Overlap Studies for ATLAS MUCTPI

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A project report submitted as part of the
CERN Summer Student Programme

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6. September 2019

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Glossary

Acronym	**Meaning**
CERN	European Organization for Nuclear Research
LHC	**L**arge **H**adron **C**ollider
ATLAS	**A** **T**oroidal **L**HC **A**pparatu**S**
CTP	**C**entral **T**rigger **P**rocessor
MUCTPI	**MU**on **CTP** **I**nterface
RoI	**R**egion **of** **I**nterest

1. Introduction

The ATLAS Muon Central Trigger Processor Interface uses information from the muon trigger detector system to check, if certain trigger conditions are met. Before checking, it attempts to remove muons that were counted twice by the trigger detector because of overlap between different detector modules. This process is called overlap removal. This report will attempt to determine the impact of the overlap removal on the efficiency of the muon trigger system.
Additionally, this report will outline some possible encodings, by which the muon trigger system can transmit data on muon hits to the topology trigger of the ATLAS Trigger system.

2. The Muon CTP Interface (MUCTPI)

The ATLAS experiment generates 60 TB of data per second. It is not possible to store all of this data. Hence, the ATLAS Trigger System selects for specific events, which are to be exported and stored outside of the detector. The main component of this Trigger System is the Central Trigger Processor (CTP). It receives information from the calorimeter and the muon system of the ATLAS detector. Based on this information a decision is made on whether or not an event will pass the Level 1 trigger. If so, the event information is forwarded to the Level 2 trigger, where a final decision on recording the eent is made. The trigger information by the muon system is preprocessed and transfered to the CTP by the Muon CTP Interface (MUCTPI) [1].
The MUCTPI calculates this information in the form of multiplicities of thresholds of certain transverse momenta p_T, that were exceeded. For Run 2 these thresholds were 4 GeV, 6 GeV, 10 GeV, 11 GeV 15 GeV and 20 GeV. The Muon Trigger System can differentiate between six different channels, that are triggered, when a certain p_T-threshold is exceeded. The multiplicities of these channels are calculated in several segments of the system and the combined in the MUCTPI. The segmentation of the muon trigger system follows a tree-like structure. The entire detector is split up into the following parts:

- The detector is split into two **hemispheres** (one for positive, one for negative η).
- Each hemisphere consists of eight **octants**.
- Every octant is built up of 13 **sectors**. Four sectors lie in the Barrel region of the detector, six in the Endcap region and three in the Foreward region.
- Every sector consists of a number of **Regions of interest (RoIs)**. The number of

RoIs varies depending on the sector type. In total there are $\sim 19,000$ RoIs in the muon trigger system.

An exemplary octant with its 13 sectors and their respective RoIs is shown in Figure 2.1. During every bunch crossing, every RoI records the highest p_T-channel that is triggered. Every sector then collects up to two RoIs, which have recorded the highest p_T-values. The information on these two RoIs (i.e. the ID of the RoI and the exceeded p_T-threshold) is then sent to the MIOCT-module, which calculates the multiplicities of p_T-thresholds of one octant. The MIBAK-backplane then receives the multiplicities of all MIOCTs, sums them up and sends the information to the CTP via the MICTP. The CTP then evaluates the multiplicities together with information from the calorimeter and derives the overall decision for the first stage of the ATLAS Trigger.

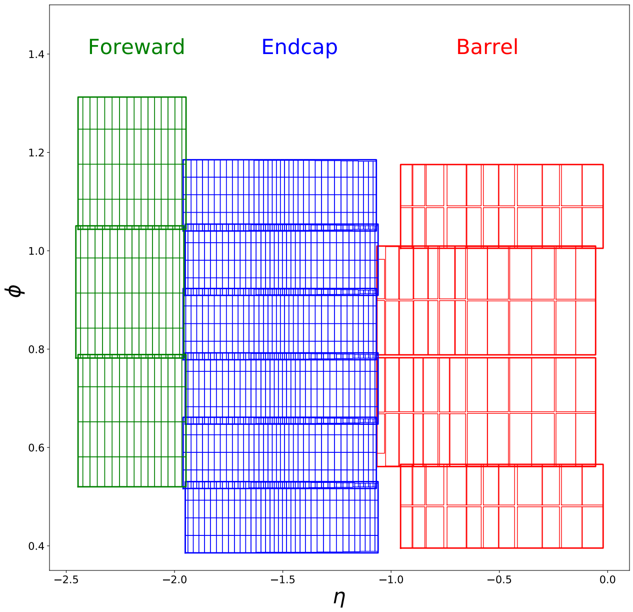


Figure 2.1.: Schematic of octant 1. The wide lines enclose different sectors with their respective RoIs. The different colors signify the sector types (Barrel, Endcap and Foreward).

2.1. Overlap Regions

As can be seen in Figure 2.2, there are some overlaps between certain RoIs. Hence, if two overlapping RoIs report an event, it is possible, that both RoIs have been triggered by the same muon. The overlap of RoIs in the same sector is handled by the on-detector electronics. The overlap of two neighboring sectors, however, is handled by the MIOCT-module. The module checks, if the RoI-IDs of two neighboring sectors are listed in a look-up-table, which includes all the overlaps between sectors. Should that be the case, the RoI, which reported the lower p_T-value is discarded and not used in the multiplicity calculation.

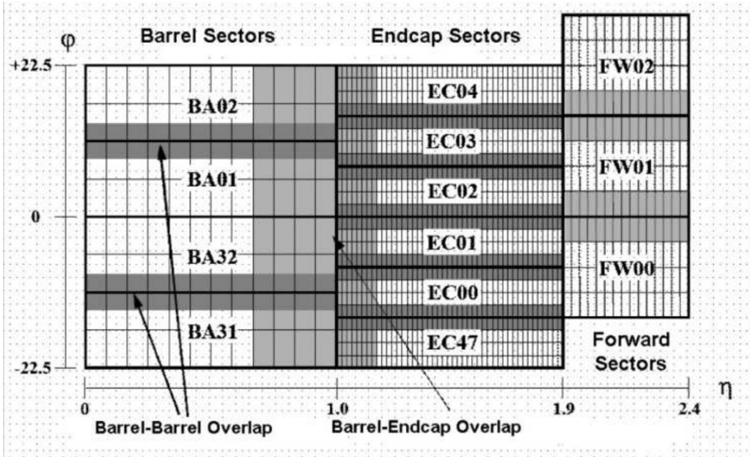


Figure 2.2.: The Overlap regions of octant 0. The overlapping RoIs are marked according to the sector type, with which they overlap (i.e. Barrel-Barrel, Barrel-Endcap, Endcap-Endcap, Endcap-Foreward, FOreward-Foreward) [1].

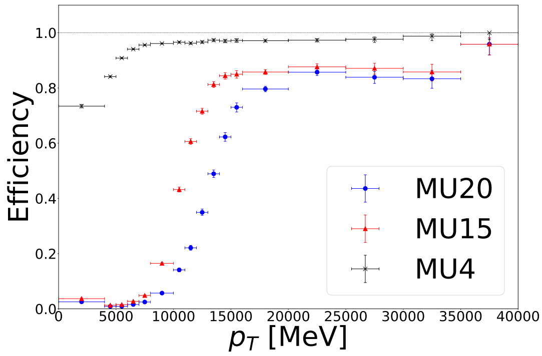
In Run 2 the overlap between the RoIs of different octants is not taken into account. This is supposed to change by Run 3. Additionally, the number of available p_T-channels is set to increase to 13. Hence scalable simulations of the muon trigger system are needed in preparation for this upgrade.

3. Overlap Studies

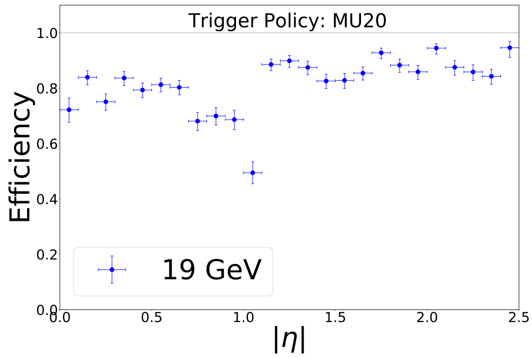
The main goal of this project was to find out, in what way the aforementioned overlap removal impacts the efficiency of the MUCTPI. This was achieved with a program that takes ROOT files of simulation data as input and calculates multiplicities before and after the overlap removal. With these multiplicities it could then be tested, under which conditions certain triggers fired. Since currently there are no simulation data for Run 3 available, the program was written as modular as possible. This way, it is currently possible to analyze Run 2 simulations and the support for Run 3 simulations can be implemented without much effort. The gathering of hits from the input ROOT file is shown in Figure A.1. This report will not go into the details of the program and instead focus on the results that were achieved with it.

3.1. Efficiency of Single Muon Triggers

The MUCTPI checks if the calculated multiplicities fulfill a certain trigger condition. If so, this information is sent to the CTP. One category of such trigger conditions are the single muon triggers. These check, if at least one muon exceeded a certain p_T-threshold. Three different types of single muon triggers were analyzed for this project: MU4, MU15 and MU20. Te numbers in the trigger word correspond to the p_T-threshold that needs to be exceeded for the trigger to fire. The determined efficiencies after overlap removal for the different single muon triggers as a function of p_t and $|\eta|$ can be seen in Figure 3.1.



Efficiency as function of the real p_T of the leading muon



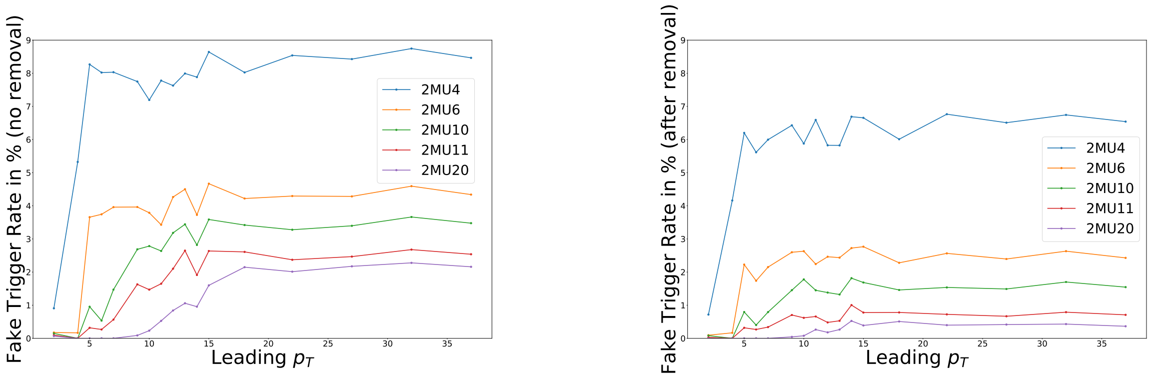
Efficiency as function of the real $|\eta|$ of the leading muon

Figure 3.1.: The efficiency for single muon triggers as a function of p_T and $|\eta|$.

It can be observed that the efficiency as a function of p_T is close to zero for p_T-values below the respective trigger threshold. Close to the threshold the efficiency then increases and saturates at the respective p_T-thresholds. This is precisely the way, in which the trigger-efficiency should behave.
For the efficiency as a function of $|\eta|$ two clear dips at $|\eta| \approx 0$ and $|\eta| \approx 1$ are visible. These dips result from a lack of detector material in this area of the detector (cp. Figure A.2). Also here the efficiency behaves as expected.
A comparison between the efficiency before and after the overlap removal shows no difference between the two. The reason for this is that the overlap removal only removes the muon which was registered with a lower p_T. Hence the muon with the highest p_T in the bunch crossing will never be removed. For the single muon triggers, however, only the muon with the highest p_T is important to check, if a certain p_T-threshold was exceeded. In conclusion, the overlap removal does not impact the single muon trigger efficiency in any way.

3.2. Efficiency of Di-Muon Triggers

Similar to the single muon triggers, the efficiency of di-muon triggers can be analyzed. For the di-muon triggers an effect of the overlap removal is to be expected, as both the leading and the second-to-leading muon need to fulfill the trigger condition. Primarily, the efficiency of the overlap removal is analyzed. This is done, by checking the fake di-muon trigger rate in single muon events before and after the overlap removal. Plots of both rates as a function of the p_T of the single true muon can be seen in Figure 3.2.



Before overlap removal

After overlap removal

Figure 3.2.: The fake di-muon trigger rate before and after the overlap removal. The trigger rate is given as a function of the true p_T of the only muon in the event.

Especially for high-p_T di-muon triggers the overlap removal shows some significant effect. This effect can be quantified as the overlap removal efficiency, by dividing the fake di-muon trigger rate after the overlap removal by the fake di-muon trigger rate before the overlap removal. The efficiency plots for different di-muon triggers as a function of the p_T of the single true muon can be seen in Figure 3.3.

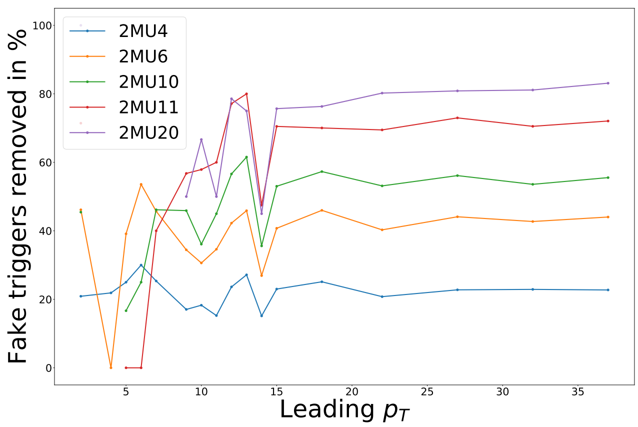


Figure 3.3.: The efficiency of the overlap removal as a function of the true p_T of the only muon in the event. The efficiency is calculated as the fraction of fake muon triggers after and before the overlap removal.

As can be seen, the overlap removal only becomes efficient for higher p_T triggers. It gradually increases up to $\sim$80 % for the 2MU20 trigger. To be able to recommend the overlap removal or not, its possible negative effects need to be checked. The main disadvantage of the overlap removal is, that it could possibly remove true di-muon events, if both muons pass through RoIs that lie in an overlap region. To check this, pure di-muon events from J/Ψ-decays are analyzed. Again, the number of triggered events before and after the overlap removal is determined. For real di-muon events, however, the p_T of the leading muon no longer holds relevant information. Hence, the efficiency is determined as a function of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, a measure for the angle between the two muons. The analysis was conducted for the 2MU4 and the 2MU20 triggers, the lowest and the highest p_T-triggers. Dividing the trigger efficiency after the overlap removal by the trigger efficiency after the overlap removal yields the plot seen in Figure 3.4.

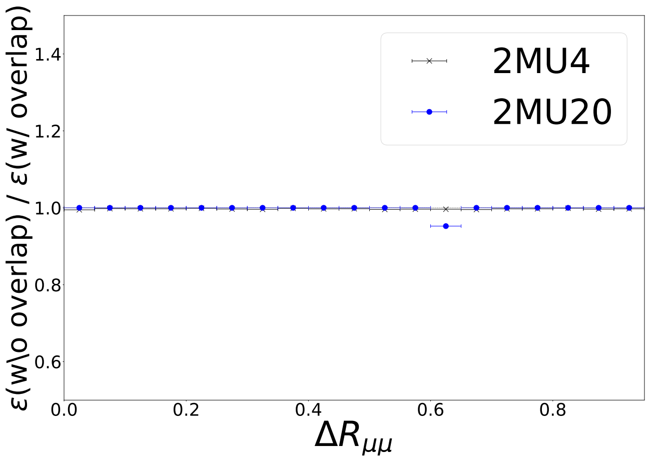


Figure 3.4.: The efficiency of the 2MU4 and the 2MU20 trigger after the overlap removal divided by the efficiency before the voerlap removal. The values are obtained from pure di-muon events. Any value less than 1 means, an overlap has been removed falsely.

All values are extremely close to one, with one exception around $\Delta R = 0.6$ for the 2MU20 trigger, which is negligible. It can be concluded, that regardless of the p_T-threshold of the trigger, the overlap removal identifies true di-muon events as such. Hence, the overall usefulness of the overlap removal can be determined using only the fake di-muon trigger rates. This means, that the overlap removal becomes more efficient, the higher the p_T-threshold of the trigger is. Even for the lowest p_T trigger, 2MU4, around 20 % of fake di-muon events are removed. The overlap removal as a whole can therefore be recommended as a mean to increase the overall efficiency of the ATLAS muon trigger.

4. Additional Project: Encoding for the topology trigger

As mentioned previously, in Run III of the LHC the muon trigger system will receive an upgrade in the form of better p_T-resolution and more complex multiplicity calculation. However, not only the muon part of the trigger will be upgraded. The topology trigger, which derives trigger information from the positions of detected muons and conveys this information to the CTP, is also set to be updated to higher resolution. The topology trigger will receive its information from the MUCTPI. However, the MUCTPI only deals with hit encoding in the from of RoI-IDs (together with the hemisphere and octant- / sector-ID). The topology trigger requires information on the η- and ϕ-coordinates of the hit. These should be available independent of each other, as this simplifies the decoding process immensely.

The topology trigger receives a 32-bit word from the MUCTPI for every RoI that reported a hit (after overlap removal). 16 bits of this word are available for the η-ϕ-information on the respective RoI. The aim of this side project is to find an encoding that needs the fewest number of look-up-tables for en- and decoding. Additionally, it should have the maximum possible resolution in η as well as ϕ.
The main problem that comes with these requirements is the fact, that the η- and ϕ-information cannot be encoded separately in 16 bits. While there are 18800 RoIs, which can easily be encoded in 16 bits, detaching the ϕ-information from the respective η-information of the RoI requires at least 18 bits. Hence it is not possible to encode η and ϕ separately while maintaining the full resolution. Two encoding proposals will be presented here, one of which decreases resolution for an independent encoding and one, which keeps the full resolution at the cost of non-independent η- and ϕ-values.

4.1. Independent η- and ϕ-encodings

The first encoding decreases the resolution in the endcap part of the detector to allow for an independent η-ϕ-encoding. For this, 9 bits are used for the ϕ-encoding and 6 bits + 1 hemisphere bit are used for the η-encoding. The unequal distribution of bits is to allow for an easier decoding of the ϕ-component (cp. Figure A.3). Additionally, this allows for the full resolution in ϕ to be preserved. The resolution in η, however, had to take some cutbacks. Firstly, the resolution in the endcap region was cut in half. This is, because the endcap region had the highest η-resolution of the three detector types. Additionally, for the endcap and the forward region the η-shift of every second sector (cp. Figure 4.1) could not be taken into account. The encoded points and the RoI-centers to be encoded are visible in Figure 4.1. The encoding scheme requires an estimated 34 LUTs on the MUCTPI-side and an estimated 129 LUTs on the side of the topology trigger.

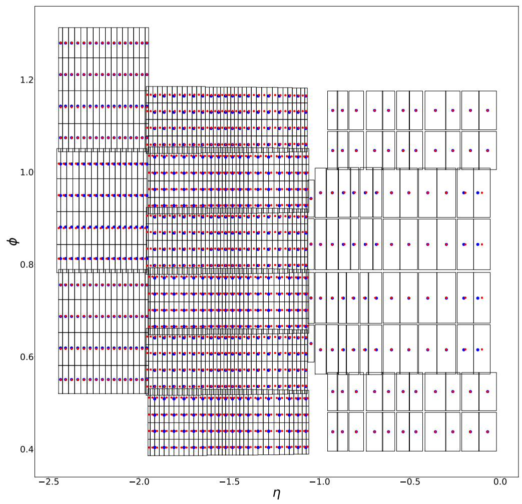


Figure 4.1.: The encoded points for the independent η-ϕ-encoding. The blue points represent the RoI-centers to be encoded. The red points represent the coordinates that are encapsulated by the encoding. Each blue point is encoded by the closest red point.

4.2. Full RoI-word without encoding

As an alternative to the independent η-ϕ-encoding there is the possibility to preserve the full resolution of the MUCTPI while sacrificing independence of the two dimensions. The most straight-forward way to do this is to send the entire RoI-word, as information on the entire dimension can be (theoretically) extracted from it. It would additionally decrease the susceptibility of the entire coding for errors, since all manipulation of the RoI-word would be coming from the topology-side of the trigger. This would, however, also mean that the number of LUTs on the topology side would increase. This encoding would require an estimated 290 LUT-entries on the topology-side and no LUTs on the MUCTPI-side. The encoded points and the RoI-centers to be encoded are visible in Figure 4.2.

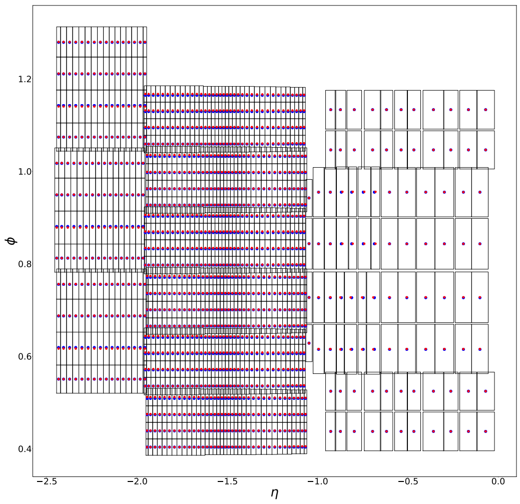


Figure 4.2.: The encoded points for the encoding via the full RoI-word. The blue points represent the RoI-centers to be encoded. The red points represent the coordinates that are encapsulated by the encoding. Each blue point is encoded by the closest red point.

4.3. Comparison

There are obvious advantages of the independent encoding over the sending of the full RoI-word. The main advantage is the requirement of fewer resources. The question is, whether the increase in resolution achieved by sending the full RoI-word outweighs the resourcefulness of the independent encoding. To analyze this, it is useful to find out how precise physical quantities can be measured with the two resolutions. For this a set of Monte Carlo J/Ψ-to-$\mu\mu$-events is analyzed in terms of the invariant mass of the two muons. The expectation is to find a peak around 3.1 GeV. The width of this peak should give information on the resolution of the respective encodings. A plot of the reconstructed invariant masses for the different encodings can be seen in Figure 4.3.

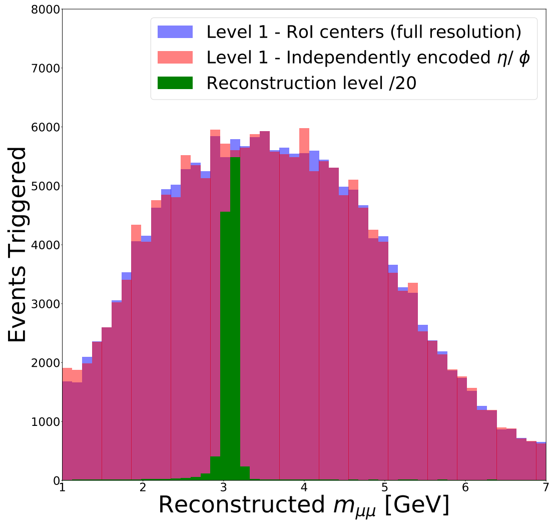


Figure 4.3.: The reconstructed invariant masses of the two different encodings. The two histograms for the different encodings have an opacity of 0.5 for better comparison. The green histogram shows the invariant masses at reconstruction level divided by a factor of 20.

The plot shows no significant difference in resolution for the two different encodings. Compared to the results that can be achieved at reconstruction level, both encodings allow for equally little conclusions regarding the reconstructed masses. Hence it can be concluded that using the independent η-ϕ-encoding is more resourceful and most likely has a negligible impact on the overall performance of the Level 1 topology trigger compared to the use of the full MUCTPI-resolution.

5. Summary

The aim of this project was, to determine the efficiency of the overlap removal in the ATLAS MUCTPI and determine its usefulness. For the purpose of this analysis a general purpose program has been created that can calculate multiplicities and remove overlaps from simulation data. This program was structured in a way that allows for a similar analysis to be done on the Run 3 overlap removal with little changes in the source code.

The efficiency of the various di-muon triggers could be shown to increase with the overlap removal. The efficiency of the removal increases with the p_T-threshold of the di-muon trigger. It ranges from $\sim 20\,\%$ for the 2MU4 trigger to $\sim 80\,\%$ for the 2MU20 trigger. At the same time, the number of false positives, i.e. removed true di-muon events, is negligible for all di-muon triggers. This means that the overall efficiency of the ATLAS muon trigger increases due to the overlap removal. Hence, this reports concludes that the overlap removal as a useful component of the muon trigger system, with little to no downside, taken aside the resources it requires.

For the topology encoding two different methods were compared. One that simplifies decoding by sending η- and ϕ-information separately while decreasing the resolution, and one that remains the full resolution without encoding η and ϕ separately. To answer, which of these encodings had more benefits, the invariant mass of the J/Ψ was calculated with both encoded resolutions. No significant difference could be observed. Hence, the independent η-ϕ-encoding can be recommended, as it requires only half as many resources and achieves comparable results.

Appendix

A. Figures

A.1. Overlap Studies

Data/Bilder/HitStorage.pdf

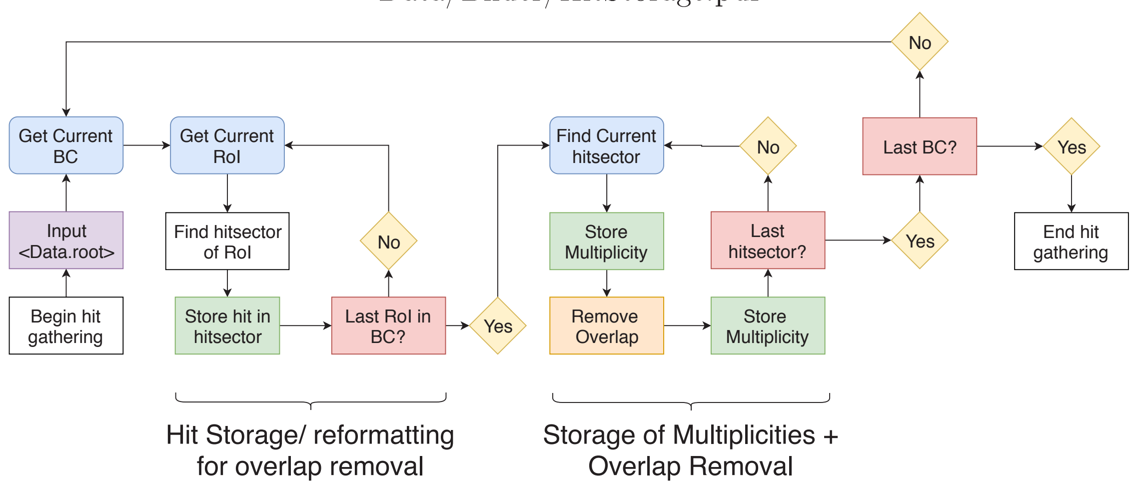


Figure A.1.: The schematic of hit storage in the program for overlap removal studies. The program loops through every bunch crossing (BC) in the simulation input file. It then stores all RoIs that were hit in "hitsector"-constructs that simulate the on-detector hit gathering and overlap removal. Then the multiplicities of p_T-thresholds are calculated from these hitsectors, both before and after the overlap removal. The multiplicities are stored and the program repeats for the next BC.

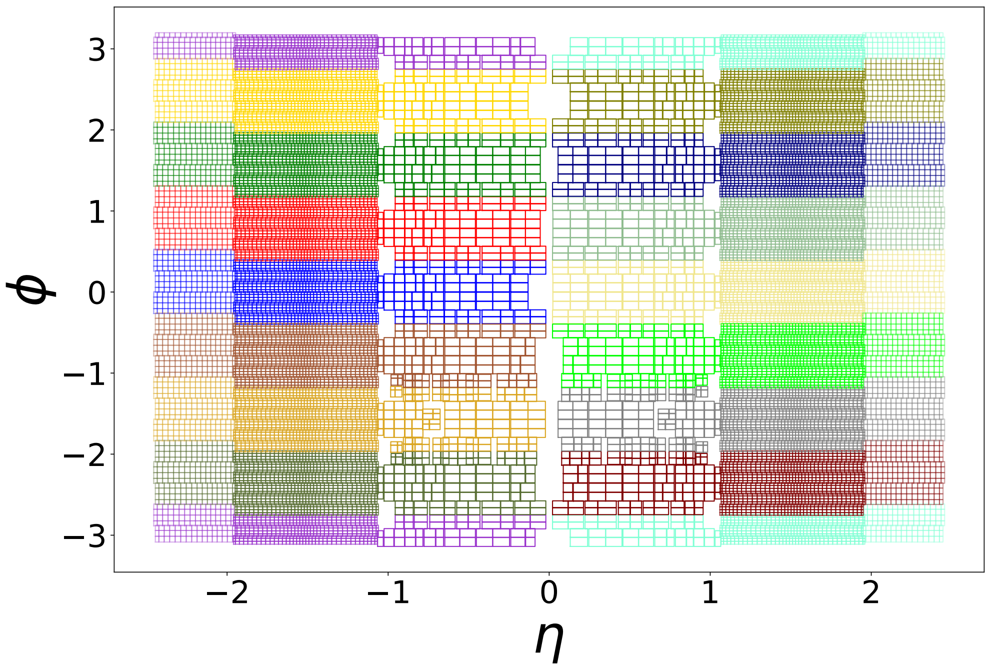
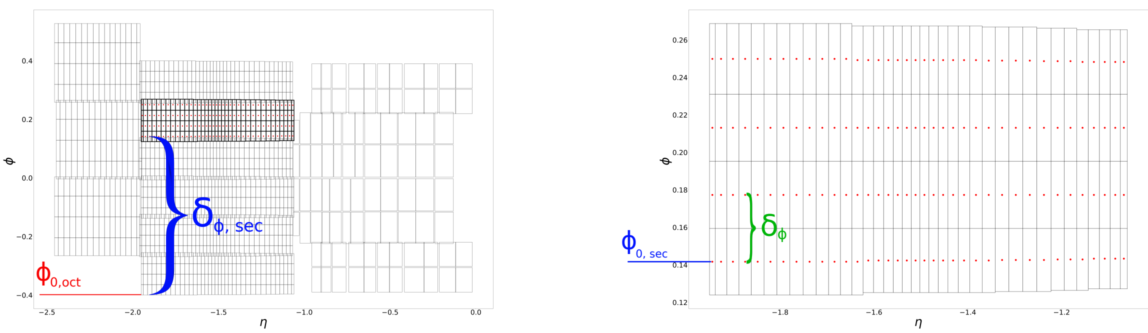


Figure A.2.: A plot of the full muon trigger detector in the η-ϕ-plane. Different octants are colored in different colors. Note the lack of detector material at $|\eta| \approx 0, 1$.

A.2. Additional Project: Encoding for the topology trigger



Finding sector offset. Finding RoI offset.

Figure A.3.: Schematic of ϕ-encoding. The regularity of octants and sectors allows for a reduction of LUTs needed for the ϕ-decoding. Instead of every value being encoded as one entry in a ∼350-entry LUT, only three LUTs are needed: One for the octant offsets (8 entries), one for the sector offsets (13 entries) and one for the RoI-distance in sectors (13 entries). $\phi_{tot} = \phi_{0,oct} + \phi_{0,sec} + x \cdot \delta_{\phi}$.

Bibliography

[1] S. Ask, D. Berge, P. Borrego-Amaral, D. Caracinha, N. Ellis, P. Farthouat, P. Gãllnö, S. Haas, J. Haller, P. Klofver, A. Krasznahorkay, A. Messina, C. Ohm, T. Pauly, M. Perantoni, H. Pessoa Lima Junior, G. Schuler, D. Sherman, R. Spiwoks, T. Wengler, J.M. de Seixasg and R. Torga Teixeira. *The ATLAS central level-1 trigger logic and TTC system*. 7 August 2008. `https://iopscience.iop.org/article/10.1088/1748-0221/3/08/P08002/pdf`.