B-physics and LVL1 di-muon trigger in the ATLAS experiment at the LHC

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for the ATLAS LVL1 di-muon trigger group
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Abstract. Many interesting physics processes in the ATLAS experiment at the LHC will be characterized by the presence of pairs of muons in the final state. For this reason, the ATLAS first level muon trigger has been designed to allow the selection of di-muon events. However, in order to increase the trigger acceptance of the muon spectrometer, several regions of overlap between the trigger chambers are foreseen in the detector layout. A muon crossing one of these regions may generate two separate triggers, thus producing a false di-muon trigger. The trigger system must therefore be aware of the geometrical overlaps, in order to resolve such fake double triggers. The overlap solving mechanism of the ATLAS LVL1 muon trigger has been intensively studied with the final detector layout. The overlap flags, needed by the trigger logic to properly handle fake double triggers due to geometrical overlap of the trigger detectors, have been set on a strip-by-strip basis. The chosen method consisted mainly in simulating the propagation of single-muons through the ATLAS spectrometer. The simulated response of the trigger system was then analyzed in order to locate the events for which two muon triggers were generated. Two studies have been performed to evaluate the impact of the overlap flags on the performance of the LVL1 muon trigger and its impact on B-physics: a single muon sample was used to check the proper removal of the fake double triggers and a di-muon B physics sample was used to check the amount of real double triggers that are lost due to the overlap removing mechanism. In addition the chosen B physics channel was the $\Lambda_c \rightarrow \Lambda \mu \mu$, a rare decay channel with a particular muon trigger interest because of the di-muon topology.

1. Introduction
The information provided by the trigger chambers (RPCs and TGCs) is used by a dedicated Muon Trigger System to decide whether muons above a given threshold were produced in a certain event. The sharpness of the $p_t$ cut applied by the trigger is mainly given by the information read out from the detectors in the bending projection.
The basic principle of the algorithm is to require a coincidence of hits in the different chamber layers within a road. The width of the road is related to the $p_T$ threshold to be applied. Space coincidences are required in both views, with a time gate close to the bunch-crossing period (25ns).

The level-1 (LVL1) muon trigger has to provide the multiplicity of muon candidates for each of the six $p_T$ thresholds to the Central Trigger Processor (CTP). This is important so that, for example, a low-$p_T$ di-muon trigger can be maintained at high luminosity. It is foreseen that the threshold on the di-muon trigger will be kept at about 6 GeV per muon for $L = 10^{34}$cm$^2$ s$^{-1}$, while the threshold for the single muon trigger will have to be about 20 GeV for an acceptable trigger rate. Given the steeply falling muon $p_T$ distribution, it is important that muons should only very rarely be double counted for example in areas of overlapping chambers, giving fake di-muon triggers from single-muon events. It is therefore required by design that at most 10% of the di-muon triggers shall be due to doubly counted single muons.

For the semi-muonic exclusive rare B physics decays, most of the authors suggest to measure variables describing the di-muon system namely: shapes of $s=\text{mass} (\mu \mu)^2$ and forward-backward asymmetry $A_{FB}$ as a function of $s$. The calculations show differences between SM and SUSY in some parts of phase space.

The shapes of these distributions are sensitive to trigger and offline selection cuts especially for small di-muon opening angle and for $p_T$ near threshold. The acceptance control is one of the main subjects in these studies.

2. The ATLAS LVL1 muon
A description of the Level 1 trigger and of the muon spectrometer is given in the ATLAS TDRs [1], [2]. Specialized trigger detectors are used: RPCs, Resistive Plate Chambers, in the barrel part ($|\eta| < 1.05$) of the muon spectrometer, and TGCs, Thin Gap wire Chambers, in the end-cap. RPCs are disposed in three stations, two of them (RPC1 and RPC2) cover the internal and external faces of the middle precision chamber and the third (RPC3) is located close to the external precision chamber, as shown in figure 1. Each station is composed of an RPC doublet with read-out in two orthogonal views, $\eta$ and $\phi$, referred as bending and non-bending projections respectively. The barrel is divided in two half-barrels, symmetric with respect to $\eta = 0$, and azimuthally segmented in octants; each octant is further subdivided in two parts, referred as Large and Small sectors. RPC chambers are classified, according to their location, into BML (Large sectors of RPC1 and RPC2), BMS (Small sectors of RPC1 and RPC2), BOL (Large sectors of RPC3) and BOS (Small sectors of RPC3). The trigger logic is based on coincidences between different stations, one of the inner two stations being chosen as pivot. The two innermost stations are used to trigger low-$p_T$ muons (mainly for b-physics studies), while the outermost is used to trigger high-$p_T$ muons.
3. LVL1 di-muon trigger

A trigger scheme with the possibility to discriminate events with two muons has been foreseen in the ATLAS experiment in order to increase the sensitivity of the detector to inclusive di-muon decays, which are the signature of many interesting processes, such as rare B decays.

In order to increase the trigger acceptance of the muon spectrometer, several regions of overlap between the trigger chambers are foreseen in the detector layout.

A muon crossing one of these regions may generate two separate triggers, thus producing a false di-muon trigger. The trigger system must therefore be aware of the geometrical overlaps, in order to reject such fake double triggers.

Three kinds of geometrical overlaps are present in the barrel trigger chambers:
- $\eta$ overlaps between two Covariance Matrices (CMs) belonging to the same pad.
- $\eta$ overlaps between two CMs belonging to adjacent pads in the same sector.
- $\phi$ overlaps between two adjacent sectors.

The removal of the fake double triggers by different parts of the LVL1 trigger logic proceeds as follows:
- $\eta$ overlaps between two CMs belonging to the same pad are solved by the pad itself, which indeed passes to the Sector Logic (SL) only one of the triggers detected by its matrices, i.e. the one with the highest threshold.
• $\eta$ overlaps between two CMs belonging to adjacent pads in the same logic sector are solved by the SL board the pads belong to. The SL collects the triggers from all its pads, and when it finds two triggers in two adjacent pads, both with the $\eta$ overlap flag asserted, it ignores one of them.

• $\phi$ overlaps between two adjacent sectors can be solved by the barrel trigger logic, and the Muon Interface to Central Trigger Processor (MuCTPI) is designed to deal with such overlaps. It checks the phi overlap flags of the muon candidate coming from the SL boards and properly removes the fake double triggers. At this stage the overlaps between the barrel and the endcap trigger systems will also be solved.

The trigger system needs to be aware of the strips that are located in geometrically overlapping regions, and hence are likely to produce fake double triggers. This information is stored in each CM configuration file that attaches to each of its triggers the corresponding value of the overlap flag, which is used by the Pad, SL and MuCTPI to properly remove double triggers.

In principle, the overlaps are categorized in the following 3 categories at the MuCTPI level:

• Barrel-Barrel (B-B) that are resolved by the MuCTPI and the RPC Sector Logics
• Barrel-Endcap (B-E) resolved by the MuCTPI
• Endcap-Endcap resolved by the TGC

A detailed description of the performance of the ATLAS LVL1 di-muon trigger and also its impact on B-physics will be presented in this paper.

4. LVL1 muon trigger simulation

The MuCTPI simulation is mimicking the hardware perfectly and it is capable of handling overlaps between the sectors. It needs overlap bits coming from the detector simulations to be set correctly and then the overlap handling is done in the simulation of the octant boards (MIOCT) [3].

From geometrical considerations, there is ~ 3% chance that a single muon gets counted twice in the barrel by the sector logics. This increases the LVL1 di-muon trigger rate significantly and implies as strong cuts as possible, to eliminate all the fake double counts. On the other hand too tight cuts on selecting fake double counts could get rid of true double muons. Therefore, to understand the fake di-muon rate in LVL1 is very important and needs detailed study.

The MuCTPI simulation – just as the hardware itself – uses look-up tables to detect fake double-counts. The look-up tables define for each MIOCT, under what circumstances a muon candidate received from the sector logics should be suppressed in the multiplicity count sent to the CTP. The rules specify which RoIs of close-by sectors can be overlapping, and if there is a muon candidate in both of these RoIs of the specified sectors - with their overlap bits set as defined in the look-up table -, how the simulation should add these candidates to the multiplicity sum. The look-up tables are in a format, which is easy to translate into configuration files that the hardware can load.

The B-B (Barrel-Barrel) overlap handling was done by the MuCTPI simulation based on preliminary lookup tables. These tables were created by mapping the overlapping RoIs between the 0-1 and 30-31 RPC sector pairs with 6 GeV positive and negative muons. The overlap treatment relies on the RPC sector logic simulation setting the $\phi$ overlap flags correctly.

The treatment of the B-E (Barrel-Endcap) overlap region was done with look up tables that define all the sector and RoI combinations in which the MIOCTs can resolve a possible overlap. So if a muon is detected in the $\geq$ 17 RoI range in a barrel sector, and another one is detected in the $\leq$ 31 RoI range of one of the overlapping endcap sectors, the candidate in the endcap sector is not regarded in the multiplicity count sent to the CTP. The simulation at this point assumes that neither the barrel, nor the endcap sets the overlap flag for a possible B-E overlap.
5. Motivation for the di-muon trigger study of the rare decays $\Lambda_b \rightarrow \Lambda \mu \mu$

5.1. Physics motivation for the rare decays $\Lambda_b \rightarrow \Lambda \mu \mu$ [4]

Flavor changing neutral current (FCNC) decays involving $b \rightarrow s$ or $b \rightarrow d$ transitions occur only from loop-level in the SM. Therefore, they come with small branching ratios and thus provide an excellent probe of indirect new physics effects.

Investigation of rare semi-leptonic decays induced by FCNCs (Flavour Changing Neutral Current) transition $b \rightarrow s$ provides an important test of the Standard Model (SM) [5]. Due to CLEO measurements of the radiative $b \rightarrow s\gamma$ decay [6], interest has been focused on the rare decays caused by $b \rightarrow s l^+ l^-$. This transition in B-mesons has been widely studied [7] and recently several papers on the B-baryon sector have been written, dealing with branching ratio (BR) calculations and finding physical quantities sensitive to new physics effects. Concerning $\Lambda^0_{b_s}$, $b \rightarrow s l^+ l^-$ transition is represented by baryonic rare decay $\Lambda^0_{b_s} \rightarrow \Lambda^0 l^+ l^-$. Rare decays are forbidden at the tree level and at the lowest order occur through 1-loop diagrams only.

The studies in [8] [9] showed the sensitivity of forward-backward asymmetry ($A_{FB}$) on the type of considered model (SM, SUSY). Figure 5a from [9] comparing SM and generic SUSY prediction for $A_{FB}$ is reproduced in the right figure 2. It clearly indicates possibility to distinguish between the two models using $s = q^2/10^4$ ($\Lambda^0_{b_s}$) dependence of $A_{FB}$. Except angular distribution, BR of $\Lambda^0_{b_s} \rightarrow \Lambda^0 l^+ l^-$ has been calculated (see left figure 2) in the two articles. The total BR is according to [9] approximately $2 \times 10^{-6}$.

![Figure 2](image)

**Figure 2.** Branching ratio (a) and forward-backward asymmetry (b) of rare $\Lambda^0_{b_s} \rightarrow \Lambda^0 l^+ l^-$ decay taken from article [9]. (a) The solid line corresponds to SM, dashed line to generic SUSY model. (b) The dashed and dash-dotted lines in the BR involve different description of non-factorisable contributions to $b \rightarrow s\gamma$ decay at $q^2 = 0$. $A_{FB}$ in low di-muon invariant mass region (outside $J/\psi$ resonances) shows significant sensitivity to new physics effects.
5.1.1. Sensitivity to new physics in $\Lambda^0_b \rightarrow \Lambda^0 \mu^+ \mu^-$ preliminary results [10]

Figure 3. The $A_{FB}$ as a function of $q^2/M_{b}^2$ for 1500 $\Lambda^0_b \rightarrow \Lambda^0 \mu^+ \mu^-$ events with 30 fb$^{-1}$. (a) ATLAS statistics errors corresponding to 1500 events – expected after 3 years, (b) ATLAS MC events generated with SM after trigger and reconstruction analysis, c) ATLAS MC events generated with MSSM $C_{7eff}>0$ after trigger and reconstruction analysis.

ATLAS can already after 3 years @10$^{33}$cm$^{-2}$s$^{-1}$ = 30 fb$^{-1}$ distinguish MSSM $C_{7eff}>0$ from SM in low values of di-muon mass as it is shown in figure 3.

5.2. Semi-muonic rare decays $\Lambda^0_b \rightarrow \Lambda \mu \mu$ sensitive to trigger [10]

A preliminary study for these rare decays has been done in order to investigate their sensitivity to trigger effects. The figure 4 shows a comparison of $q^2/M_{b}^2$ (a) and of $A_{FB}$ versus $q^2/M_{b}^2$ (b) before and after trigger. The shape of the $A_{FB}$ vs $q^2/M_{b}^2$ is less sensitive to trigger cuts than the $q^2/M_{b}^2$ distribution. The purpose of the study is to include a control of fake and real di-muon background sources that may have impact especially on small opening angles.
6. LVL1 muon trigger performance study without and with overlap flags [11]

Two studies have been performed to evaluate mainly the impact of the overlap flags - determined as described above - on the performance of the LVL1 muon trigger:

- single muons were used to check the proper removal of the fake double triggers
- B physics rare decay di-muons were used to check the amount of real double triggers that are lost due to the overlap removing mechanism.

![Figure 4](image-url) (a) $q^2/M_{b}^2$ and (b) $A_{FTR}$ versus $q^2/M_{b}^2$ (b) before and after trigger.

![Figure 5](image-url) Fake di-muon trigger barrel probability as a function of $p_{t}$ without overlap flags
6.1. Single muons

The purpose of the primary study without overlap flags was to find the probability of a single muon to give a fake LVL1 di-muon trigger. The study of the di-muon trigger has been done using the full LVL1 simulation software chain for RPC and TGC detectors in ATHENA with the ATLAS offline release 9.0.4 and analyzing the MuCTPI output. The fake di-muon rate in all the single muon studies means the number of events with 2 or more muon candidates received by the MuCTPI from the sector logics, over the number of events with at least one muon candidate.

The fake di-muon trigger probability is found to be around $(2.5\pm0.2)\%$ (figure 5) in the barrel for muons of $p_T = 6$ GeV without any trigger logic recovery i.e. without any overlap flags used at a barrel efficiency of $80\%$, (figure 6).

The fake di-muon trigger rate is found around $(550\pm44)$ Hz assuming a 22 kHz single muon rate and the rate expected from the real di-muons is around 150 Hz at the luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$ for a di-muon $\mu^+\mu^-$ event.

![Figure 6. Barrel efficiency as a function of muon $p_T$](image)
The di-muon trigger probability without the overlap flags as a function of $p_T$ for the whole pseudorapidity $\eta$ range is found between $(2.5\pm0.2)\%$, (figure 7).

The di-muon trigger probability was studied without the overlap flags for the endcap region $\eta$: 1.2-2.4 and it was found for 6 GeV $\mu^+$ around $(2.2\pm0.2)\%$.

The di-muon trigger probability for the overlap region between barrel and endcap $\eta$: 0-8-1.2 was studied as a function of $p_T$ and found for $\mu^+$ between $(3.2\pm4.4\pm0.8)\%$, (figure 8).
Furthermore, the di-muon trigger probability without overlap flags was studied for the barrel-endcap overlap region at 0.8 < $\eta$ < 1.2 with ATLAS release 10.0.1 (+ tag Trigger/TrigT1/TrigT1TGC-00-00-50). The results are shown in Table 1. A kind of “charge-asymmetry” effect was observed. Negative muons in this side of the detector bend in a way, that they are much more probable to be detected by both a barrel and an endcap sector, than the positive muons, which bend the other way. This gives in overall higher fake di-muon rates in the 0.8 < $\eta$ < 1.2 region for negative muons. Also it seems that the $p_T = 6$ GeV muons are more sensitive than the $p_T = 20$ GeV muons to this overlap area.

Table 1. LVL1 di-muon trigger rates without overlap flags for B-E (+0.8 < $\eta$ < +1.2), layout Q, 10 K, single muons with ATLAS release 10.0.1 + tag TrigT1TGC-00-00-50

| $+0.8<\eta <+1.2$ | $p_T = 6$ GeV | $p_T = 20$ GeV |
|------------------|-------------|-------------|
| di-muons (\%) $\mu^+$ (MuCTPI) | 2.8±0.2 | 3.3±0.7 |
| di-muons (\%) $\mu^-$ (MuCTPI) | 6.6±0.3 | 5.2±0.8 |

Table 2. LVL1 di-muon trigger rates with overlap flags, layout Q, 10 K, single muons $p_T = 6$ GeV with ATLAS release 10.0.1+ tag TrigT1TGC-00-00-50 + RPCcabling-00-03-32+ i) Muctpi-00-00-27, ii) Muctpi-00-01-00

| $\eta$ region | di-muons (\%) (MuCTPI) | di-muon trigger rate (Hz) |
|----------------|------------------------|---------------------------|
| Barrel ($\eta \leq 1$) (i) | 0.76±0.1 | 167±22 |
| Barrel-Endcap (ii) (+0.8<\eta <+1.2) | $\mu^+$ 2.4±0.2 | 528-616±44 |
| | $\mu^-$ 2.8±0.2 | |
Then the di-muon trigger probability was studied using the ATLAS release 10.0.1 (+ the tag Trigger/TrigT1/TrigT1TGC-00-00-50) after the inclusion of the $\eta$ overlap flags from the sector barrel logic (using the tag MuonSpectrometer/MuonCablings/RPCcabling/RPCcabling-00-03-32).

The di-muon trigger probability after the barrel $\eta$ overlap flags treatment in the area of $\eta$ 0.8-1.2 where the most of the $\eta$ overlaps occur (around $\eta$=1) is found to be less than 1% (0.99±0.1)% for the single muons of $p_T = 6$ GeV i.e. a di-muon rate of about (230±22) Hz. The di-muon rate for the barrel single muons of $p_T = 6$ GeV was found (1.97±0.5)%, i.e. (433±110) Hz.

The di-muon trigger probability after the correct inclusion of the phi overlap flags using the MuCTPI code, with the tag Trigger/TrigT1/TrigT1Muctpi/TiggerT1Muctpi-00-00-27 was found for the barrel and for single muons of $p_T = 6$ GeV around (0.76±0.1)% i.e. (167±22) Hz, (see Table 2).

The di-muon trigger probability after the barrel-endcap overlap treatment for the region 0.8<$\eta<$1.2 using the new MuCTPI code, with the tag Trigger/TrigT1/TrigT1Muctpi/TiggerT1Muctpi-00-01-00 was found for muons $\mu^+$ with $p_T= 6$ GeV (2.8±0.2)% and for $\mu^-$ (2.4±0.2)% i.e. (616±44) Hz and (528±44) Hz, (see Table 2).

6.2. B-physics rare decays and LVL1 di-muon trigger

There is a strong B-physics interest in order to find a flexible strategy for B-physics studies from initial running to final luminosity. It is needed to study the impact of the di-muon trigger strategy on the discovery potential of B-physics channels.

The B-trigger at the luminosity of $L > \sim 2x10^{33}$ cm$^{-2}$s$^{-1}$ will be based on the LVL1 di-muon trigger that is 2 muons with $p_T > \sim 6$ GeV.

The LVL1 rate is dominated by the real di-muons, $b\bar{b}$ and $c\bar{c}$ events with two muons and also events with one muon doubly counted due to the overlap of the trigger chambers (i.e. fake di-muon).

B-physics rare decays $\Lambda_b \rightarrow \Lambda\mu\mu$ were studied. The rare decay di-muons are close with each other in space so a double trigger indeed could be lost in the case that both the muons go through the same overlap region when the overlap flags are used.

The rare decays $\Lambda_b \rightarrow \Lambda\mu\mu$ B-physics events (about 100 K) were simulated with Geant4 with the ATLAS release 9.0.4 and with Rome-initial layout (“layout Q”) in the full $\eta$ region.

The events $\Lambda_b \rightarrow \Lambda\mu\mu$, about 50 K, were digitized first without any overlap flags either $\eta$ or $\phi$, with ATLAS release 10.0.1 (+ tag Trigger/TrigT1/TrigT1TGC-00-00-50) and analyzed with the CBNT.

After a comparison with Monte Carlo truth, for rare decay muons with $p_T > 5$ GeV and in $|\eta| < 2.7$ the single muon trigger efficiency (number of triggered muons over the number of simulated muons) was found to be around (76.0±0.4)\% and the trigger muon >1 efficiency (the number of events with >1 triggered muons over the number of events with > 1 simulated muons) was found to be around (58.4±0.3) \%, (see Table A1).

The Sigma of $\Delta\eta$ and $\Delta\phi$ of the di-muons from $\Lambda_b$ events for generated muons is around 0.26 and 0.28 respectively. For triggered muons ($\sim 2$) (di-muon trigger) it was found to be 0.25 and 0.26 respectively and in the case that only one triggered muon was found ($\sim 2$) (single-muon trigger) it is 0.27 and 0.29 respectively.

The mass distribution is quite similar for the triggered, Fig. 9(a), and non-triggered muons, figure 9(b), but non-triggered di-muons slightly prefer lower di-muon invariant masses compared to triggered di-muons. No obvious correlation has been found between $\Delta\eta$ and $\Delta\phi$ for di-muon trigger, figure 10(a), and single-muon trigger events, figure 10(b).
Figure 9. di-muon mass distribution for (a) the di-muon trigger and (b) single-muon trigger
Figure 10. $\Delta \eta$ versus $\Delta \phi$ for (a) di-muon trigger ($\geq 2$) and (b) single-muon trigger

There is a tendency for the triggered muons ($\geq 2$) figure 11(a) to have a slightly larger opening angle in comparison with the non-triggered case, figure 11(b).
Figure 11. di-muon muon opening angle for (a) di-muon trigger and (b) single-muon trigger case.

The trigger efficiency as a function of $\Delta \eta$, figure 12(a) and $\Delta \phi$, figure 12(b) is found to be around $(56.1 \pm 0.4)\%$.

The trigger efficiency as a function of opening angle is found to be $(56.1 \pm 0.4)\%$ with possibly a slight tendency of dropping for small opening angles of $\leq 0.05$, figure 13, (see Table A4).
Figure 12. Efficiency as a function of (a) $|\Delta \eta|$ and (b) $|\Delta \phi|$ for di-muon trigger

Figure 13. Efficiency versus di-muon opening angle
The efficiency versus the di-muon opening angle in the barrel is found to be around \((58\pm0.7)\)% and is shown in figure 14 (a). For the endcap region it is found to be around \((55.5\pm0.6)\)% and is shown in figure 14 (b), (see Table A4).

The case of two muons that are placed very close in space \(|\Delta\eta|<0.1\) and \(|\Delta\phi|<0.1\) which makes not more than 10% of the total number of generated muons was also studied. The efficiency versus the di-muon opening angle in the barrel is found to be around \((49.2\pm1.6)\)% (see also Table A4).

Then the special case of rare decay di-muons with \(p_T \geq 10\) GeV was studied, (see Table A5).

The higher \(p_T\) muons have smaller opening angle, so the chance for one of them not to be triggered may be larger. In addition the magnetic field has weaker effect on the higher \(p_T\) muons than in the case of the low \(p_T\) muons, that means that muons with a very small opening angle at the vertex keep their...
initial direction and are detected closer to each other in the detector, hence the higher probability for one of them not to be picked up by the LVL1 electronics.

It was observed that there is a stronger tendency for the non-triggered muons (<2), figure 15(a), to have smaller opening angle than the triggered muons (≥2), figure 15(b). The efficiency as a function of opening angle of around (63.1 ± 0.9)% had a stronger tendency to drop for the very small opening angles (< 0.05), figure 16, (see Table A5). The Sigma of Δη and Δφ is smaller for high p_T than for the low p_T muons.

Figure 15. di-muon muon opening angle for (a) single-muon trigger and (b) di-muon trigger of p_T ≥ 10 GeV.

Figure 16. Efficiency versus di-muon opening angle for muons of p_T ≥ 10 GeV.
Figure 17. Efficiency versus di-muon opening angle for (a) barrel $|\eta|<1.0$ and for (b) endcap $|\eta|>1.0$
for muons with $p_T \geq 10$ GeV.

In figure 17 (a) and (b) the efficiency as a function of opening angle for barrel (58.7±1.3) % and for
endcap (68±1.3) % is shown respectively, for all the muons with $p_T \geq 10$ GeV, (see Table A5).

The efficiency as a function of opening angle for barrel was found (45.9±2.3)% and for endcap
(66.1±2.9)% for all the muons with $p_T \geq 10$ GeV, when they fulfill $|\Delta \phi|<0.1$ and $|\Delta \eta| <0.1$, (see Table
A5).

It seems that there is no problem with the total trigger efficiency for the low $p_T$ rare decay di-muons
because of their topology, i.e. very close in space. Only the barrel muons that they are in $|\Delta \phi|<0.1$ and
$|\Delta \eta| <0.1$ (i.e. about 7% of the total muons), could give lower trigger efficiency of about 10% in
comparison with the barrel efficiency.

Then, the rare decays $\Lambda_c \rightarrow \Lambda \mu \mu$ were studied in order to check the amount of real double
triggers that are lost due to the sector logic overlap removing mechanism with the $\eta$ overlap flags.
The events (about 50 K) were digitized with the tag Trigger/TigT1/TrigT1Muctpi/Muctpi-00-00-27

with the ATLAS release 10.0.1 (+ tag MuonSpectrometer/MuonCablings/RPCcabling/RPCcabling-00-03-32, Trigger/TrigT1/TrigT1TGC-00-00-50) and analyzed with the CBNT.

After a comparison with Monte Carlo truth, the single muon efficiency (number of triggered muons over the number of simulated muons) from rare decay muons with $p_T > 5$ GeV and $|\eta| < 2.7$ was found around $(78.1\pm0.4\%)$, (see Table A2). The $(\geq 2)$ muon trigger efficiency (the number of events with $\geq 2$ triggered muons over the number of events with $\geq 2$ simulated muons) was found $(59.0\pm0.4\%)$, i.e. about 2.3% higher than without the $\eta$ overlap flags, (see Table A2).

The trigger efficiency as a function of $\Delta\eta$ is found around $(59.0\pm0.4\%)$.

The trigger efficiency as a function of opening angle is found around $(59.0\pm0.5\%)$ with possibly a slight tendency of dropping for small opening angles $<0.05$, (see Table A6).

The efficiency as a function of opening angle is found around $(59.0\pm0.4\%)$.

The trigger efficiency as a function of opening angle is found around $(59.0\pm0.5\%)$ with possibly a slight tendency of dropping for small opening angles $<0.05$, (see Table A6).

The case of the two muons that are placed very close in space, $|\eta| < 0.1$ and $|\phi| < 0.1$, was also studied for this setup, (see Table A6). The efficiency versus opening angle in the barrel is found to be around $(52.4\pm1.7\%)$. For the endcap region is found to be around $(58.5\pm1.7\%)$.

As in the case of no $\eta$ overlap flags, the special case of rare decay di-muons of $p_T \geq 10$ GeV was studied, (see Table A7).

It was observed again that there is a stronger tendency for the non-triggered muons ($<2$), to have smaller opening angle than the triggered muons ($\geq 2$). The efficiency as a function of the opening angle is around $(65.9\pm0.9\%)$ and has a stronger tendency than the di-muons with $p_T > 5$ GeV to drop for the very small opening angles ($<0.05$), (see Table A7).

The efficiency as a function of opening angle for the barrel is found to be around $(61.5\pm1.3\%)$ and for the endcap region around $(70.3\pm1.4\%)$, (see Table A6).

In the case that the two muons are very close together in space, $|\eta| < 0.1$ and $|\phi| < 0.1$, the efficiency as a function of the opening angle for the barrel is found to be about $(47.8\pm2.4\%)$ and for the endcap region to be around $(68.2\pm2.95\%)$, (see Table A7).

It was observed that for the higher $p_T$ muons with $p_T \geq 10$ GeV, the barrel efficiency for the case when muons are within $|\Delta\eta| < 0.1$ and $|\Delta\phi| < 0.1$, found $(47.8\pm2.4\%)$ i.e. a bit lower than for $p_T > 5$ GeV $(52.4\pm1.7\%)$.

After re-running the MuCTPI simulation with the latest version of the MuCTPI simulation code Trigger/TrigT1/TrigT1Muctpi/TrigT1Muctpi-00-01-01 on about 50 K $\Lambda_0 \rightarrow \Lambda \mu \mu$ events using the lookup tables for B-B (Barrel-Barrel) ($\eta$ and $\phi$) and B-E (Barrel-Endcap) overlaps, the results were analyzed with the CBNT.

Similar results were found after resolving the B-B and B-E overlaps as in the case of using no MuCTPI overlap treatment. The single muon trigger efficiency was found to be $(78.3\pm0.4\%)$, (see Table A3). The trigger efficiency for muons $\geq 2$ (number of events with $\geq 2$ muon trigger candidates and a muon trigger multiplicity sent to the CTP $\geq 2$, over the number of events with $\geq 2$ generated muons) was found $(61.0\pm0.4\%)$, (see Table A3). In more detail, the di-muon trigger efficiency as a function of the opening angle of the muons was found to be $(57.8\pm0.6\%)$, for the barrel it was $(61.4\pm0.7\%)$ and for the endcap it was $(57.4\pm0.6\%)$ in average, (see Table A8). Also for the case of muons with $|\Delta\eta|$ and $|\Delta\phi| < 0.1$, the di-muon efficiency was found in average $(51.7\pm1.6\%)$ and for the endcap in average $(58.3\pm1.6\%)$, (see Table A8). For the muons with $p_T \geq 10$ GeV, the di-muon trigger efficiency was found to be $(65.8\pm0.9\%)$, for the barrel $(61.0\pm1.3\%)$ and for the endcap $(70.5\pm1.4\%)$ in average, (see Table A9). Also for the case of muons with $|\Delta\eta|$ and $|\Delta\phi| < 0.1$, the barrel di-muon efficiency was found to be $(47.1\pm2.4\%)$ and for the endcap $(68.1\pm2.9%)$ in average, (see Table A9).

The amount of overlaps resolved by the MuCTPI from these physics events was studied. In total about $(0.6\pm0.04\%)$ were identified as events with fake muon i.e. the muon trigger multiplicity from the MuCTPI output was found in these events less than the number of the muon trigger candidates. However, with less than two muons multiplicity were found only $(0.16\pm0.02\%)$ of the total events, i.e.
these events could not be triggered. For the barrel were found (1.4±0.09)% and (0.4±0.04)% respectively and for the barrel muons in |Δη| and |Δφ| < 0.1 were found (1.4±0.2)% and (0.6±0.2)% respectively. The case of muons with p_T≥10 GeV was also studied. In total about (0.6±0.07)% were identified as events with a fake muon but with less than two muons multiplicity were found only (0.14±0.03)% of the total events. For the barrel were found (1.3±0.2)% and (0.3±0.07)% respectively and for the barrel muons in |Δη| and |Δφ| < 0.1 were found (1.8±0.4)% and (0.8±0.2)% respectively. That means that the overlap handling would affect less than about 0.2% of the studied B physics events and less than about 1% of the events that would happen to have both barrel muons in |Δη| and |Δφ| < 0.1.

In short, muon candidates larger than one was found in (61.2±0.4)% of the events, overlaps were resolved by the MuCTPI in (1.1±0.06)% of these cases, for the barrel were (2.3±0.1)% and for the barrel-endcap were (0.6±0.1)%. Finally, after the MuCTPI B-B, B-E overlaps treatment for the events with both muon sector logic candidate larger than one and MuCTPI muon multiplicity larger than one the muon trigger efficiency was found (61.0±0.4)%.

7. Conclusions

The overlap solving mechanism of the ATLAS LVL1 muon trigger has been intensively tested. The overlap flags, needed by the trigger logic to properly handle fake double triggers due to the geometrical overlaps of the trigger detectors have been set and used by the MuCTPI. The di-muon trigger rate with the overlap flags set was found to be around (0.8±0.1)% for p_T = 6 GeV muons, i.e. about (167±22) Hz.

A B physics rare decay sample Λ_b → Λ(μμ) has been used to evaluate the fraction of real double triggers which are lost due to the overlap solving logic. The study showed that there is no problem in loosing one of the two muons. Actually, it was found that the trigger efficiency with the η and φ overlap flags that resolve the B-B and B-E overlaps is about the same as without any MuCTPI overlap treatment.

Furthermore, the study showed that there is no obvious problem of loosing one of the two triggered muons after the resolving by the MuCTPI of the B-B overlaps (with η and φ overlap flags) and the B-E overlaps in the MuCTPI in comparison to the case without the use of the φ overlap flags at least with the present statistics of about 50 K events. However, due to the limited statistics they might be wrongly considered fake in the less of 0.5% of the events giving two muon triggers. For the about 10% of the muons that are very close (|Δφ|<0.1 and |Δη|<0.1) in the barrel, this loss due to overlap flags it could be not more than 1.6%.

Also, it seems that there is no problem with the total trigger efficiency for the low p_T rare decay di-muons because of their topology, very close in space. Only for the barrel muons that have an opening angle of |Δφ|<0.1 and |Δη|<0.1 (about 10% of the total muons) does the trigger efficiency becomes lower by about 10%, and more so for the higher p_T muons case (p_T ≥10 GeV). The overall loss is almost unaffected nevertheless because of the small fraction of events with such small opening angles. The negative effects connected with the small muon opening angle are getting worse with a higher p_T cut (p_T ≥10 GeV), because such di-muons have smaller di-muon production angle and the effect of the magnetic field is weaker than on low p_T muons.

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Appendix A: Tables

**Table A1.** Trigger efficiency without overlap flags ($p_T(\mu)>5$ GeV), 50 K $\Lambda_b$ events, layout Q. (ATLAS release 10.0.1 + Muctpi-00-00-27 + TrigT1TGC-00-00-50)

| Single muon efficiency (%) | 76.0±0.4 |
|----------------------------|----------|
| $\geq$2-muon efficiency (%) | 58.4±0.3 |

**Table A2.** Trigger efficiency with $\eta$ overlap flags ($p_T(\mu)>5$ GeV), 50 K $\Lambda_b$ events, layout Q. (ATLAS release 10.0.1 + RPCcabling-00-03-32 + Muctpi-00-00-27 + TrigT1TGC-00-00-50)

| Single muon efficiency (%) | 78.1±0.4 |
|----------------------------|----------|
| $\geq$2-muon efficiency (%) | 59.0±0.4 |

**Table A3.** Trigger efficiency with overlap flags ($p_T(\mu)>5$ GeV), 50 K $\Lambda_b$ events, layout Q. (ATLAS release 10.0.1 + RPCcabling-00-03-32 + Muctpi-00-00-01 + TrigT1TGC-00-00-50)

| Single muon efficiency (%) | 78.3±0.4 |
|----------------------------|----------|
| $\geq$2-muon efficiency (%) | 61.0±0.4 |
Table A4. Di-muon trigger efficiency versus opening angle without overlap flags ($p_T(\mu)>5$ GeV), 50 K $\Lambda_b$ events, layout Q. (ATLAS release 10.0.1 + Muctpi-00-00-27 + TrigT1TGC-00-00-50)

| Efficiency (%) | 56.1±0.4 |
|----------------|----------|
| Barrel efficiency (%) | 58.0±0.7 |
| Endcap efficiency (%) | 55.4±0.6 |
| Barrel efficiency (%) for close pairs ($|\Delta\eta|<0.1 \& |\Delta\phi|<0.1$) | 49.2±1.6 |
| Endcap efficiency (%) for close pairs ($|\Delta\eta|<0.1 \& |\Delta\phi|<0.1$) | 56.5±1.6 |

Table A5. Di-muon trigger efficiency versus opening angle without overlap flags ($p_T(\mu)>10$ GeV), 50 K $\Lambda_b$ events, layout Q. (ATLAS release 10.0.1 + Muctpi-00-00-27 + TrigT1TGC-00-00-50)

| Efficiency (%) | 63.1±0.9 |
|----------------|----------|
| Barrel efficiency (%) | 58.7±1.3 |
| Endcap efficiency (%) | 68.0±1.3 |
| Barrel efficiency (%) for close pairs ($|\Delta\eta|<0.1 \& |\Delta\phi|<0.1$) | 45.9±2.3 |
| Endcap efficiency (%) for close pairs ($|\Delta\eta|<0.1 \& |\Delta\phi|<0.1$) | 66.1±2.9 |

Table A6. Di-muon trigger efficiency versus opening angle with $\eta$ overlap flags ($p_T(\mu)>5$ GeV), 50 K $\Lambda_b$ events, layout Q. (ATLAS release 10.0.1 + RPCcabling-00-03-32 + Muctpi-00-00-27 + TrigT1TGC-00-00-50)

| Efficiency (%) | 59.05±0.5 |
|----------------|----------|
| Barrel efficiency (%) | 61.8±0.7 |
| Endcap efficiency (%) | 57.3±0.6 |
| Barrel efficiency (%) for close pairs ($|\Delta\eta|<0.1 \& |\Delta\phi|<0.1$) | 52.4±1.7 |
| Endcap efficiency (%) for close pairs ($|\Delta\eta|<0.1 \& |\Delta\phi|<0.1$) | 58.5±1.7 |

Table A7. Di-muon trigger efficiency versus opening angle with $\eta$ overlap flags ($p_T(\mu)>10$ GeV), 50 K $\Lambda_b$ events, layout Q. (ATLAS release 10.0.1 + RPCcabling-00-03-32 + Muctpi-00-00-27 + TrigT1TGC-00-00-50)

| Efficiency (%) | 65.9±0.9 |
|----------------|----------|
| Barrel efficiency (%) | 61.5±1.3 |
| Endcap efficiency (%) | 70.3±1.4 |
| Barrel efficiency (%) for close pairs ($|\Delta\eta|<0.1 \& |\Delta\phi|<0.1$) | 47.8±2.4 |
| Endcap efficiency (%) for close pairs ($|\Delta\eta|<0.1 \& |\Delta\phi|<0.1$) | 68.2±2.95 |
Table A8. Di-muon trigger efficiency versus opening angle with overlap flags ($p_T(\mu)>5$ GeV), 50 K $\Lambda_b$ events, layout Q, (ATLAS release 10.0.1 + RPCcabling-00-03-32 + Muctpi-00-00-01 + TrigT1TGC-00-00-50)

| Efficiency (%) | 58.95±0.4 |
|----------------|-----------|
| Barrel efficiency (%) | 61.4±0.7 |
| Endcap efficiency (%) | 57.4±0.6 |
| Barrel efficiency (%) for close pairs ($|\Delta \eta|<0.1 \& |\Delta \phi|<0.1$) | 51.7±1.6 |
| Endcap efficiency (%) for close pairs ($|\Delta \eta|<0.1 \& |\Delta \phi|<0.1$) | 58.3±1.6 |

Table A9. Di-muon trigger efficiency versus opening angle with overlap flags ($p_T(\mu)\geq10$ GeV), (ATLAS release 10.0.1 + RPCcabling-00-03-32 + Muctpi-00-00-01 + TrigT1TGC-00-00-50)

| Efficiency (%) | 65.8±0.9 |
|----------------|-----------|
| Barrel efficiency (%) | 61.0±1.3 |
| Endcap efficiency (%) | 70.5±1.3 |
| Barrel efficiency (%) for close pairs ($|\Delta \eta|<0.1 \& |\Delta \phi|<0.1$) | 47.1±2.3 |
| Endcap efficiency for close pairs ($|\Delta \eta|<0.1 \& |\Delta \phi|<0.1$) | 68.1±2.9 |
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