Track-based muon system alignment of the CMS detector

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Outline

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- Track-based muon alignment
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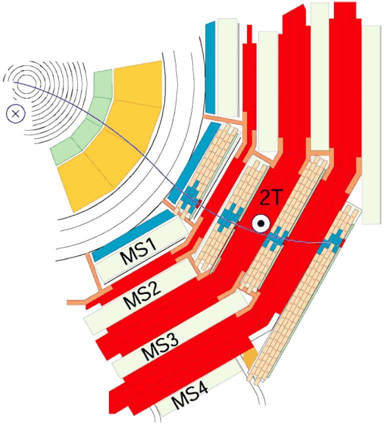
  - Muon chamber degrees of freedom (DOF)
  - Accuracy
  - Run2 performance
- Physics validation
  - CSC alignment
  - Legacy geometry
- Run3 commissioning
- Summary



CMS Muon System For Alignment

Drift Tube (DT) [1]

- Pseudorapidity regions: $|\eta| < 1.2$
- Five wheels (wheel 0 in the center and wheel 2 at the z side)
- DTs are arranged in stations, numbered from 1 to 4 with station
- Chambers in station 4 can only measure the ϕ of the tracks

Cathode Strip Chamber (CSC) [1]

- Pseudorapidity regions: $0.9 < |\eta| < 2.4$
- The system is divided into four stations mounted on iron disks in each endcap
- The CSC stations are numbered from 1 to 4 on the z side of the CMS detector, where stations 1 are closest to the interaction point
- Within each disk, CSCs are arranged in rings 1 up to 3, where ring 1 is the closest to the beam axis

Track-Based Muon Alignment

reconstructed position !
predicted position !

- Track-based muon alignment (TBMA) [2]
  - Propagate the tracker hits of muons into the muon system to predict their positions
  - Muon residual: di erence between reconstructed position and predicted position on the muon chamb
- The TBMA technique is proven to be e cient, robust, and stable in Run1 and Run2
- Sources of possible systematic uncertainties have been investigated and various improvements to reduce their e ect are being developed
- Muon system alignment is very important for muo reconstruction and TBMA has an accuracy of 100-150 mm

Track-Based Muon Alignment

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  - Propagate the tracker hits of muons into the muon system to predict their positions
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  - ...chamb

Tracker alignment of the CMS detector

See Patrick Connor's talk on Thursday (July 30)
https://indico.cern.ch/event/868940/contributions/3813530

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- Sources of possible systematic uncertainties have been investigated and various improvements to reduce their e ect are being developed
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reconstructed position !
predicted position !

Alignment Inputs

When muons scatter before the chamber, they scatter in either directions and the "pulls" cancel each other (left track). Near the chamber boundaries one direction will "scatter in" to the same chamber and the other will "scatter out" to a di erent chamber (right track). As the selection of muon candidates used in alignment of a chamber requires muons to have hits in the chamber in question, only muons that "scatter in" contribute to the alignment measurement, while muons that "scatter out" do not.

- Selected with transverse momentum (p_T) in the range 30 < p_T < 200 GeV (less scattering and less showering)
- To ensure track quality:
  - The muons must have at least ten hits in their inner tracker segments
  - Must be matched to at least two muon stations
  - Should have a normalized d^2/n.d.f. < 10 for the track t
  - The impact parameter with respect to the interaction point should satisfy D_{xy} < 0.2
- A set of ducial selection criteria are required as muon hits near the boundaries of chambers can cause directional biases

Muon Chamber DOF

- The alignment procedure is e ectively a minimization of a multidimensional function
- The procedure seeks to determine up to misalignment parameters (local coordinat
  $p_{local} = (dx; dy; dz; df_x; df_y; df_z)$
- Residuals used for alignment
  - DTs: x; y
  - CSCs: Rf
  - Local x and Rf are in the global f direction: the most sensitive direction in the p_T resolution

Accuracy

- These plots show how the alignment accuracy depends on statistics
  - 2 fb^{1} is recommended for the TBMA
  - Alignment still improves with higher luminosities
  - The accuracy depends on detector position and type (the error bar includes systematics uncertainties)

Run2 Performance

- Run2 TBMA
  - Several new capabilities have been added to this fitting procedure to solve weak mode (any small χ^2 detector deformations [3])
  - Precision on the order of 100 μm for linear DOF and 0.1 milliradians for angular DOF
- Run2 legacy alignment performed with:
  - Updated and improved tracker legacy geometries
  - Detailed interval (1 alignment/year → 3 alingments/year)
  - Higher integrated luminosities
- CSC alignment
  - A two-step process of aligning the CSC is used after the endcaps have been oper
  - The residual distribution has a sinusoidal trend due to the misalignment of the CS disk
  - The improvements in the CSCs after the track-based muon alignment are visible

Physics Validation

- Muon alignment physics validation data sets:
  - Data collected at the beginning of the 2016 (5.44 fb^{-1}), 2017 (4.79 fb^{-1}), and 2018 (3.60 fb^{-1}) proton-proton collision runs with single muon trigger
- Global muons (GLB) consist of tracks reconstructed independently in the inner tracker (tracker tracks, inner-track) and in the muon system (standalone muon tracks, STA) [4]
- Muon selection:
  - Global muon
  - $|\eta_{\mu}^{inner\ track}| < 2.4$ and $p_{T\mu}^{inner\ track} > 30\,\mathrm{GeV}$
- Di-muon invariant-mass plots:
  - Computed selecting opposite-charge muon pairs satisfying muon selection
  - Use either muon track information from: GLB+GLB or GLB+STA
- Muon p_T resolution plots:
  - Computed for every muon satisfying the muon selection
  - Measuring metric: $q/p_{T\ STA} - q/p_{T\ GBL}$
- The above metrics are sensitive to the STA fit performance (muon alignment)

Physics Validation

Di-muon (GLB+STA) invariant-mass plots

- 2017 data with 2016 geometry (red) shows wrong di-muon mass reconstruction
- Muon Alignment is important for muon reconstruction
- There is scale bias (a 1% scale bias in barrel and a up to 5% bias in the endcap [5]) due to STA leg

CSC Alignment

Before Alignment

After Alignment

- Residual on r f as a function of global f for the rst ring on the rst disk of CSC chambers in the positive endcap (ME+1/1), the residual means (red), medians (black), and distributions (blue heat map) are shown before alignmen (left) and after alignment (right)
- The residual distribution (left) has a sinusoidal trend due to the misalignment the CSC disk trigger a ected
- The sinusoidal trend disappears (right) after alignment

CSC Alignment

2018 CSC displacement

Step1: disk-level Step2: chamber-level Step1 + Step2

CSC chamber movements with respect to the 2018 startup geometry.

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CSC Alignment

2016 CSC physics validation

- Mean value of the di-muon mass (GLB+GLB) distribution vs. f_{m^+} for $-2.4 < h_{m^+} < -0.9$ (left) and resolution in p_T mean vs. h (left)
- The improvements in the CSCs after the track-based muon alignment are visible
- All entries are using the same up-to-date tracker geometry

Legacy Geometry

- Validation of Run2 legacy muon alignment using di-muon (GLB+STA) mass distributions for $Z \rightarrow \mu^+\mu^-$ event candidates
- Left: Di-muon mass as a function of the standalone muon track
- Right: Di-muon mass width as a function of the standalone muon track
- High eta (endcap) region is unstable due to low statistics

Run3 Commissioning

- Gas Electron Multiplier (GEM) has been installed at endcap station 1

GEM

Not to scale

- Left: GEM GE1/1 (red) installed at endcap station 1
- Right: GEM-CSC bending angle for triggering

Run3 Commissioning

- Gas Electron Multiplier (GEM) has been installed at endcap station 1

GEM

Not to scale

CMS GEM talks

Commissioning and prospects of rst GEM station at the CMS experiment
(https://indico.cern.ch/event/868940/contributions/3813686)
Electrical Discharge Mitigation Strategies for Future CMS GEM Systems GE2/1 and ME0
(https://indico.cern.ch/event/868940/contributions/3814118)

- Left: GEM GE1/1 (red) installed at endcap station 1
- Right: GEM-CSC bending angle for triggering

Run3 Commissioning

- Gas Electron Multiplier (GEM) has been installed at endcap station 1
  - Improve tracking performance and reduce the rate of mis-measured muons trigger rate
  - Muon alignment has been preparing to include 2 layers of triple-GEM chambers
  - GEM-CSC trigger requires precise alignment
- Muon alignment considers other methods to study weak mode and improve alignment
  - Beam Halo and cosmic muon: these datasets can help to study weak modes because the muons are not from the interaction point
- We expect the large displacement of the muon detectors due to opening endc extraction, and re-installation
  - TBMA supports iteration calculation
  - After long shutdown 2 (LS2), TBMA is expected to perform a similar performance for Run3
  - Cosmic muon data set can help initial alignment

Summary

- The performance of the track-based muon alignment in Run2 was robust and stable. It supported excellent muon reconstruction in CMS and contributed to many physics analyses with muons.
- The work ow of Run3 muon alignment has been prepared to include GEMs.
- Displacement of muon chambers after LS2 commissioning will be corrected in two steps: (a) comic ray muons; (b) pp collisions (2 fb^{1}).

References

[1] CMS Collaboration, The CMS Experiment at the CERN LHC, JINST, vol. 3, p. S08004, 2008.

[2] CMS Collaboration, Alignment of the cms muon system with cosmic-ray and beam-halo muons,JINST, vol. 5, p. T03020, 2010.

[3] CMS Collaboration, Alignment of the CMS tracker with LHC and cosmic ray data, JINST, vol. 9, p. P06009, 2014.

[4] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, JINST, vol. 13, p. P06015, 2018.

[5] CMS Collaboration, Performance of CMS Muon Reconstruction in pp Collision Events at $\sqrt{s} = 7$ TeV, JINST, vol. 7, p. P10002, 2012.

Backup

CMS Muon System For Alignment: DT

DT

- Pseudorapidity region $|\eta| < 1.2$
- Five wheels (wheel 0 in the center and wheel ± 2 at the $\pm z$ side)
- DTs are arranged in stations, numbered from 1 to 4 with station 1 closest to the beam axis
- In the azimuthal direction, the muon barrel is divided into 12 sectors, except in station 4 which has 14 sectors
- The muon system consists of 250 DT chambers
- Each chamber consists of sensitive 1-dimensional layers
- There are 12 (8) layers in stations 1 to 3 (4)
- Chambers in station 4 can only measure the global coordinate of the tracks

CMS Muon System For Alignment: CSC

CSC

- Pseudorapidity regions: $0.9 \leq |\eta| < 2.4$
- The system is divided into four stations mounted on iron disks in each endcap
- The CSC stations are numbered from 1 to 4 on the z side of the CMS detector, where stations 1 are closest to the interaction point
- Within each disk, CSCs are arranged in rings 1 up to 3, where ring 1 is the closest to the beam axis
- Each ring is formed by 18 or 36 trapezoidal chambers, depending on the disk

Muon Chamber DOF: DT (stations 1, 2, and 3)

$$= M\,P_{local}$$

DT stations 1, 2, and 3 projection matrix

$$\begin{pmatrix} x \\ y \\ \frac{dx}{dz} \\ \frac{dy}{dz} \end{pmatrix} = \begin{pmatrix} 1 & 0 & \frac{dx}{dz} & y\frac{dx}{dz} & x\frac{dx}{dz} & y \\ 0 & 1 & \frac{dy}{dz} & y\frac{dy}{dz} & x\frac{dy}{dz} & x \\ 0 & 0 & 0 & \frac{dx}{dz}\frac{dy}{dz} & 1+\left(\frac{dx}{dz}\right)^2 & \frac{dy}{dz} \\ 0 & 0 & 0 & 1\ \left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} dx \\ dy \\ dz \\ d\phi_x \\ d\phi_y \\ d\phi_z \end{pmatrix}$$

Muon Chamber DOF: DT (station 4)

$= M P_{local}$

DT station 4 projection matrix

$$\begin{pmatrix} x \\ \frac{dx}{dz} \end{pmatrix} = \begin{pmatrix} 1 & \frac{dx}{dz} & y\frac{dx}{dz} & x\frac{dx}{dz} & y \\ 0 & 0 & \frac{dx}{dz}\frac{dy}{dz} & 1+\frac{dx}{dz}^{2} & \frac{dy}{dz} \end{pmatrix} \begin{pmatrix} dx \\ dz \\ d\phi_x \\ d\phi_y \\ d\phi_z \end{pmatrix}$$

Muon Chamber DOF: CSC

$$= M\, P_{local}$$

CSC projection matrix: x residual is replaced with the arc length (Rf)

$$
\begin{pmatrix} (Rf) \\ y \\ \frac{d(Rf)}{dz} \\ \frac{dy}{dz} \end{pmatrix}
=
\begin{pmatrix}
1 & \frac{x}{R} + 3\left(\frac{x}{R}\right)^3 & \frac{dx}{dz} & y\frac{dx}{dz} & x\frac{dx}{dz} & y \\
0 & 1 & \frac{dy}{dz} & y\frac{dy}{dz} & x\frac{dy}{dz} & x \\
0 & \frac{1}{2R}\frac{dx}{dz} & 0 & \frac{x}{R} \quad \frac{dx}{dz}\frac{dy}{dz} & 1 + \left(\frac{dx}{dz}\right)^2 & \frac{dy}{dz} \\
0 & 0 & 0 & 1 \quad \left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz}
\end{pmatrix}
\begin{pmatrix} dx \\ dy \\ dz \\ df_x \\ df_y \\ df_z \end{pmatrix}
$$

Accuracy

RMS values of alignment variable distributions in local X in the CMS track-based muon alignment (TBMA) procedure on DT chambers as a function of the integrated luminosity of pp collisions. This indicates 2 fb^{1} or larger luminosity is a requirement for TBMA. Each error bar includes systematics uncertainties, such as chamber-to-chamber deviation. The alignment accuracy depends on the detector location (wheels and stations for DT) and six alignment valuables $(dx; dy; dz; df_x; df_y$; and df_z for DT). Here dx is the most sensitive in the p_T resolution, and the best alignment accuracies are obtained from chambers in the central region (Wheel 0 and 1).

Di-muon Mass: Legacy Muon Alignment

Validation of Run2 legacy muon alignment using di-muon (GLB + STA) mass distributions for $Z \to \mu^+\mu^-$ event candidates. Left: Di-muon mass (mean and width values from Gaussian fit) as a function of the standalone muon η. Right: Di-muon mass width as a function of the standalone muon η. High η (endcap) region is unstable and sensitive to operating conditions. Since one di-muon leg is STA, there is scale bias (a 1% scale bias in barrel and a up to 5% bias in the endcap [4]).

2018 CSC Residual

Before alignment After alignment

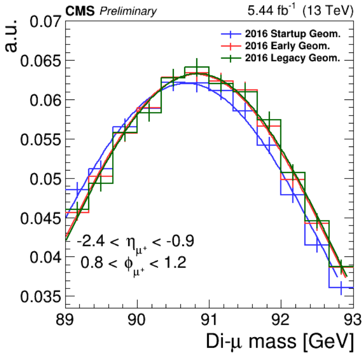
Residual on $r\phi$ as a function of global ϕ for the first ring on the first disk of CSC chambers in the positive endcap (ME+1/1). On the left, the residual distribution has a sinusoidal trend due to the misalignment of the CSC disk. On the right, the residual distribution is centered around zero after the initial geometry has been corrected. The residual means (red), medians (black), and distributions (blue heat map) are shown shown before alignment (left) and after alignment (right).

2018 CSC Displacement

Step1: disk-level Step2: chamber-level Step1 + Step2

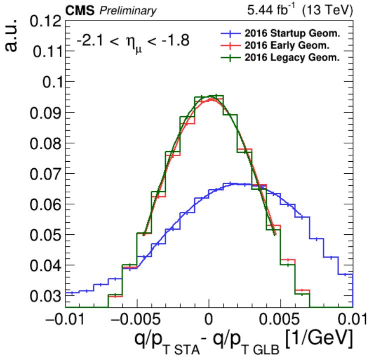
A two-step process of aligning the CSC is used after the endcaps have been opened, shown for ME +1/1: a disk-level alignment (left) followed by a chamber-level alignment using the disk-level alignment as the new reference geometry (middle). The final comparison (right) shows the sum of both alignment's chamber movements with respect to the 2018 startup geometry. Linear and angular chamber displacements are exaggerated 200-fold.

2016 CSC Di-muon Mass



Left: Di-muon mass (both GLB) distributions for muons between $0{:}8 < f_{m^+} < 1{:}2$ rad and $2{:}4 < h_{m^+} < 0{:}9$. Right: Mean value of the di-muon mass distribution vs f_{m^+} for $2{:}4 < h_{m^+} < 0{:}9$. The improvements in the CSCs after the track-based muon alignment are visible. All entries are using the same up-to-date tracker geometry.

2016 CSC p_T Resolution



Left: Resolution in p_T distributions for muons between 2:1 < h < 1:8. Right: resolution in p_T vs. h. The improvements in the CSCs after the track-based muon alignment are visible.

Di-muon Mass: 2017

The invariant mass of dimuon pairs is computed by reconstructing one muon using only standalone tracker information (STA) and the other using both the tracker and the muon system information (GLB). The mean of the dimuon invariant mass distribution is shown in bins of the standalone track h. The red distribution refers to muons reconstructed using the muon system geometry computed in 2016, while the green distribution refers to muons reconstructed using the geometry computed with early 2017 data. The performance are similar at low h, since the position of the Drift Tubes is similar in 2016 and 2017, while at high h a substantial improvement is observed, as a consequence that the CMS detector has been opened and closed.