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Implementation of position and angle uncertainties in the muon reconstruction of the CMS experiment, and impact on the performance.

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Implementation of position and angle uncertainties in the muon reconstruction of the CMS experiment, and impact on the performance

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Abstract—The alignment of muon chambers relative to each other and to the inner tracker is crucial to achieve the optimal performance of muon reconstruction at high momentum, in particular the best possible momentum measurement. With the energy and luminosity increase in LHC Run2, the high momentum muons have become more important for the searches of new particles with masses around the TeV scale. The muon reconstruction of the CMS experiment has been recently improved and made more robust with the introduction of alignment uncertainties on the positions and angles of the segments in the muon chambers. Not only does the momentum resolution improve at high energy, but, owing to the better quality of the muon track building and fit, also the trigger efficiency increases, especially in the initial phase of data-taking, after the opening and closure of the detector.

I. INTRODUCTION

THE primary aim of the CMS experiment [1] is to search for new physics in the wide energy range which can be accessed at the CERN LHC. Many predictions of new physics require to detect muons from the decay of hypothesized new particles, which involves triggering, identification, and precise muon reconstruction.

The muon reconstruction in CMS is performed using the silicon tracker at the centre of the detector, immersed in a 3.8 T solenoidal magnetic field, and four stations of gas-ionisation muon detectors installed outside the solenoid and sandwiched between the layers of the steel return yoke. A detailed description can be found elsewhere [2].

At low and intermediate momentum, below 100 GeV/c, the muon p_T resolution is dominated by the hits measured on the silicon tracker. Instead hits and segments measured on the muon chambers are significantly affected by multiple scattering of the muon trajectory while passing through the calorimeter depth. This gets reduced with increasing momentum and above ≈ 200 GeV/c the muon chamber measurements start to impact on the measured p_T . The ultimate performance at high- p_T is then determined by the precision of the muon chamber measurements.

The alignment of the silicon tracker is a challenging task, achieving a statistical accuracy better than 10 μm on the position of individual detector modules [3], [4]. This excellent precision does not reduce significantly the typical intrinsic resolution of silicon hits, ranging from 10 to 30 μm . Systematic uncertainties are kept under control by the use of events

with different topologies: general tracks from pp collisions, reconstructed $Z \rightarrow \mu^+\mu^-$ decays and cosmic ray tracks.

The intrinsic precision of the muon Drift-Tube (DT) chambers, in the barrel region $|\eta| < 1.2$, and the Cathode Strip Chambers (CSC), in the endcap region $1.2 < |\eta| < 2.4$, is of the order of 100 – 200 μm , to which the possible chamber misalignment has to be added in quadrature [5].

All DT chambers are first aligned by a hardware system [6], utilizing lasers and cameras, in the *startup* phase, at the beginning of a data-taking period, as soon as the detector is closed and the magnetic field is turned on at its nominal value. The typical precision of the hardware alignment is $\sim 0.5 - 1$ mm on positions and $\sim 0.3 - 0.4$ mrad on angles of the individual chambers.

The CSC chambers in the two endcaps do not feature an equally granular system and their initial geometry can be determined by hardware measurements refined by alignment with beam-halo muons that traverse overlapping chambers [6]. This procedure is relatively complex and has not been routinely carried out in the last years, also because a much better alignment can be obtained with muon tracks from collisions in a relatively short period of data-taking. The uncertainty of the initial CSC geometry, at the beginning of a data-taking period, has been estimated from the accuracy of geometrical survey and photogrammetry measurements, ~ 2 mm on positions and ~ 1 mrad on angles.

The startup performance is expected to be suboptimal, in particular due to large misalignments after the opening and closure of the detector during the LHC shutdown periods, and to the magnetic field cycles.

The final alignment of the individual muon chambers (both DT and CSC) is determined starting from the aligned silicon tracker geometry, by extrapolating selected muon tracks from the inner tracker to the muon chambers (*track-based* muon alignment) [7]. The algorithm can use both cosmic muons and muons from pp collisions, selected with high purity and transverse momentum above a minimum threshold to limit the multiple scattering ($p_T > 30$ GeV for collisions muons in 2016 run [8]). With the track-based alignment the muon chambers' positions are determined with a precision of ≈ 200 μm in the most sensitive coordinate, which measures the magnetic bending of the muon track and is crucial for the precise momentum measurement.

Overall the full alignment of the tracking and muon systems

TABLE I
MUON STARTUP AND ASYMPTOTIC APE FOR DT AND CSC SYSTEMS

	Startup APE		Asymptotic APE	
	DT	CSC	DT	CSC
local- x	0.5-2 mm	2 mm	0.2-0.5 mm	0.1-0.6 mm
local- y	0.9-2 mm	2 mm	0.1-1.3 mm	0.3-0.6 mm
local- z	0.9-2 mm	2 mm	0.6-1.1 mm	2 mm
local- ϕ_x	0.4-1 mrad	1 mrad	0.3-0.6 mrad	0.5-1 mrad
local- ϕ_y	0.4-1 mrad	1 mrad	0.3-0.5 mrad	2-2.8 mrad
local- ϕ_z	0.3-1 mrad	1 mrad	0.05-0.2 mrad	0.04-0.5 mrad

is a complex task, which needs a minimum statistics of selected muons per chamber and takes a few weeks to be run and validated. Performance results obtained from the 2016 run are reported elsewhere [8], [9].

Until 2015, the CMS muon reconstruction has neglected the alignment uncertainties of the muon chambers (so-called *Alignment Position Errors*, or **APE**). Some shortcomings have been known for a long time, as observed pulls larger than unity for the muon segment parameters with respect to the extrapolated track from the inner tracker. The best possible reconstruction for a high- p_T muon track can be reached by a correct relative weighting of tracker and muon hits. In the high-momentum regime this balance requires considering appropriate muon alignment uncertainties in the Kalman fit.

From the beginning of the 2016 run, the muon reconstruction has been using non-null muon APE for the first time ever in CMS [10]. Many tests have been carried out to validate this update. Both data and Monte Carlo (MC) simulation events have been analyzed, spanning over the different sets of alignment conditions (from day-1 startup to the final track-based alignment, the so-called *asymptotic* alignment). The muon APE have been introduced for all 6 degrees of freedom (3 positions: local- x , $-y$ and $-z$, and 3 angles: local- ϕ_x , $-\phi_y$ and $-\phi_z$) chamber-by-chamber, for both DT and CSC systems, and taken as uncorrelated as a first approximation.

The muon APE are not yet calibrated offline with data: APE for the startup scenario are defined by the uncertainties of hardware measurements; APE for the asymptotic scenario are determined from MC as the residual uncertainties with respect to the true geometry after the full alignment procedure is carried out as if it were real data.

During the 2015 LHC winter shutdown period, only the endcaps were opened and not the barrel, so the DT chambers remained aligned with respect to each other and to the inner tracker as after the final track-based muon alignment in 2015. Nevertheless a conservative approach has been adopted for the startup phase of the 2016 run and the hardware APE have been used for the DT chambers as well. The size of muon APE for both the startup and asymptotic scenarios is given in Table I.

This report summarizes the results for muon trigger and offline reconstruction performance with the muon APE, obtained using $\sim 2.2 \text{ fb}^{-1}$ of data collected in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ in 2016, and MC simulations. In Section II, the behaviour of residual distributions is discussed for data and MC, which provides an important validity check to the muon track reconstruction performance. The simulation

studies defining the expected muon performance with APE are described in Section III. Finally the results of muon performance studies using the real data are given in Section IV.

II. RESIDUALS OF TRACK-TO-SEGMENT MATCHES

The residuals of track-to-segment matches are the observables used by the standard track-based muon alignment procedure as the means to obtain chamber-by-chamber alignment. They are defined from the distance between the extrapolated inner track at a given reference plane on the muon stations, and the muon segment reconstructed in the matched station. The residual distributions are studied, in particular for the most important segment parameter, the local- x position, measuring the displacement in the magnetic bending plane.

A clean sample of dimuon events, with invariant mass greater than $80 \text{ GeV}/c^2$, has been exploited to select candidate muons with $p_T > 20 \text{ GeV}/c$, with high quality on the tracker variables but only loose requests on the matching with muon segments, to avoid possible biases [10].

The RMS width of the local- x residual distribution has been compared for data and Drell-Yan MC simulated events (both of which are reprocessed with asymptotic scenario and corresponding APE), as shown in Fig. 1a and 1b as a function of the muon station number, for the DT and CSC systems respectively. The width increases from the innermost to outermost muon stations (from MB1 to MB4 in the DT system and from ME1 to ME4 in the CSC system) as expected, due to the amount of material upstream of the muon station and the distance over which the track is extrapolated. A very good agreement is observed between data and simulation.

The residuals for track-to-segment matches have also been studied as a function of the muon momentum and pseudorapidity. The first muon station is the most important for the muon reconstruction, as it is where the track's sagitta, determined by the magnetic field inside the solenoid, is largest, and its measurements are the least affected by multiple scattering and showering effects due to less upstream material.

The RMS width of the residual of the local- x position as a function of muon pseudorapidity is shown in Fig. 2. A selection on the momentum $p > 90 \text{ GeV}/c$ has been applied to be consistent with the published results [2], for the sake of comparison. As expected from the η dependence of the distance between the inner tracker and the first muon station and of the material thickness, the residual width reaches the maximum values in the overlap region, $0.9 < |\eta| < 1.2$. Overall data and MC are in good agreement for the whole η range.

Fig. 3a and 3b show the momentum dependence of the RMS width, for the barrel and endcap regions respectively. The width decreases with increasing momentum because of smaller multiple-scattering effects. Data and MC are in quite good agreement for the whole probed momentum range. At low momentum, the residuals are mainly driven by multiple scattering, and the impact of misalignments is relatively small. Misalignments are expected to become important for $p > 200 \text{ GeV}/c$.

(a)

(b)

Fig. 1. RMS width of residuals of the local- x position, given by the distance of the muon segment from to the extrapolated tracker track, as a function of the muon station, for the DT system in the barrel region (a), and for the CSC system in the endcap region (b). Data are compared with MC expectations, for asymptotic alignment and corresponding APE.

Fig. 2. RMS width of residuals of the local- x position for the track-to-segment match in the first muon station as a function of the muon pseudorapidity, with a requirement on momentum $p > 90$ GeV/c. Data are compared with MC expectations, for asymptotic alignment and corresponding APE.

III. MUON PERFORMANCE IN SIMULATION

The inclusion of APE in the muon reconstruction is expected to result in:

- improved pattern recognition (increased average number of hits per track) as larger uncertainties on the muon segments make them more likely to be efficiently matched;
- width of pulls getting closer to unity which ultimately leads to better χ^2 of the track fit;
- correct relative weight assignment to the muon segments and inner track which obtains the best momentum estimate for the tracker plus muon fit, in particular at high

momentum.

The expectations have been tested by MC simulation of back-to-back dimuons with flat momentum, pseudorapidity and azimuth, within the range [5 GeV/c, 2.5 TeV/c].

Startup and asymptotic scenarios with and without the corresponding APE have been simulated, together with the ideal scenario with no misalignment at all and, consequently, APE set to zero. Muons are selected with tight identification and isolation criteria to perform these studies [10]. Fig. 4 shows the average number of muon hits reconstructed for the global muon track, as a function of pseudorapidity. The momentum range [20, 500] GeV/c has been considered, to compare reasonably with the real data. For the startup scenario, an average gain of about 2 muon hits per track is observed after the inclusion of APE, for the whole pseudorapidity range. Moreover it gets in better agreement with the ideal scenario. Asymptotic APE have a lesser effect but small improvements are visible in comparison to the asymptotic scenario without APE.

The average normalized χ^2 for the global track (with $20 < p < 500$ GeV/c), is shown in Fig. 5 as a function of the muon pseudorapidity. For the startup scenario without APE, large χ^2 values are observed as an effect of the misalignments degrading the track quality, in particular in the endcaps. Applying APE brings the average χ^2 close to the expectation for the ideal scenario. Actually it slightly overshoots the expectation in the endcaps. This could result from correlations among APE, which are not yet taken into account. Another possible reason could be an overestimation of uncertainties of the local reconstruction of muon segments in the endcap chambers. For the asymptotic scenario, the χ^2 gets closer to ideal for the whole pseudorapidity range by the introduction of APE.

The momentum resolution has also been studied using the

Fig. 3. RMS width of residuals of the local- x position for the track-to-segment match in the first muon station as a function of the muon momentum in the barrel region (a), and in the endcap region (b). Data are compared with MC expectations, for asymptotic alignment and corresponding APE.

simulated events. It is determined from the Gaussian width of the distribution of the relative residual between reconstructed and true signed inverse momentum q/p . A dedicated reconstruction algorithm, specialized for high- p_T muons (so-called *picky* [2]), has been considered. Results are shown in Fig. 6a and 6b for the barrel and endcap regions respectively. The performance of the tracker-only fit is also given for the comparison purpose. Significant improvements are found with the inclusion of APE in the startup scenario. In the endcaps, the startup performance is worse than tracker-only, but gets recovered with APE. In the barrel region, the performance gets closer to asymptotic by including APE. There are also small improvements for the asymptotic scenario itself due to APE, for both barrel and endcaps.

IV. MUON PERFORMANCE IN DATA

The performance on real data has been studied with a dataset corresponding to an integrated luminosity of 2.2 fb^{-1} , collected in the startup period of the 2016 run, with an inclusive trigger selecting isolated muons with $p_T > 20 \text{ GeV}/c$. A “tag-and-probe” technique has been used [2], where prompt dimuon events are selected with high purity with tight identification and isolation cuts on the tag muon, which is matched to the triggering object, and loose cuts on the probe muon to avoid biases. The probe muon is then used to measure the trigger efficiency and to test the effects on the muon reconstruction [10].

The efficiency of the High-Level Trigger [11] (HLT, a sophisticated software algorithm run on a large computer farm during the data-taking) has been measured for the selected probe muons in events passing the Level-1 trigger (hardware trigger, whose output is the seed for the HLT). The muon HLT path with the minimum p_T threshold of $20 \text{ GeV}/c$ has been probed for the startup scenario with and without APE, by running the HLT algorithm offline with the corresponding

Fig. 4. Average number of hits reconstructed in the muon system for the global muon track as a function of pseudorapidity, for various misalignment scenarios with and without APE. Comparison with the ideal scenario is also given.

conditions. Results are shown in Fig. 7a as a function of muon pseudorapidity. The startup APE increase the HLT efficiency by $\sim 7\%$ for $2.1 < \eta < 2.4$, $\sim 3.5\%$ for $-2.4 < \eta < -2.1$ and $\sim 1\%$ over the remaining endcap regions. The stronger impact of the APE observed for the highest positive eta bin ($2.1 < \eta < 2.4$), larger compared to the corresponding negative side, results from an overall rotation of the whole positive endcap detector after the 2015 LHC winter shutdown. This was cured by the track-based alignment, and the corresponding updated conditions were introduced during the Summer 2016 data collection, after the startup phase.

The HLT efficiency for the endcap regions as a function of

Fig. 5. Average normalized χ^2 for the global muon track as a function of the muon pseudorapidity, for various misalignment scenarios with and without APE. Comparison with the ideal scenario is also given.

p_T is shown in Fig. 7b. A consistent increase of $\sim 2\%$ in efficiency over the whole p_T range and an improved turn-on are observed with the inclusion of APE.

The effects of using non-null APE have been also verified for the offline muon reconstruction with real data, for startup with and without APE, and asymptotic with APE scenarios, by rerunning the muon reconstruction algorithm with the corresponding conditions.

Fig. 8 shows the average number of muon hits for the reconstructed muon track as a function of pseudorapidity. An average gain of 1-2 hits per track is obtained with the use of APE in the startup alignment scenario over the whole angular range. This brings the result of the startup plus APE scenario close to that of the asymptotic scenario. In the latter case the APE are not expected to produce big changes as they are small after the final track-based alignment. The overall effects are qualitatively similar to what has been found in MC simulation (Fig. 4).

The APE scale can be tested by using the residuals of track-to-segment matches, discussed in Section II. One can define the pulls as the normalized residuals, which depend on the uncertainties of the extrapolated inner track (summing up the initial track uncertainty with effects added in the propagation: material description, magnetic field and multiple scattering), the intrinsic uncertainty of the reconstructed muon segment and the uncertainty related to the alignment of the muon chambers. The RMS width of the pull- x distribution for the first muon station, as a function of muon momentum, is shown in Fig. 9 for the endcap regions, which was most affected by the initial misalignments in the startup phase. At low momentum pulls are mainly driven by the multiple scattering of the muon track. Misalignments come at play for momentum above 100 GeV/c. For the startup scenario without APE a diverging trend of the RMS pull is observed for increasing momentum. The APE flatten it even beyond

the MC expectations. This may result from neglecting the correlations or from over-estimation of the local uncertainties on muon segment parameters. Furthermore, the startup APE come from the hardware measurements and lack an offline calibration from data. This will be pursued in the future. The adopted choice seems conservative as it under-weights the muon hits with respect to the tracker hits in the region which is most affected by the misalignments. In the asymptotic scenario including APE the resulting pull is quite close to the expectation from MC simulation.

V. CONCLUSION

From the beginning of the 2016 run, the CMS muon reconstruction has been using Alignment Position Errors (APE) for the parameters of muon chamber segments, for the first time ever. The muon trigger and offline reconstruction performance with the muon APE have been studied using $\sim 2.2 \text{ fb}^{-1}$ of data collected in the first part of the 2016 run, from pp collisions at $\sqrt{s} = 13 \text{ TeV}$. Significant improvements are observed due to the introduction of muon APE. The benefits are larger for the startup alignment scenario, as expected. In particular the p_T resolution improves significantly. Also the muon track quality improves: 1-2 more hits are collected in average per track, and the track normalized χ^2 gets closer to unity. These effects turn out to impact significantly even the trigger efficiency, in particular in the positive endcap regions where the startup misalignments are relatively large. The trigger efficiency is increased by $\sim 7\%$ for $2.1 < \eta < 2.4$, $\sim 3.5\%$ for $-2.4 < \eta < -2.1$ and $\sim 1\%$ for the remaining endcap regions. Small improvements are observed also for the asymptotic alignment conditions, while no drawbacks appear as well.

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(a)

(b)

Fig. 6. Muon momentum resolution in the barrel region $|\eta| < 0.9$ (a) and in the endcap region $1.2 < |\eta| < 2.4$ (b), for a specialized high- p_T algorithm (the *picky* reconstructor) as a function of muon momentum, for the various misalignment scenarios with and without APE. A comparison with the ideal scenario is also given. The performance of the tracker-only fit is shown for comparison.

(a)

(b)

Fig. 7. HLT efficiency of the trigger path requiring muons with $p_T > 20$ GeV/c: (a) as a function of the muon pseudorapidity; (b) as a function of the muon momentum, in the endcap region, for startup alignment scenario with and without APE.

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Fig. 8. Average number of hits in the muon system for the global muon track as a function of the muon pseudorapidity, for startup alignment scenario with and without APE and asymptotic alignment scenario with APE.

Fig. 9. RMS pull between the reconstructed segment in the first muon station and the extrapolated tracker track for the local- x position as a function of the muon momentum in the endcap region, for the startup scenario with and without APE and the asymptotic scenario with APE. A comparison with the MC (with asymptotic scenario and corresponding APE) is also given.