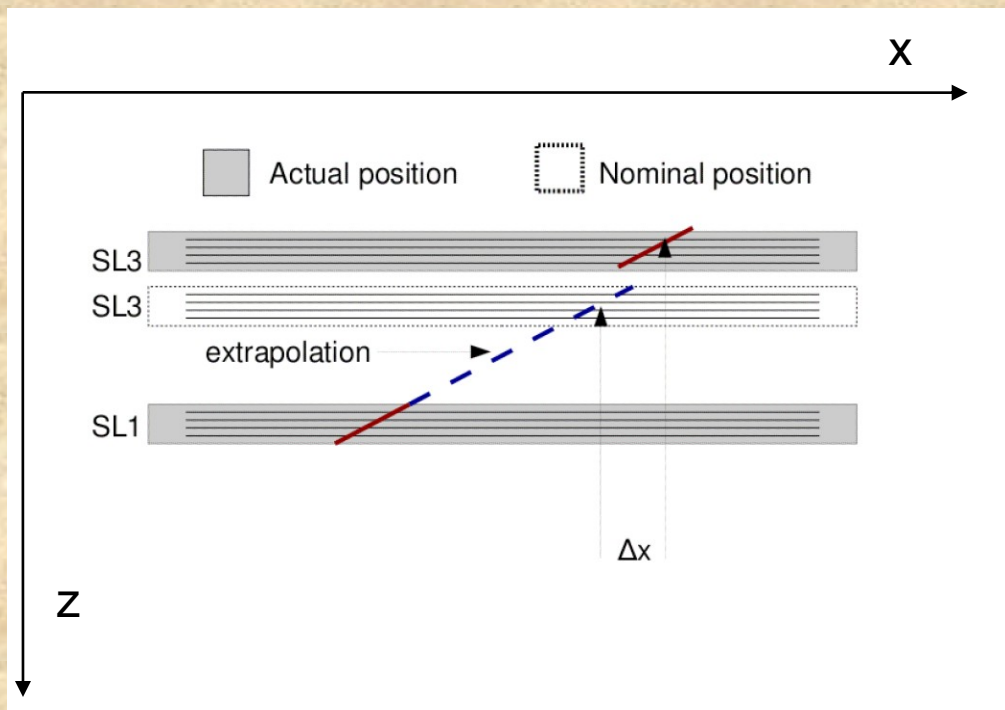


- Alignment is done with muons reconstructed in DT
 - no reconstruction in tracker is required
 - cosmics and collisions data
 - muons $p_T > 50$ GeV



Test on data ongoing
 • Cosmics
 • pp collisions

- 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