Evolution of trigger efficiency through Run 3

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Abstract

The trigger system of the ATLAS experiment is crucial for the success of the experiment, since it selects in real time the interesting collisions at the rate of a few Hz out of the 40 MHz collision rate. The reference to compute the performance of many triggers is given by the Minimum Bias Trigger Scintillators (MBTS), a detector built on purpose to give a very fast signal any time it is crossed by even a single charged particle, with an efficiency close to 100%. Due to radiation damage and saturation effects, large deviations from this ideal behaviours have been recently observed, and it is important to extend these studies to the whole of Run3 data taking, and to study the relation with other triggers. This project is very important for the ATLAS trigger system, and for all analyses willing to use MBTS and jet triggers.

1 Introduction

Minimum Bias Trigger Scintillators (MBTS) are mainly used for low-luminosity (or soft-interaction) runs, van der Meer scans (accurate way to determine luminosities) and heavy-ion runs [1]. Whereas low-luminosity runs and van der Meer scans are mainly recorded for the calibration of the Large Hadron Collider (LHC), heavy-ion runs are primarily recorded to study the strong force and the created quark-gluon plasma. When heavy ions collide at high speeds, a quark-gluon plasma is formed due to the high energies, which immediately turns the quarks and gluons into other particles (hadronization) which can be studied. By looking at how jets interact (jet quenching) when passing through this quark-gluon plasma, properties of the plasma can be investigated [2]. Understanding of this state is essential for understanding the development of the early universe and the behavior of the strong force. The

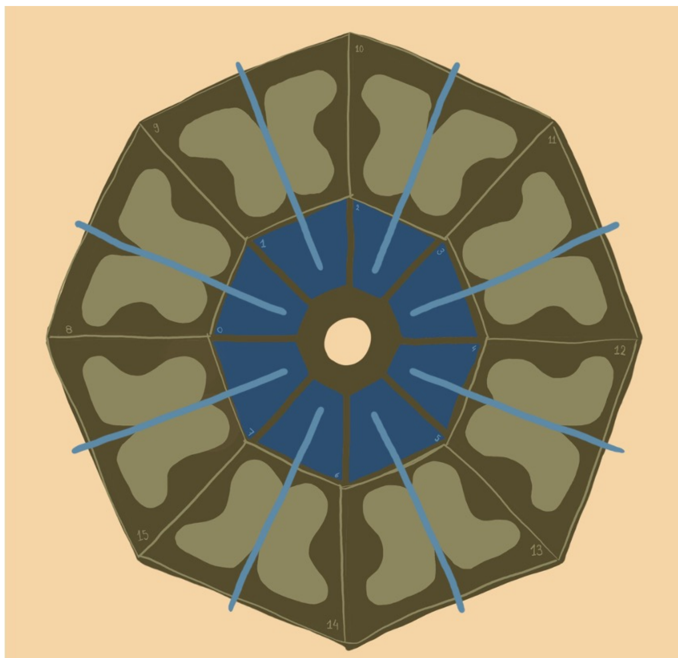

Figure 1: Graphical depiction of MBTS, with the inner scintillators in blue and the outer scintillators in dark green. This depiction is one of sides A/C. Courtesy to Isabella Baiardini.

detectors are shaped like a disk with 8 inner and outer scintillators as seen in Figure 1 on each side of the beamline, divided into sides A and C. As a beam of protons collides at ATLAS, charged particles are emitted and move through MBTS, they first enter the scintillators. Scintillators transfer the signal by emitting light when charged particles interact with the material. This light is then collected by photomultiplier tubes (PMTs) where its transferred into electrical signal. Depending on the increase of the intensity of the signal, a trigger for data collection is fired. Afterwards, more precisely described in [3], the trigger signal is propogated to the Central Trigger Processor (CTP), where it is accepted if it arrived in a predefined time window with respect to the expected collision time. If a signal is accepted, a L1 trigger is fired.

1.1 Triggers

An essential part in determining what data are useful lies in the trigger system. A trigger is defined as a certain selection criterion at which data are saved. Depending on the goal of the run, different triggers are selected to be enabled during the run, as it's not possible to use all triggers due to electronic restrictions due to the short time window. Important triggers for determining the efficiency of MBTS have been listed in Table 1. We differentiate between first-level hardware-based triggers (L1) and higher-level triggers (HLT), which may perform more complicated software-based analysis of additional information. The accepted L1 triggers from the CTP are combined with information from the other subdetectors which seeds into HLT triggers. Examples of first-level triggers are L1_MBTS_1,

Trigger	Definition
L1_MBTS_1	Atleast one active counter on either side A/C
L1_MBTS_2	Atleast two active counters on either side A/C
L1_MBTS_1_1	Atleast one active counter on each side A/C
HLT_mb_sp_L1RD0_FILLED	Hit in one of the silicon detectors
HLT_mb_sptrk_L1RD0_FILLED	Hit in one of the silicon detectors and a reconstructed track
HLT_mb_sptrk_L1ZDC_A_C_VTE50	Hit in one of the silicon detectors and a reconstructed track using ZDC instead of MBTS
HLT_noalg_L1TE50	Passing events with a transverse energy larger than 50 GeV
HLT_noalg_L1MBTSA0-15	Active counter in module 0-15 on the A-side
HLT_noalg_L1MBTSC0-15	Active counter in module 0-15 on the C-side

Table 1: List of MBTS triggers

which triggers when there is at least one active counter on either side A/C, L1_MBTS_2 which triggers when there are at least two active counters on either side A/C or L1_MBTS_1_1, which triggers when there is at least one active counter on each side A/C. Examples of higher level triggers require some amount of activity in the silicon detectors (sp) or a reconstructed track of the path of the particle (trk) or even no additional selection (noalg). Higher level triggers are organized into a structure like HLT_SelectionAlgorithm_FirstLevelSeed. Additionally, triggers for the individual MBTS counters are present for both the A (HLT_noalg_L1MBTSA0-15) and C-side (HLT_noalg_L1MBTSC0-15).
To determine the efficiency for proton-proton runs, a well-defined sample of events is required. To achieve this for the proton-proton runs, HLT_mb_sp_L1RD0_FILLED and HLT_mb_sptrk_L1RD0_FILLED are used as reference triggers, which are almost 100% efficient for minbias events with one track. Here, L1RD0_FILLED alludes to triggering at each colliding bunch in the LHC according to parameters of the beam (fixed position of the beam arriving at a fixed time): to make sure the timing is correct. To determine the efficiency for the heavy-ion runs, HLT_mb_sptrk_L1ZDC_A_C_VTE50 and HLT_noalg_L1TE50 are combined for the respective low and high multiplicity events (low/high number of selected tracks). TE50 and VTE50 mean that the transverse energy registered in the calorimeters is larger and lower than 50 GeV, respectively. When a heavy-ion collision occurs, there are almost always neutrons remaining which follow the direction of the beam. Zero Decree Calorimeters (ZDC) collect these neutrons and the $L1ZDC\_A\_C$ trigger is fired when atleast one neutron is detected in ZDC on both the A and C side to rule out empty events. HLT_noalg_L1TE50 is used to trigger the events with high energy (>50 GeV) collisions.

1.2 Efficiency determination

In the LHC Run 2, the efficiency of MBTS was determined for the trigger L1_MBTS_1 as shown in Figure 2. These efficiencies have been described more extensively in papers [4] and [1]. It was shown the efficiencies degrade throughout the years due to radiation exposure. The scintillators are relatively close to the beam, causing the material to become more opaque due to the radiation causing defects to form in the scintillator's crystal structure. It has been shown this radiative damage scales with the integrated luminosity [4], causing concern for MBTS as the luminosity keeps rising throughout the years with new upgrades. This decrease in efficiency can be partially countered by changing the voltages over the PMTs and by adjusting the CDF trigger thresholds (thus causing a change in the current required in the PMT before the trigger fires). Additionally, during the technical stops throughout the year, it has been shown that the scintillators partially recover their efficiency [4]. The scintillators were replaced during the Long Shutdown 2 (2019-2022) after the LHC Run 2 due to the radiation damage. Additionally the inner ring was replaced for both sides A/C with a more radiation-resistant material, whilst the outer ring consists of the same material used in the LHC Run 2. Although there are other ways to trigger events like ZDC, LUCID or TE, these generally have a lower efficiency, therefore MBTS is still preferred.
The main goal of this project is to scope whether MBTS triggers are in good shape for physics analyses during the LHC Run 3, and to look what the effect of the new scintillator material has been. The efficiency will be determined by comparing the fraction of events triggered by L1_MBTS_1, L1_MBTS_2 and L1_MBTS_1_1 with respective reference triggers as seen in Table 1. The second goal of this project is to do a similar analysis on the data recorded during the heavy-ion (Pb + Pb collisions) programme

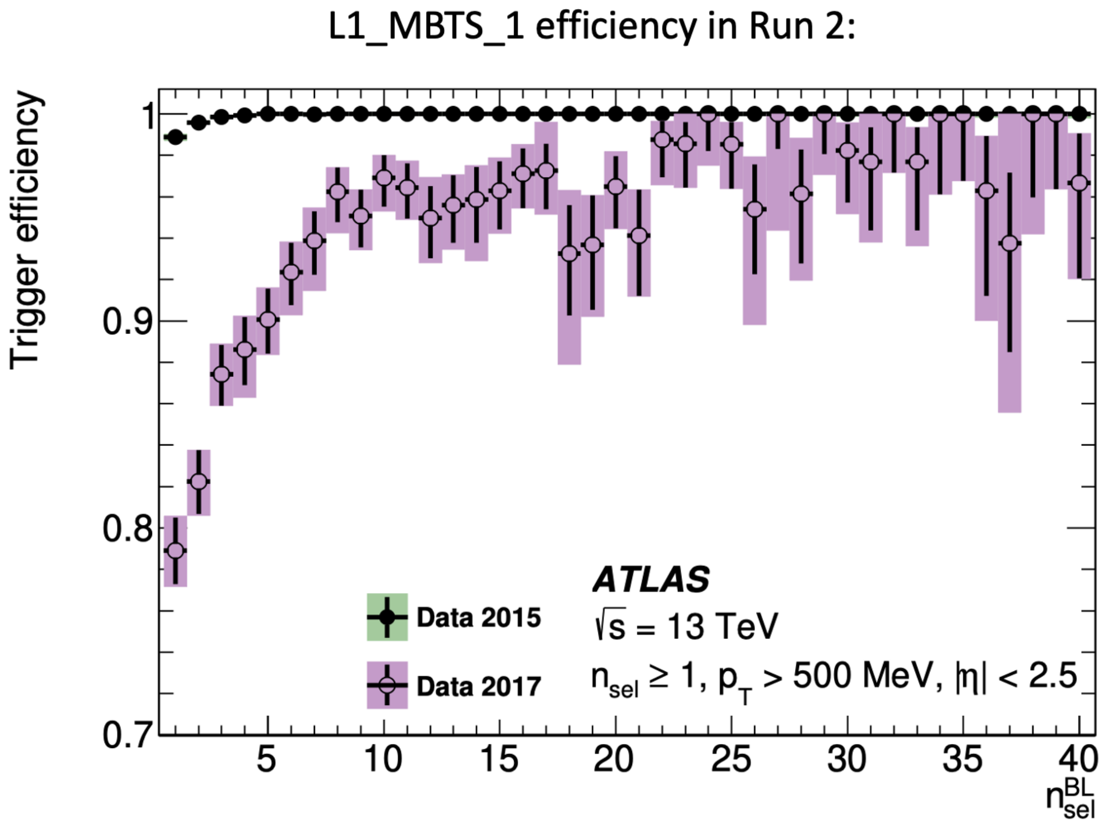

Figure 2: Efficiency of L1_MBTS_1 using LHC Run 2 data [4]

Type	Run	Date	μ	Reference trigger	Bunches	Colliding bunch spacing
p-p collisions	427929	12 July, 2022	0.005	HLT_mb_sptrk_L1RD0_FILLED	64	525 ns
	455818	1 July, 2023	0.05	HLT_mb_sp_L1RD0_FILLED	386	25 ns
	460348	7-8 Sept, 2023	0.005	HLT_mb_sp_L1RD0_FILLED	60	1000 ns
	497630	13 May, 2025	0.05	HLT_mb_sptrk_L1RD0_FILLED	434	25 ns
HI collisions	462022	3 Oct, 2023	<0.0001	HLT_mb_sptrk_L1ZDC_A_C_VTE50 HLT_noalg_L1TE50	506	50 ns
	462717	29 Oct, 2023	<0.0001	HLT_mb_sptrk_L1ZDC_A_C_VTE50 HLT_noalg_L1TE50	1088	50 ns
	489164	10 Nov, 2024	<0.0001	HLT_mb_sptrk_L1ZDC_A_C_VTE50 HLT_noalg_L1TE50	1032	50 ns
	490085	21 Nov, 2024	<0.0001	HLT_mb_sptrk_L1ZDC_A_C_VTE50 HLT_noalg_L1TE50	1032	50 ns

Table 2: List of proton-proton and heavy ion runs.

in 2023 and 2024. This is to scope and predict the efficiencies of the upcoming heavy-ion runs in November of 2025.

2 Data taking in LHC Run 3

The selection of runs suitable for determining MBTS efficiencies is limited by what LHC configuration is present during the run. Next to having the same energy/triggers present, low μ (interactions per bunch crossing) is required due to oversaturation of the scintillators: as particles hit the scintillator, signals remain present for some time window. If there are either too many particles resulting from a collision or too many collisions in a short time (bunch spacing: at least 100 ns), the scintillator oversaturates. Additionally, the scintillator material degrades more quickly. For this reason, the analysis is limited to lower-energy and heavy-ion runs at the end of the year as the luminosity is lower during these runs. For these reasons, 4 runs have been selected which can be compared with a few caveats which will be described later in this project. The properties of these runs, together with 4 heavy ion runs have been given in Table 2.

There are no two proton-proton runs with the exact same configuration. The low μ requirement and amount of bunches are required so MBTS doesn't oversaturate, which means that as long as there is an overall low μ, further differences will not impact the efficiency. Colliding bunch spaces are acceptable up until 25 ns, although already less efficient. For the heavy-ion runs, only the colliding bunch spacing is relevant and the same across all the runs.

2.1 Voltages and CDF trigger thresholds

The voltage over different PMTs and the CDF trigger thresholds (if this changes, it changes the threshold signal at which the trigger fires) are changed depending on the performance of the counters throughout the years, to optimize MBTS performance and uniformity in their response. The changes of the high-voltage are shown in Figure 3 for the A-side and in Figure 4 for the C-side.

The same is done for CDF threshold changes in Figure 5 and Figure 6 in mV for both sides. In 2023, the CDF thresholds were set at -40 mV for the inner counters and -80 mV for the outer counters. After the run selection process, runs were investigated using Tier0 and Graphana, which are both platforms that monitor raw data, to see whether there are any anomalies and if there were not, the run was selected and analyzed.

3 Data analysis strategy

After run selection, AOD files are extracted using rucio (ATLAS's data management system [5]) and subsequently analyzed using the framework provided by Krzysztof Wozniak. The code is an ATLAS EventLoop analysis module which uses a Root Ttree to store event information and histograms

Counters	2022	2023	2024	2025
A00	700	700->695(March 31st)	695->689(April 3rd)	689->756(April 22th)
A01	700	700->723(March 31st) 723->721(Sept 5th)	721->716(April 3rd)	716->783(April 22th)
A02	700	700->715(March 31st) 715->711(Sept 5th)	711->708(April 3rd)	708->771(April 22th)
A03	680->700(July 25th)	700->752(March 31st) 752->741(Septh 5th)	741->748(April 3rd)	748->828(April 22th)
A04	700	700->708(March 31st) 708->712(Sept 5th)	712->709(April 3rd)	709->776(April 22th)
A05	650->670(July 25th)	670->701(March 31st)	701	701->764(April 22th)
A06	680	680->701(March 31st)	701->698(April 3rd)	698->763(April 22th)
A07	660	660->649(March 31st) 649->652(Sept 5th)	652->647(April 3rd)	647->702(April 22th)
A08	700->680(July 25th)	680->708(March 31st) 708->618(April 18th)	618->623(April 3rd)	623->689(April 22th)
A09	700	700->674(March 31st)	674->680(April 3rd)	680->750(April 22th)
A10	700	700->751(March 31st) 751->656(April 18th)	656->659(April 3rd)	659->726(April 22th)
A11	650	650->635(March 31st) 635->625(Sept 5th)	625->628(April 3rd)	628->681(April 22th)
A12	700	700->702(March 31st)	702->706(April 3rd)	706->780(April 22th)
A13	750->800(June 27th) 800->700(July 8th)	700->706(March 31st) 706->660(April 18th) 660->649(Sept 5th)	649	649->721(April 22th)
A14	650->700(June 12th)	700->650(March 31st) 650->655(Sept 5th)	655->660(April 3rd)	660->728(April 22th)
A15	701	701->778(March 31st) 778->687(April 18th) 687->691(Sept 5th)	691->697(April 3rd)	697->769(April 22th)

Figure 3: High voltage changes in the MBTS PMTs on the A-side throughout 2022 till August of 2025. The counters which have a difference of over 100 V between 2022 and 2025 are colorcoded in blue.

Counters	2022	2023	2024	2025
C00	700	700	700->695(April 3rd)	695->761(April 22th)
C01	699	699->691(March 31th) 691->727(April 18th) 727->747(Sept 5th)	747->741(April 3rd)	741->818(April 22th)
C02	700	700->665(March 31th) 665->670(Sept 5th)	670->665(April 3rd)	665->762(April 22th)
C03	679	679->642(March 31th)	642->627(April 3rd)	627->690(April 22th)
C04	700	700->650(March 31th)	650->640(April 3rd)	640->696(April 22th)
C05	700	700->685(March 31th) 685->688(Sept 5th)	688->681(April 3rd)	681->742(April 22th)
C06	700	700->680(March 31th) 680->677(Sept 5th)	677->670(April 3rd)	670->728(April 22th)
C07	700	700->713(March 31th)	713->709(April 3rd)	709->767(April 22th)
C08	700	700->791(March 31th) 791->695(April 18th)	695->697(April 3rd)	697->774(April 22th)
C09	700	700->651(March 31th) 651->649(Sept 5th)	649->654(April 3rd)	654->724(April 22th)
C10	700	700->786(March 31th) 786->691(April 18th) 691->710(Sept 5th)	710->735(April 3rd)	735->818(April 22th)
C11	700	700->627(March 31th) 627->624(Sept 5th)	624->628(April 3rd)	628->688(April 22th)
C12	700	700->692(March 31th)	692->702(April 3rd)	702->777(April 22th)
C13	700	700->717(March 31th) 717->630(April 18th) 630->625(Sept 5th)	625	625->690(April 22th)
C14	700	700->605(March 31th)	605	605->661(April 22th)
C15	700	700->792(March 31th) 792->694(April 18th)	694->703(April 3rd)	703->775(April 22th)

Figure 4: High voltage changes in the MBTS PMTs on the C-side throughout 2022 till August of 2025. The counters which have a difference of over 100 V between 2022 and 2025 are colorcoded in blue.

Counters	Module	Type	12-04-2023	07-09-2023	22-09-2023	28-09-2023	05-04-2024	23-04-2025
A00	EBA57	Inner(PMT 5)	30	30.6	/	/	31	56
A01	EBA58	Inner(PMT 5)	35	30.8	/	/	33	52
A02	EBA39	Inner(PMT 5)	20	11.7	20	16	28	44
A03	EBA40	Inner(PMT 5)	50	29.3	//	/	50	84
A04	EBA41	Inner(PMT 5)	25	24.9	/	/	32	/
A05	EBA42	Inner(PMT 5)	40	25.8	/	/	42	/
A06	EBA55	Inner(PMT 5)	25	24.5	/	/	33	/
A07	EBA56	Inner(PMT 5)	25	20.9	/	/	17.5	/
A08	EBA03	Inner(PMT 13)	60	31.2	/	/	49	/
A09	EBA08	Inner(PMT 13)	40	29.8	/	/	39	/
A10	EBA20	Inner(PMT 13)	60	30.4	/	/	45	/
A11	EBA24	Inner(PMT 13)	25	25.1	/	/	42	/
A12	EBA43	Inner(PMT 13)	35	30.5	/	/	37	50
A13	EBA46	Inner(PMT 13)	55	36.0	/	/	39	/
A14	EBA54	Inner(PMT 13)	25	35.1	/	/	41	/
A15	EBA59	Inner(PMT 13)	85	26.8	30	32.5	32	51

Figure 5: CDF trigger thresholds for the A-side throughout April 2023 till 2025 in mV.

Counters	Module	Type	12-04-2023	07-09-2023	22-09-2023	05-04-2024	05-04-2024	04-11-2024	23-04-2025
C00	EBC57	Inner(PMT 5)	25	25.1	/	39	/	/	/
C01	EBC58	Inner(PMT 5)	20	27.9	/	45	/	/	/
C02	EBC39	Inner(PMT 5)	30	30.0	/	48	/	/	/
C03	EBC40	Inner(PMT 5)	25	30.6	/	53	/	/	/
C04	EBC41	Inner(PMT 5)	20	31.0	/	44	/	30	/
C05	EBC42	Inner(PMT 5)	35	32.8	/	33	/	/	/
C06	EBC55	Inner(PMT 5)	25	31.9	/	32	/	/	/
C07	EBC56	Inner(PMT 5)	25	29.5	/	39	/	/	/
C08	EBC03	Inner(PMT 13)	85	29.8	/	42	/	/	/
C09	EBC08	Inner(PMT 13)	25	30.2	/	47	/	/	/
C10	EBC19	Inner(PMT 13)	80	31.1	/	54	/	/	/
C11	EBC24	Inner(PMT 13)	12	14.6	20	23	19.5	/	52
C12	EBC43	Inner(PMT 13)	40	32.0	/	63	/	/	/
C13	EBC46	Inner(PMT 13)	80	32.9	/	53	/	/	/
C14	EBC54	Inner(PMT 13)	23	30.9	/	46	/	/	/
C15	EBC59	Inner(PMT 13)	75	30.9	/	45	/	/	/

Figure 6: CDF trigger thresholds for the C-side throughout April 2023 till 2025 in mV.

and applies trigger selection. Afterwards, relevant data in the trees are extracted (to calculate the efficiencies) and the efficiencies are plotted as a function of the number of reconstructed tracks of charged particles and as a function of each individual module. The total number of tracks is compared to the tracks after 3 different track reconstruction quality criteria used in physics analyzes have been applied: Heavy Ion Tight (HiTight), Heavy Ion Loose (HiLoose) and Minimum Bias (MinBias). These algorithms select particle tracks based on different properties. HiTight and HiLoose both accept tracks with a wide range of transverse momenta, require hits on one layer of pixel detectors, but differ in their requirement of the closeness of the track to the reconstructed vertex. HiTight requires a track close to the vertex, whilst larger distances are allowed in HiLoose. The main difference with MinBias is that MinBias requires a transverse momentum of more than 500 MeV, compatibility with the reconstructed vertex (when compared to the collision point) and signals in the silicon detectors. The ratio plots are made by dividing the efficiencies and the corresponding drop in efficiency at low multiplicity is reported, as almost all efficiencies saturate at 100% when looking at higher multiplicities. The reason there is no complete saturation for increasing tracks is due to the aforementioned issues with oversaturation, timing issues and the possibility of particles not hitting MBTS.

4 Results

There is a clear degradation of the efficiency of MBTS over time. This pattern is different depending on how selective the trigger is and the type of run (proton-proton or heavy ion runs). The efficiencies for the proton-proton runs with corresponding ratio plots for all years are shown for the triggers in Figure 7 for the MinBias tracks.

Solely the MinBias tracks are shown due to comparison with the LHC Run 2 results and because the other selection algorithm tracks showed approximately the same results. In all of these plots, a pattern in MBTS efficiencies was found: the more selective the trigger and the later in time, the lower the efficiency. Although the efficiency in September of 2023 is higher than in July of 2023, this is due to the lower bunch spacing in July. The same is done for L1_MBTS_2 and L1_MBTS_1_1 in Figures 8 and 9. The ratio plots show L1_MBTS_1 working at 85%, L1_MBTS_2 at 65% and L1_MBTS_1_1 at 50% of the original efficiency at low multiplicities when comparing data recorded in 2022 and 2025. When

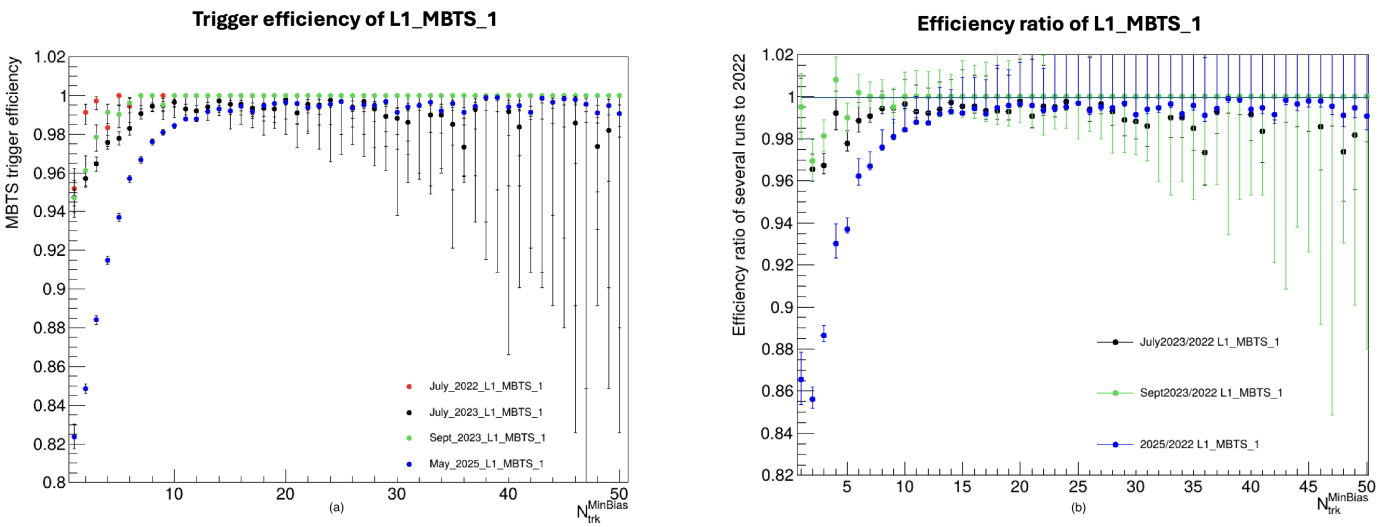

Figure 7: Efficiencies of L1_MBTS_1 for proton-proton runs (a) and a ratio of these efficiencies (b)

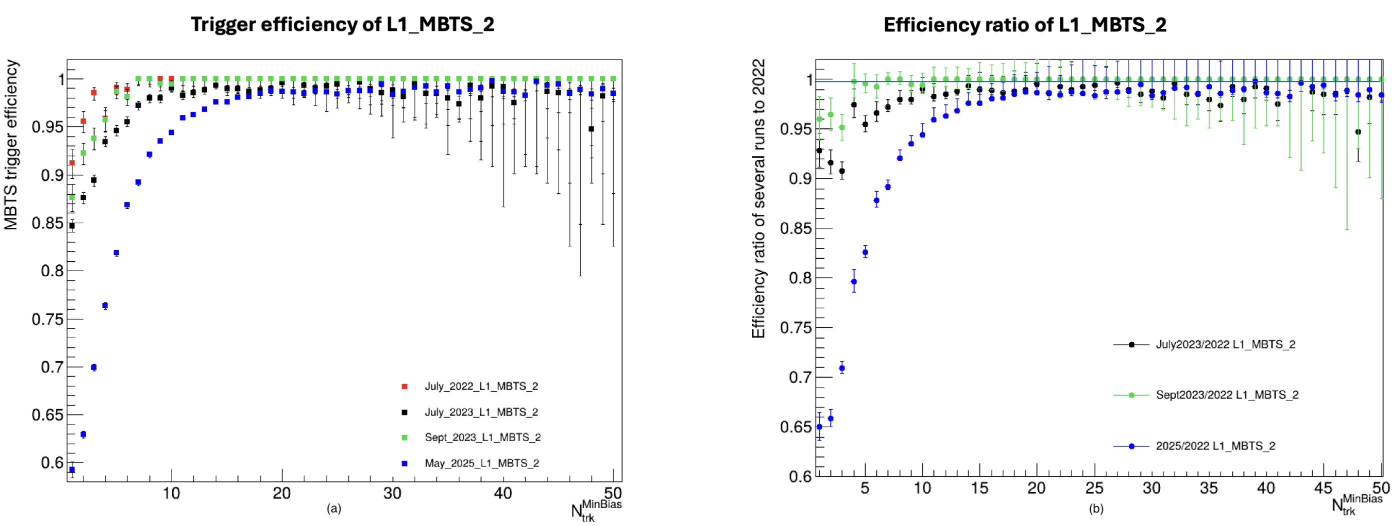

Figure 8: Efficiencies of L1_MBTS_2 for proton-proton runs (a) and a ratio of these efficiencies (b)

comparing these results to the LHC Run 2, there is a slight increase in the performance of MBTS as approximately the same degradation was present between 2015 and 2017 for L1_MBTS_1, even though the luminosity (and thus radiation dosage) has increased, and the LHC Run 3 degradation is over 3 years instead of 2.

Additionally, the efficiencies per MBTS counter are plotted in Figure 10 for data recorded in 2022 and 2025. Some counters are off due to some electronic issues (A13 and C01 in 2022 and C04 in 2025). The efficiency is much lower in 2025 when compared to 2022, but the mean efficiencies and the decrease is very similar for modules with standard green and radiation-harder blue scintillators.

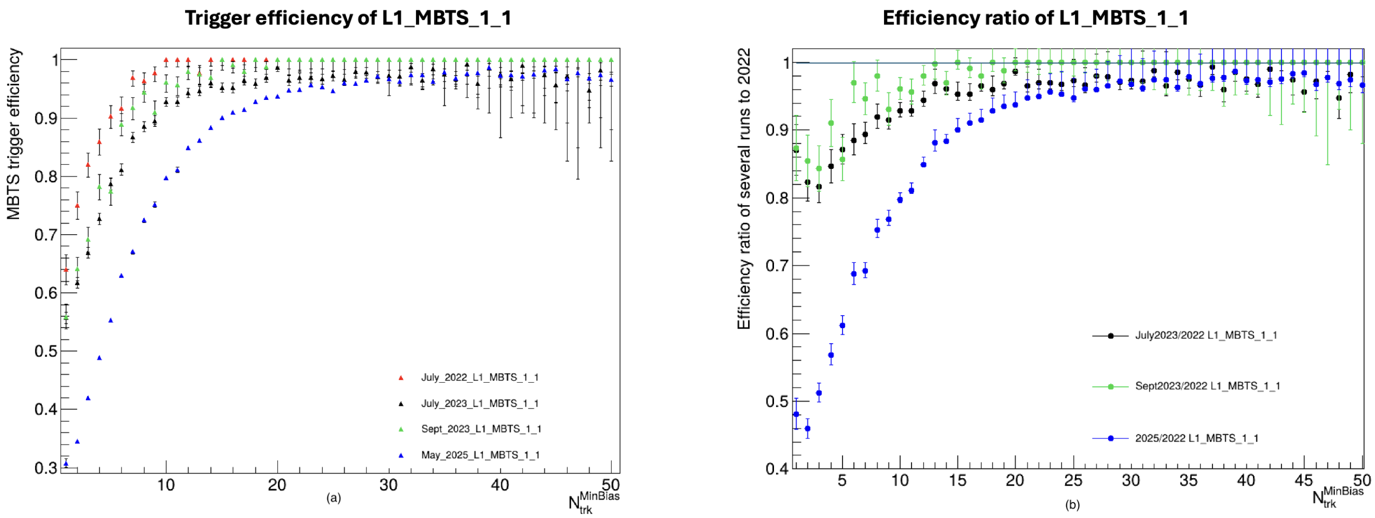

Figure 9: Efficiencies of L1_MBTS_1_1 for proton-proton runs (a) and a ratio of these efficiencies (b)

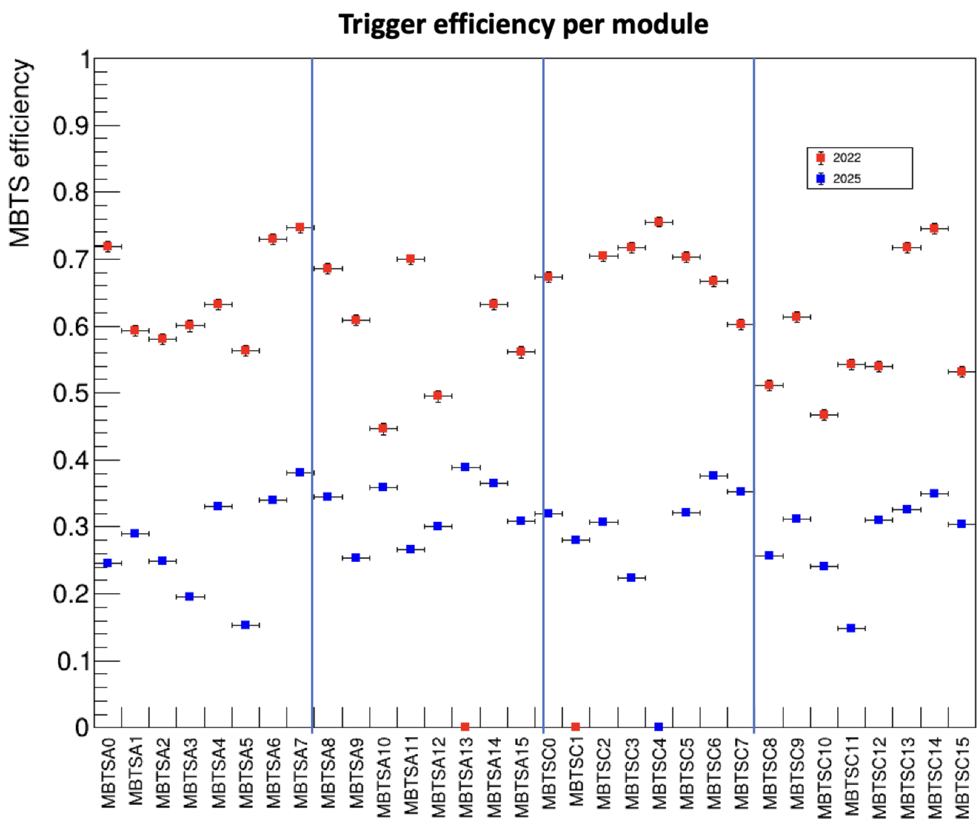

Figure 10: Efficiencies for the individual counters using the datasets recorded in 2022 and 2025. The lines denote the differences between the inner and outer ring (first 8 inner, last 8 outer per side)

For the heavy-ion runs, the same pattern is present, although the efficiencies degrade more severely. The efficiencies for consecutively L1_MBTS_1, L1_MBTS_2 and L1_MBTS_1_1 are shown in the same pattern as before in Figures 11, 12 and 13. The ratio plots show L1_MBTS_1 working at 50%, L1_MBTS_2 at 25% and L1_MBTS_1_1 at almost 10% of the original efficiency at low multiplicities when comparing 2023 and 2025. Two other runs from 2023 and 2024 were compared to their counterparts to check whether there was some impact from a specific run, which was found to not be the case as seen in Figure 14.

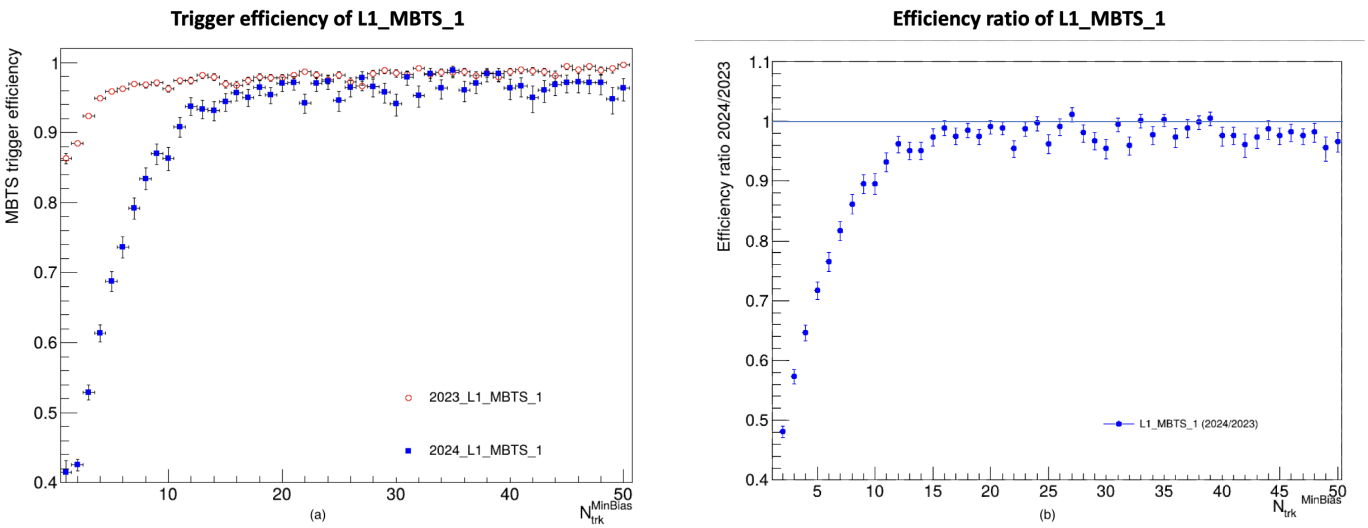

Figure 11: Efficiencies of L1_MBTS_1 using heavy-ion runs recorded in 2023/2024 (a) and a ratio of these efficiencies (b)

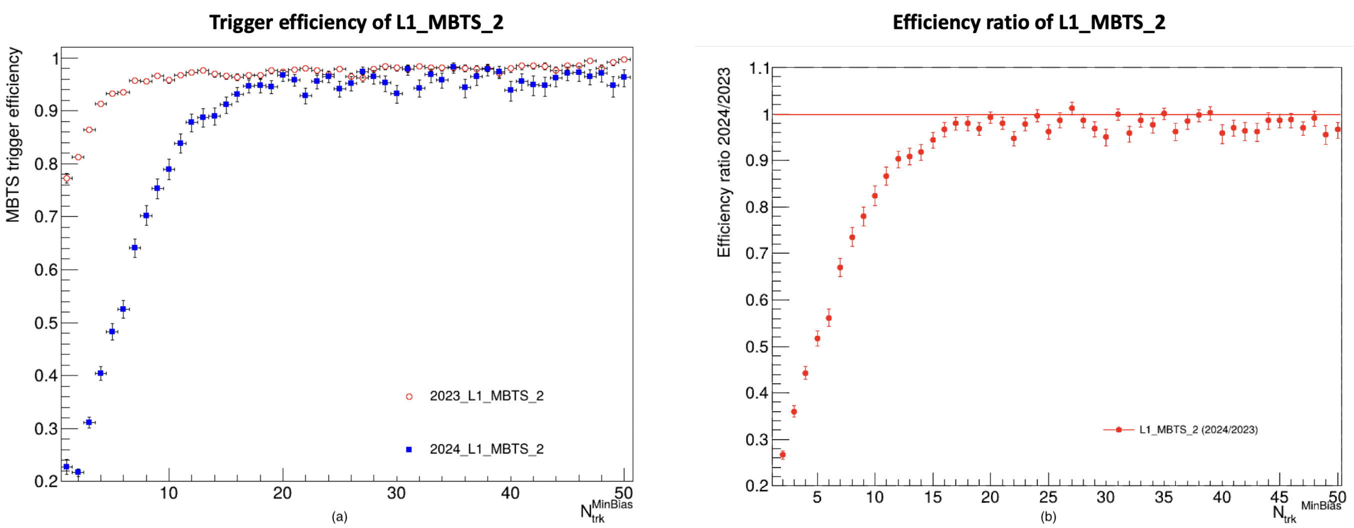

Figure 12: Efficiencies of L1_MBTS_2 using heavy-ion runs recorded in 2023/2024 (a) and a ratio of these efficiencies (b)

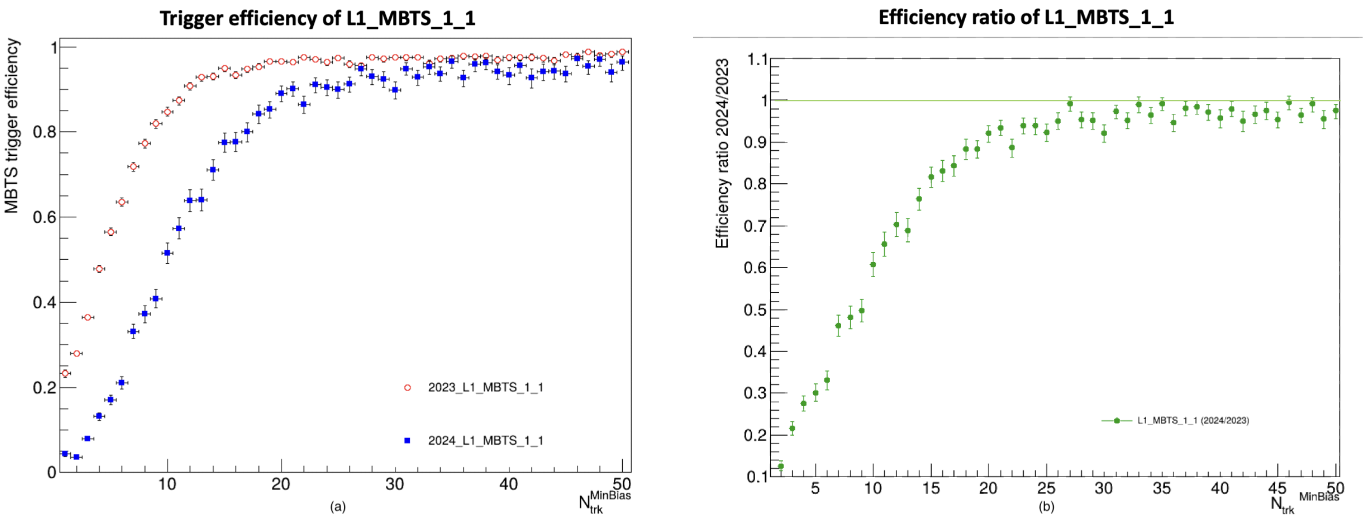

Figure 13: Efficiencies of L1_MBTS_1_1 using heavy-ion runs recorded in 2023/2024 (a) and a ratio of these efficiencies (b)

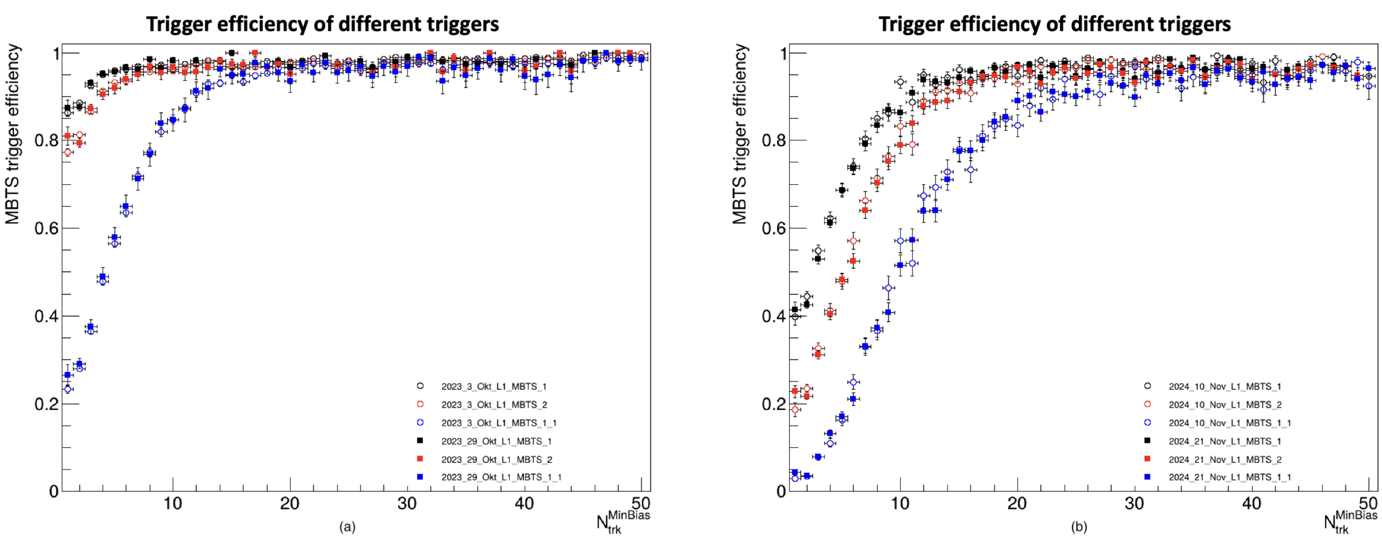

Figure 14: Comparison of the efficiencies using heavy ion runs recorded in 2023/2023 (a) and 2024/2024 (b)

5 Conclusions

Minimum Bias Trigger Scintillators (MBTS) imperative for low-luminosity and heavy-ion runs have been thought to degrade due to radiation damage, causing the efficiencies to drop over time. Consisting of scintillator tiles interacting with charged particles surrounding the beam line on two sides (A/C), MBTS are used for event detection and include triggers like L1_MBTS_1 (active counter on either A/C side), L1_MBTS_2 (two active counters on either A/C side) and L1_MBTS_1_1 (active counter on each side). The efficiencies of these MBTS triggers were determined for 13.6 TeV proton-proton collisions. This was done for 4 different runs, one run from 2022, two runs from 2023 and one run from 2025 due to the lack of special runs available as a low average number of interactions per bunch crossing was required to not let MBTS oversaturate. The efficiency of the triggers degrades differently over time depending on how selective the trigger was. When comparing ratio plots of 2025/2022, L1_MBTS_1 works at 85%, L1_MBTS_2 at 65% and L1_MBTS_1_1 at 50% of the original efficiency at low multiplicities. When comparing these results to a similar, but less extensive analysis on the LHC Run 2, it was found that the efficiency degradation is less severe in the LHC Run 3. This points to a major improvement in performance. Next, a similar process was done for heavy-ion runs. These runs, two from 2023, two from 2024, showed much larger degradation, with L1_MBTS_1 working at 50%, L1_MBTS_2 at 25% and L1_MBTS_1_1 at almost 10% of the original efficiency at low multiplicities. These results could not be compared with Run 2, as there were no runs with a suitable LHC configuration. With the heavy-ion runs approaching in November of 2025, an even larger drop of efficiency is expected. More detailed studies require data for collisions with low μ that are collected with all L1MBTS items and appropriate reference triggers.

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