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Efficiency studies of the CMS L3 muon trigger

Abstract

The current muon L3 reconstruction algorithms are tested with various muon HLT paths in order to settle the basis for a comparison with the new L3 reconstruction algorithms. Efficiency and fake rate measurements have been performed for single and double muon paths.

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1 Introduction

The CMS trigger system is used to reduce the high output rate of the high-energy hadron collider by selecting the most useful events for the following physics analysis. A hardware-based layer makes a first selection of interesting events which decreases the event outpute rate from $\sim$ 40MHz to $\sim$ 100kHz. The selected events must then pass the High Level Trigger (HLT) which decides, based on algorithms applied on the rapidly reconstructed event candidates, whether the event is stored for offline analysis. This selection restricts the output rate to $\sim$ 100 - 1000Hz. The HLT consists further of two layers: the second level (L2) which uses calorimeter and muon information and the third level (L3) which uses tracking information to make a decision. The reconstruction algorithms of the HLT are similar to the full offline reconstruction but simplified because the trigger only has a limited amount of time to decide which events are kept. Therefore, the efficiency of this reconstruction is important information for the offline analysis. As a new code for the L3 will be available, the perfomance of the current L3 needs to be tested against the new L3. The efficiency and fake rate of the following single muon paths have been studied:

- HLT_Mu8_v*
- HLT_Mu8_TrkIsoVVL_v*
- HLT_Mu17_v*
- HLT_Mu17_TrkIsoVVL_v*
- HLT_Mu20_v*
- HLT_IsoMu22_v*
- HLT_Mu50_v*

The following double muon paths that have been monitored:

- HLT_Mu17_Mu8_DZ_v*
- HLT_Mu17_TkMu8_DZ_v*
- HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v*
- HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v*
- HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v*

2 Efficiency

The efficiency studies have been performed on large data samples from 2015 and Monte Carlo (Drell Yan) samples, where events involving $Z \rightarrow \mu^- \mu^+$ decays have been selected. Although all the mentioned paths have been studied, efficiency plots will only be shown for the isolated path HLT_IsoMu22_v2 as an illustration.

2.1 Single muon paths

The efficiency of single muon paths has been measured using a tag and probe method. The tag and probe method exploits the Z-boson resonance to make sure the muons considered for the efficiency studies are good muons.
The study starts by selecting only those events that have fired the particular trigger path of interest and are made up of at least two reco muons (reconstructed by the Particle Flow offline reconstruction algorithm). The method consists in selecting one tag (reco) muon that satisfies a tight identification (ID) and a p_t (transverse momentum) threshold imposed by the minimal p_t of the path (e.g. the minimal p_t of the selected muons by the IsoMu22 path is 22). If the considered path has an isolation cut, the tag should also be chosen to satisfy it. At last, the tag muon should also have been reconstructed by the HLT reconstruction algorithm and triggered the L3-filter and isolation-filter if applicable. Hence, a matching condition is imposed between the reco muon and the set of HLT muons of the event that fired the last filter of the path. The matching condition consists in asking a separation $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ smaller than 0.1. This way, the risk that the selected tag is a fake muon is greatly reduced.
Afterwards, a probe is chosen. The probe is requiered to be a reco muons having a p_t above the threshold imposed by the path. In order to avoid fake muons, the invariant mass of the tag-probe pair is computed and requiered to lie close to the Z-boson mass. The probe muon should be requiered to have the opposite charge of the tag muon. Using this method, the muon pairs probably come from Z-bosons and the probe muon used to compute the efficiency are most likely true muons. The selected probes are subsequently studied to see if the HLT L3-filter has been fired as it should have. However, it should be noted that the definition of the probe muon can vary depending on the identification imposed on the probe. In an efficiency study with a certain identification, the denominator is chosen to be the set of probes with that ID while the numerator is the set of those probes firing the filter.

This method has been used on data samples and Monte Carlo samples. Efficiencies can be plotted against a kinematic variable of the event or of the probe muon. As an example, the efficiency is plotted in Figure 1 for the path IsoMu22 as a function of the transverse momentum of the probe

(HLT) muon, eta of the (HLT) muon and the number of primary vertices of the event (pile-up), where the probe muon had no identification requirements. The efficiency in function of eta shows that the efficiency is lower in the endcap region ($\eta > 1.479$). Dips in the efficiency are also observed near $|\eta| = 0.25$, which is due to the holes in that region of the CMS system. The efficiency seems to be not very sensitive to higher pile-up for Monte Carlo samples while the efficiency drops a little bit with pile-up for data. However, the statistics are not high enough to conclude the same at high pile-up (> 20). Besides those variables, the efficiency has been studied as a function of the angle phi of the probe muon which did not show a strong dependence, as expected from the cylindrical shape of the CMS detector. The number of jets (subject to a loose ID) and the hadronic activity were computed for each event and used as a kinematic variable. No strong dependence was observed there either.
From the shape of the efficiency as a function of the transverse momentum, it can be seen that the efficiency reaches a plateau value at high p_t. It can be noted that the turn on happens faster in MC-samples where the plateau is reached in 15 GeV while the turn on is spread over almost 35 GeV on the data efficiency plots. The plateau value can be computed by fitting the efficiency using the error-function. This yields one single efficiency value for high enough p_t for each efficiency measurement in function of the transverse momentum of the probe muon. The values for the different single paths can be found in Table 1.

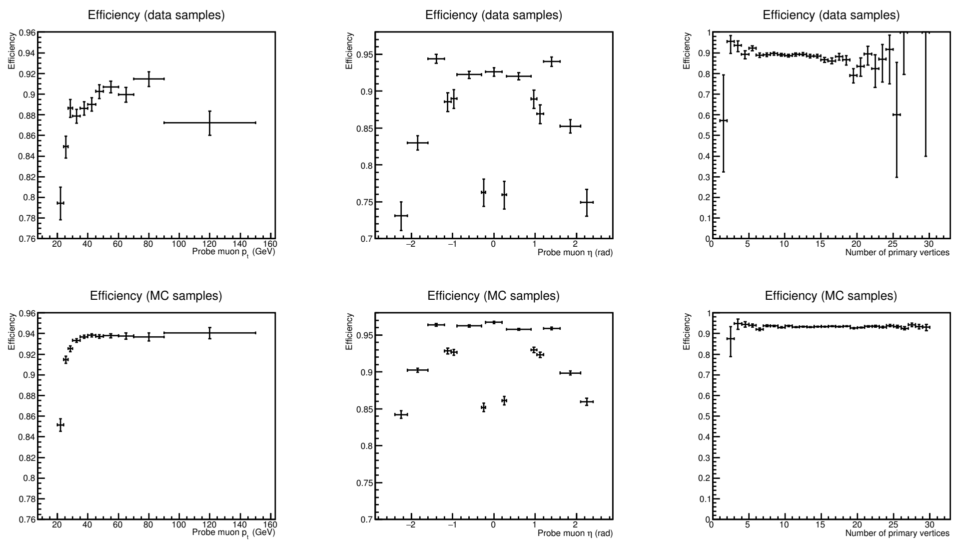

Figure 1: The efficiency of path HLT_IsoMu22_v2 for probe muons without identification for the current L3.

The same plots are showed in Figure 2 and 3 where the probes have been selected to satisfy a tight and soft identification respectively. In each of those three identifications and in Table 1, it can be observed that the efficiency using Monte Carlo samples is systematically higher than the efficiency computed on data samples. This can be a consequence of the fact that, for the resonance, the selection of events containing a Z-boson is more accurate in Monte Carlo samples than in data samples, such that the efficiency study contains more fakes in data samples. This leads to a lower efficiency in data samples.

A close inspection of the plateau value for the presented identification shows a slightly higher efficiency for loose muons than for muons without ID, though very comparable, and a net increase in efficiency of 1 to 2 percent for tight muons both for data and Monte Carlo. This behaviour is a quite general feature for other paths as well. This raise in efficiency can be understood by a similar reasoning as above, since identification requirements reduce the number of fake muons that are considered.

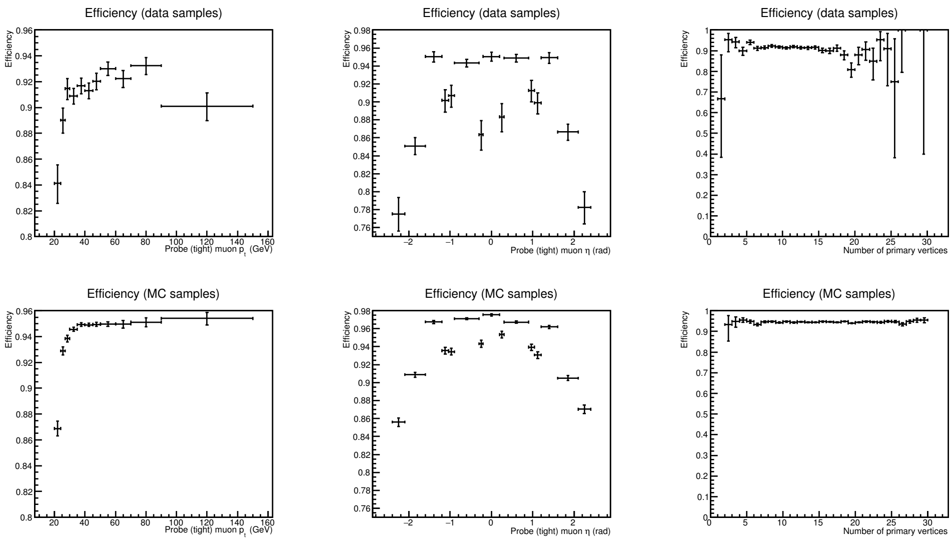

Figure 2: The efficiency of path HLT_IsoMu22_v2 for probe muons with a tight identification for the current L3.

2.2 Double muon paths

The efficiency of double muon paths is the product of the efficiency of the two legs that compose the path. Therefore, in order to know the efficiency of a dimuon path in some (high) transverse momentum region of the pair leading-trailing muon, it is enough to take the plateau value computed for both single muon paths. This method yields a value of 0.9073 ± 0.0009 and $0.9074 \pm$

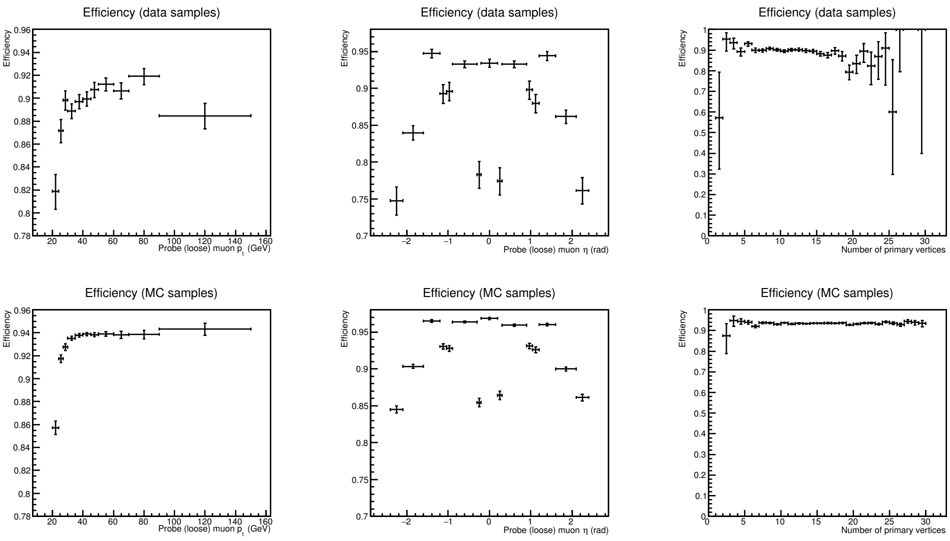

Figure 3: The efficiency of path HLT_IsoMu22_v2 for probe muons with a loose identification for the current L3.

Path	ϵ_{data}	ϵ_{mc}
HLT_Mu8_v*	/	0.9579 ± 0.0006
HLT_Mu8_TrkIsoVVL_v*	/	0.9579 ± 0.0006
HLT_Mu17_v*	0.9116 ± 0.0054	0.9473 ± 0.0007
HLT_Mu17_TrkIsoVVL_v*	0.9138 ± 0.0050	0.9472 ± 0.0007
HLT_Mu20_v*	0.8836 ± 0.0066	0.9405 ± 0.0007
HLT_IsoMu22_v*	0.8991 ± 0.0035	0.9372 ± 0.0007
HLT_Mu50_v*	0.9093 ± 0.0059	0.9479 ± 0.0047

Table 1: The L3-filter efficiency comparision per single muon path for data samples and Monte Carlo samples.

0.0009 for the paths HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL(_DZ)_v* and HLT_Mu17_Mu8_DZ_v* respectively, consistently equal to one another within the uncertainties. Since double muon paths have two legs with their own uncertainties, the total efficiency is lower than for single muon paths. Those efficiencies are computed using the Monte Carlo samples only, as there were not enough statistics in the data sample for the Mu8 paths. The double muons paths names comprising TkMu8, the efficiency of the L3-filter cannot be computed this way because there is no single path available of that form. The efficiency of that leg would have to be measured using another method.

2.2.1 Double muon paths with DZ cut

The efficiency study of the DZ-filter of the dimuon paths has been performed to complete the efficiency studies. DZ stands for the relative difference Δz of z-coordinate of the vertex position of the muons. For this matter, reco muon pairs were selected in each event that triggered the DZ-path. The pair is selected to have one muon that triggered the leading leg and one muon that triggered the trailing leg. If an isolation cut is imposed on the muons by the trigger path, the muons should also have triggered the isolation filter. Each of these muon pairs are tested against the triggering of the DZ-cut at HLT level and contribute to the denominator of the efficiency. The passing events form the numerator of the efficiency, where passing requires that both muons have fired the DZ-filter. This efficiency has been plotted against the Δz-value for each pair and the p_t of the trailing muon. The efficiency was almost 100% efficient for Δz-values up to the DZ-cut of 0.2 cm or the various paths, with the last path (HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v2) as an exception. A small dip in efficiency of the order of 5% was observed there around 0.8 cm (see Figure 4).

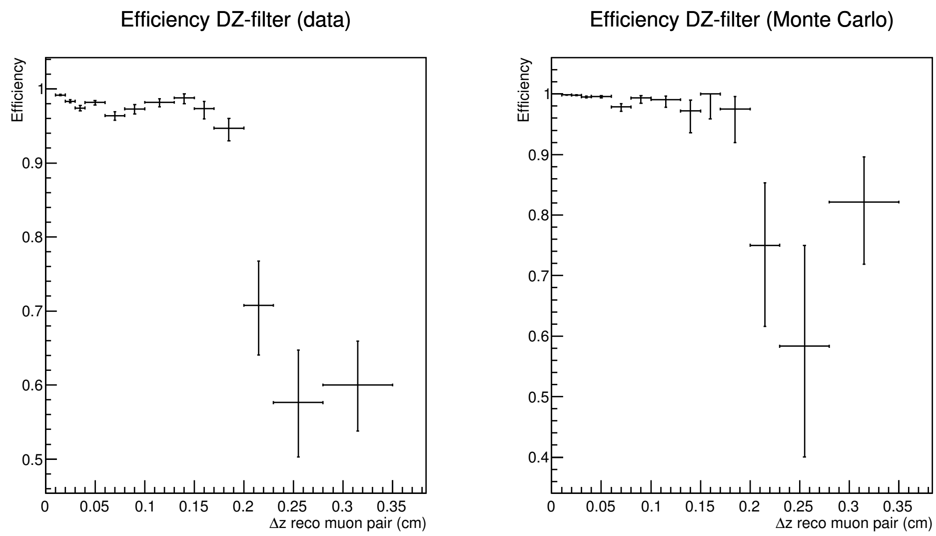

Figure 4: The efficiency of the DZ-filter for the path HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v2, with a dip around $\Delta z = 0.8$ cm in both data and Monte Carlo.

3 Fake rate

A second quantity that has been measured during this study is the fake rate of the L3-filter. In order to be able to compute this rate, we consider a QCD sample enriched with non-prompt muon. Hence for this study, a QCD Monte Carlo sample has been used. The definition of a fake muon used here is an HLT muon having a transverse momentum that actually lies below the threshold of the filter (when compared to generated information) or an HLT muon that does not find a generated object to be matched with, normalised by the total amount of (HLT) muons triggering the filter. When a double muon path is being monitored, the studied objects are HLT muon pairs consisting of one leading muon (that fired the highest p_t filter) and a trailing muon (that fired the lowest p_t filter) instead of single muons. In this case, from the moment one of the muons is a fake muon for the transverse momentum imposed by the threshold of the filter they are considered for, the pair is a fake pair.

3.1 Single muon paths

The fake rate of a path can be tested against the full reconstruction (offline) or the generated information in Monte Carlo samples. Depending on the situation, an HLT muon is tried to be matched with a reco or a generated muon.

The fake rate measurement starts by selecting, per event that the trigger accepted, all the HLT muons that fired the L3-filter of interest. The HLT muon fails the fake rate test if it matches a reco/generated muon, with the additional requirement that the reco/generated muon has a p_t higher than the filter threshold. The fake rate has been studied using the offline reconstruction, as a function of the kinematics of the HLT muon (transverse momentum, eta and phi) for loose and medium muons. For tight muons and muons without identification, additional fake rate plots have been made as a function of the number of primary vertices, the hadronic activity and the number of loose jets of the event. As the full reconstruction algorithm (offline) has some uncertainties, the computed fake rates may be erroneous. However, when using Monte Carlo samples, we can rely on the known true kinematics of the event. The method is very similar and only differs in the search for a generated muon to be matched with an HLT muon instead of a reco muon. As the generated muons do not have any identification, the fake rate has only been computed as a function of the six variables above. Those plots, with a distinction between the barrel and endcap region of the detector for the transverse momentum and the number of primary vertices, are given in Figure 5 and 6.

The fake rate is observed to be not very sensitive to the number of primary vertices, hadronic activity nor the number of jets. The fake rate as a function of the angle phi of the muon is approximately constant within the uncertainties. Even if the decrease in the endcap region in the eta-plot could be partially due to the larger uncertainty, it is reasonable to interpret that the reconstruction is less easy in that region such constraints to

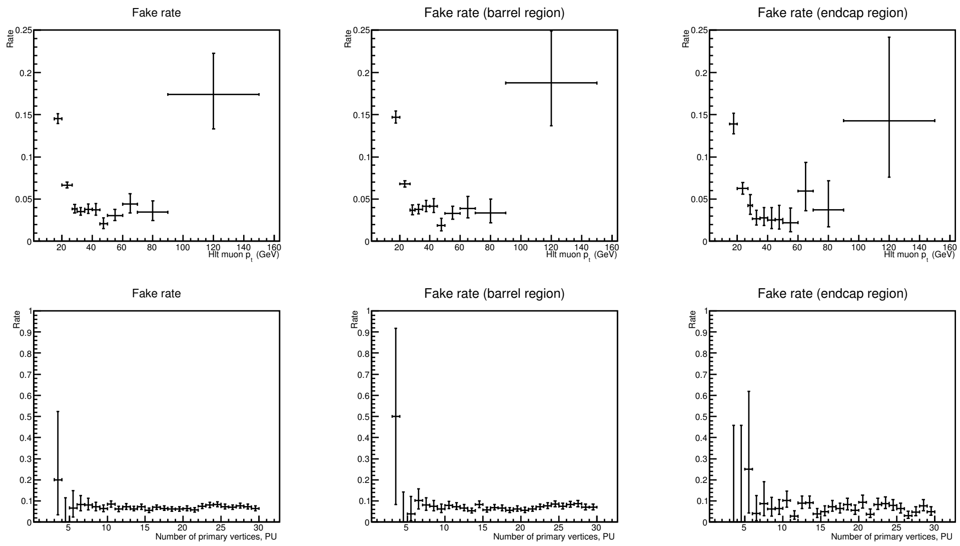

Figure 5: The fake rate of path HLT_Mu17_v2 for the current L3, using the generated information (MC samples).

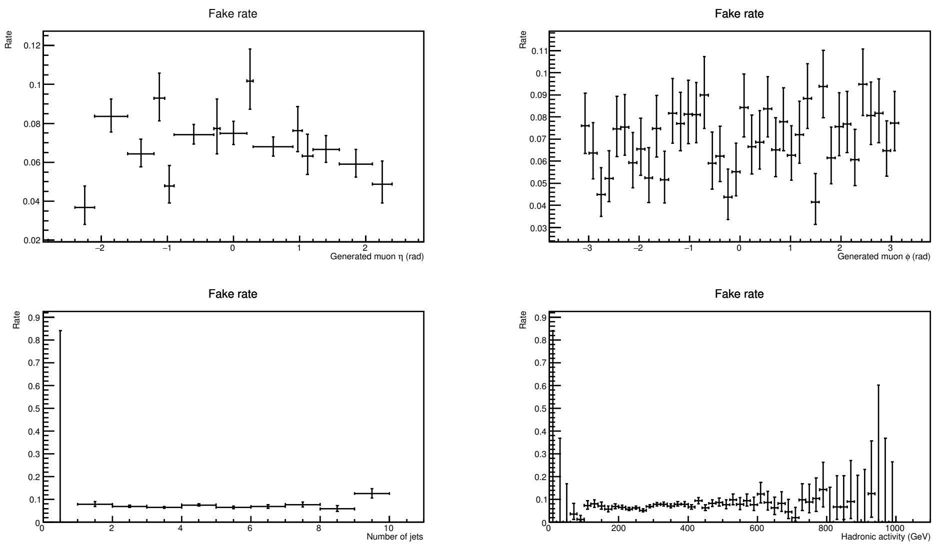

Figure 6: The fake rate of path HLT_Mu17_v2 for the current L3, using the generated information (MC sampels).

consider something a muon are higher. Hence less fake muons would be measured there. The fake rate as a function of transverse momentum of the muon shows that the fake rate at small p_t is higher than the average value because of the momentum difference that the HLT measures and the true

Path	Fake rate
HLT_Mu8_v*	0.1255 ± 0.0018
HLT_Mu8_TrkIsoVVL_v*	0.1373 ± 0.0041
HLT_Mu17_v*	0.0689 ± 0.0023
HLT_Mu17_TrkIsoVVL_v*	0.0694 ± 0.0046
HLT_Mu20_v*	0.0596 ± 0.0025
HLT_Mu50_v*	0.0830 ± 0.0083
HLT_Mu17_Mu8_DZ_v*	0.2323 ± 0.0141
HLT_Mu17_TkMu8_DZ_v*	0.4472 ± 0.0141

Table 2: The fake rate for various paths using a QCD sample and the Monte Carlo (generated) information.

momentum of the particle. The amount of muons that are triggered to have a higher p_t than the threshold but from which we know from the generated information that their true momentum is lower, is more important at lower transverse momentum.
From the very small dependence of the fake rate on the number of primary vertices, one fake rate value can be extracted from that plot. A zeroth order polynomial has been fitted through the fake rate for each path and the resulting value is presented in Table 2. The paths that were omitted in this table suffered from a too large uncertainty to contain significant information and should be computed using other samples. It can be seen that the Mu8 single muon paths have a higher fake rate, probably due to the lower threshold. Moreover, double muon paths have a higher fake rate than single muon paths. The

3.2 Double muon paths

The fake rate study for dimuon paths is similar to the procedure used in single muon paths with the difference that pairs of leading and trailing HLT muons must be considered. All those pairs are looped over and a failing pair is defined to have machting reco/generated muons with transverse momentum above the threshold of the considered filter. The other pairs either contain fake muons or the HLT did not recover their right transverse momentum. The fake rate has been plotted as a function of each of the transverse momenta, eta and phi, and the number of primary vertices, hadronic activity and number of jets of the event. The fake rate for two of the double muons paths can be found in Table 2 and is observed to be higher than for single muon paths. Those values are, similar to single muon paths, computed using the zeroth order polynomial approximation on the fake rate as a function of the number of primary vertices. However, due to larger uncertainties, this approximation is no longer obvious from the plots in double muon paths. Hence, paths where the fake rate value had a too large uncertainty are not presented in Table 2 and the values presented are illustrative of the general behaviour of a higher fake rate for double muon paths. The plots as a function of the different variables for the path HLT_Mu17_Mu8_DZ_v* showed a similar behaviour as for single muon paths, even though a study with more statistics would be necessary.

4 Conclusions

This project was a first approach to testing the performance of the current L3 both in efficiency and fake rate. In the future, the same efficiency and fake rate studies can be performed with the new L3 and be compared with the results presented here to test the performance of the upgrade. Alongside, the shortcomings of the current L3 should be studied further in order to identify the ameliorations to be examined in the new L3.

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References

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