Alignment of the CMS Muon System with Tracks

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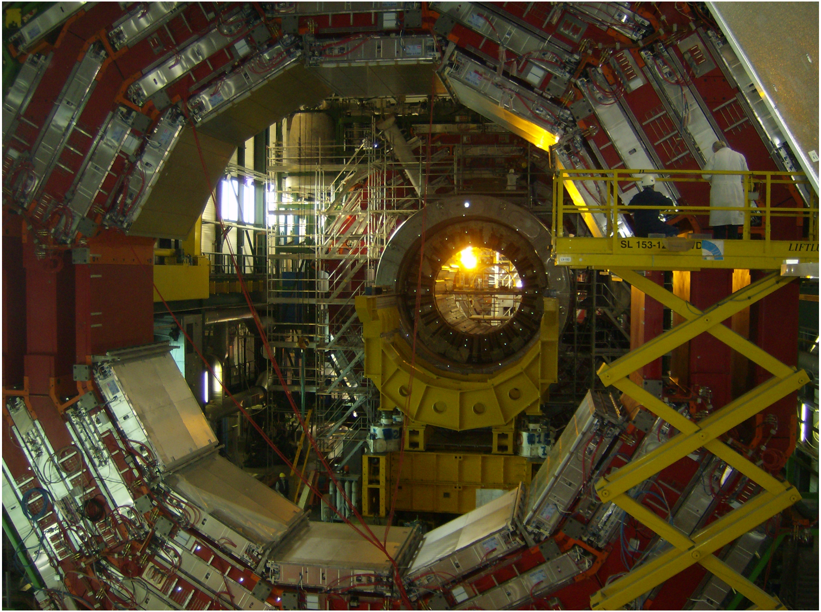
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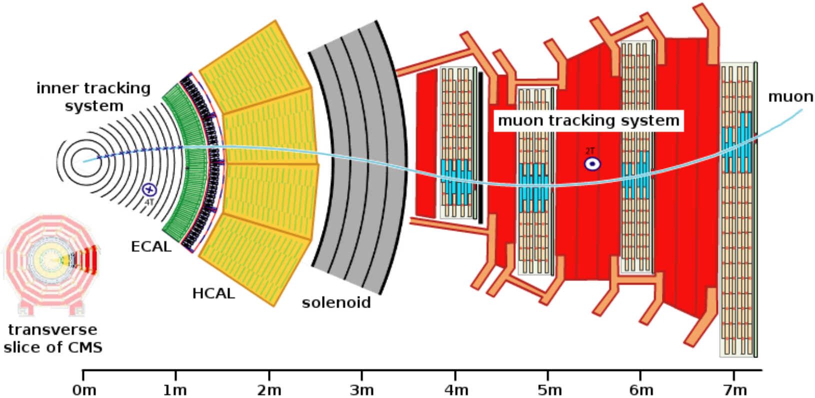
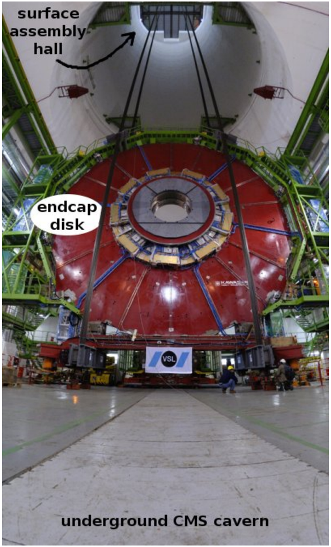
CMS muon tracking system

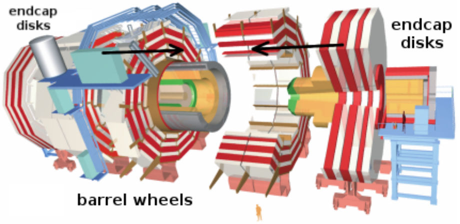
Outermost part of the Compact *Muon* Solenoid (CMS)



- Every muon passes through 18–44 layers: a complete tracking system
- Measure muon momentum by curvature of its 7-meter long track, combined with high-precision inner silicon tracker
- Layers grouped into 6–12 layer chambers, separated by iron yoke

Modular components



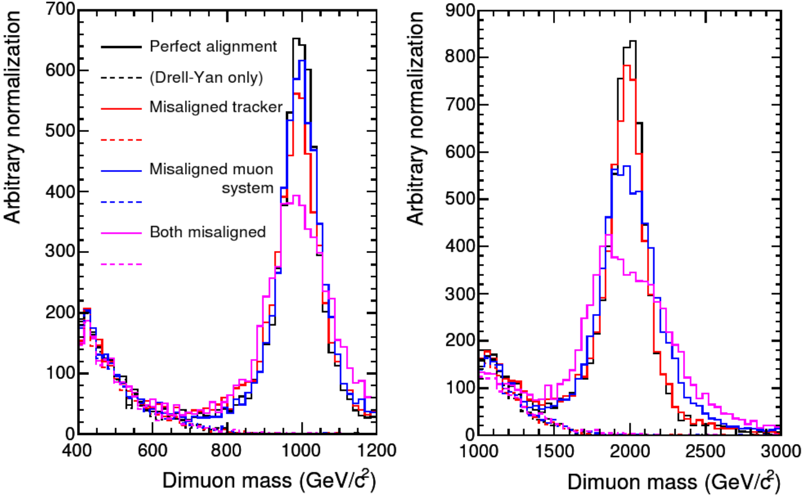


- Built in an assembly hall and lowered, piece by piece, to the interaction point
- Iron disks shift and bend centimeters in CMS's 3.8 T magnetic field
- 718 chambers mounted on ball-joints to remain internally rigid

Hit resolution depends on precise knowledge of chambers' position and orientation in space

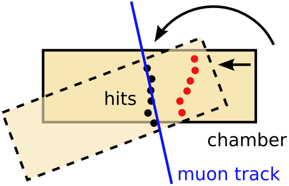
Importance of muon alignment for discoveries

Simulated Z' peak shape with misaligned tracker and muon chambers

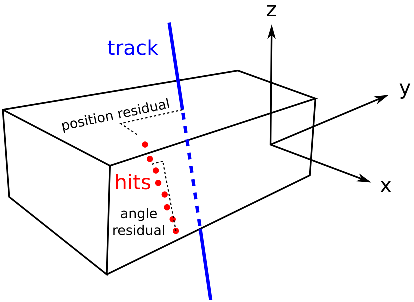


Alignment of the muon system is most important at the highest energies

Track-based alignment



- Find corrections to assumed chamber positions by minimizing residuals (track intersection − hit position)

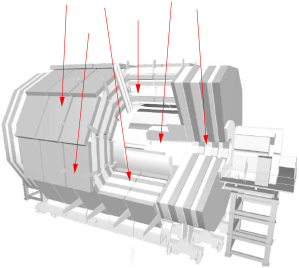


- Muon chambers are internally well aligned: 6 degree-of-freedom rigid bodies
- Combine internal hits into 4-component residuals:
  - x, y position residuals
  - $\tan^{-1}\left(\frac{dx}{dz}\right)$, $\tan^{-1}\left(\frac{dy}{dz}\right)$ angle residuals
- Alignment corrections influence multiple residuals components with different dependencies on track position, entrance angle: a highly constrained system of equations

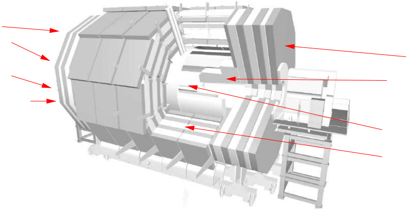
Global alignment of the CMS tracking system

- Inner silicon tracker and muon chambers must be aligned in the same coordinate system
  1. Align the tracker independently
     - homogeneous magnetic field, low-material environment
     - resolve chicken-and-egg problem of track-fitting and detector component alignment with three methods: iteration/convergence, simultaneous solution in a large matrix, accumulate knowledge of systematic effect in track-fitter
  2. Fit tracks with aligned tracker, propagate into muon system
  3. Align muon chambers with the fixed tracks
     - propagates alignment knowledge from high-precision tracker to the rest of CMS
     - automatically resolves chicken-and-egg problem: track-fits and alignment are independent
     - scattering in iron statistically broadens distributions, but does not introduce systematic bias

Alignment before first collisions



Cosmic rays for barrel

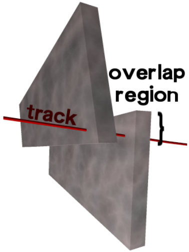


LHC “beam-halo” for endcaps

Cosmic ray and beam-halo alignments provide

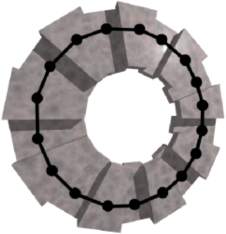
- a test of the alignment techniques in a fully realistic environment
- improved momentum resolution for ongoing cosmic ray analyses
- a future cross-check using non-projective tracks
  - non-projective tracks relate alignable detector elements in different combinations than interaction point muons

Beam-halo alignment method



- Endcap muon chambers were designed with a small overlap region for alignment
- Tracks passing through overlap region connect chambers without any intervening scattering material or long-distance propagation
- High-precision relative pair-wise alignment
- Propagate around each ring with a simultaneous solution of 18 (36) chambers $\times$ 3 parameters (1 translation, 2 angles)

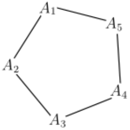
Simplified example:



$$\chi^2 = (\alpha_{12} - A_1 + A_2)^2 + (\alpha_{23} - A_2 + A_3)^2 + \ldots$$

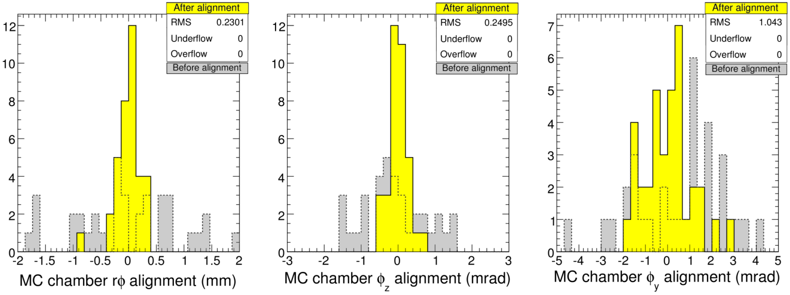
$$\frac{1}{2}\frac{\partial\chi^2}{\partial A_2} = (\alpha_{12} - A_1 + A_2) - (\alpha_{23} - A_2 + A_3) = 0$$

$$\begin{pmatrix} 0 \\ \alpha_{23} - \alpha_{12} \\ \alpha_{34} - \alpha_{23} \\ \alpha_{45} - \alpha_{34} \\ \alpha_{51} - \alpha_{45} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ -1 & 2 & -1 & & \\ & -1 & 2 & -1 & \\ & & -1 & 2 & -1 \\ -1 & & & -1 & 2 \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{pmatrix} \quad \text{for}$$



Test of the method in Monte Carlo

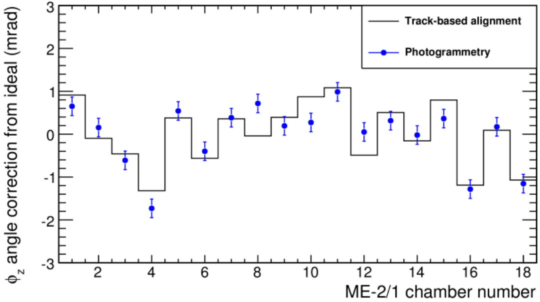
- Procedure applied to Monte Carlo sample with statistics comparable to 2008 LHC single-beam run
- Predict accuracy by comparing value of each parameter for each chamber with MC-truth

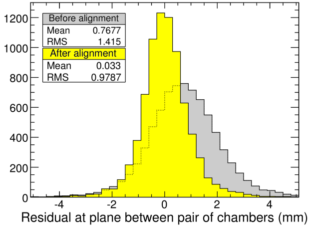


Results from 2008 LHC single-beam run

- Real-data track-based alignment independently verified by photogrammetry (alignment from a literal photograph of the detector)

- Both saw corrections relative to the design description, with high correlation





- Application of track-based alignment narrows and centers residuals distribution, improves tracks

Results from 2008 LHC single-beam run

- Chamber-by-chamber comparisons with photogrammetry:
  - agreement with 270 μm position and 0.35 mrad angular accuracy
  - close to the 166 μm intrinsic hit uncertainty (for these chambers)
  - from 33,000 events: 9 minutes of LHC beam (3/4 of the 2008 run)