Truth level signal efficiency with lepton p_T cuts in 2-lepton final state of the decay $A \to H^{\pm}W^{\mp} \to b\bar{b}WW$ in 2HDM model

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Abstract

Modern high-energy physics experiments produce vast amounts of data, and trigger systems are crucial for selecting the most interesting events. In this project, we look at the trigger efficiency for the dileptonic final state of the 2HDM process $A \to H^{\pm}W^{\mp} \to (H \to b\bar{b})\,WW$ using Monte Carlo simulations at the truth level. We emulate the ATLAS lepton triggers by applying p_T cuts to truth electrons and muons, compute the signal efficiency across a scan of (m_A, m_H) mass points, and study the effect of additional kinematic selection cuts.

To visualize these results, we create two-dimensional heatmaps in (m_A, m_H) highlighting regions of high and low trigger efficiency. We find that an inclusive (OR) combination of single-lepton and di-lepton selections provides the best coverage, with efficiencies of about 87% at 300/200 GeV rising to $\sim$ 97.8% near 700/300 GeV, while a single-muon path alone underperforms at low masses. This analysis quantifies the ATLAS trigger acceptance for this specific signal at truth level and motivates using combined electron–muon menus for studies of this channel.

1 Introduction

The study of particle decays and interactions lies at the core of high-energy physics. Leptons, such as electrons and muons, serve as particularly valuable probes due to their clean and well-understood signatures within particle detectors. Dileptonic decays of heavy bosons provide experimentally accessible final states, offering precise insight into fundamental interactions and opening a window to phenomena beyond the Standard Model.

The Standard Model (SM) has been remarkably successful, but it leaves open questions such as the nature of dark matter, the origin of the matter–antimatter asymmetry, and the mechanism behind the mass hierarchy of fundamental particles. These gaps motivate searches for extensions of the Higgs sector, such as the Two-Higgs-Doublet Model (2HDM). The 2HDM predicts five Higgs bosons: two neutral scalars (h, H), a pseudoscalar (A), and a pair of charged Higgs bosons $(H^{\pm})$. In this study, we investigate the decay chain

$$A \to H^{\pm}W^{\mp} \to (H \to b\bar{b})\,WW,$$

which leads to a final state containing two b-jets and two W bosons. The subsequent W decays define the experimentally observable signatures: the fully hadronic mode (both W bosons decay into quarks), the semileptonic mode (one W decays hadronically and the other leptonically), and the dileptonic mode (both W bosons decay to charged leptons and neutrinos).

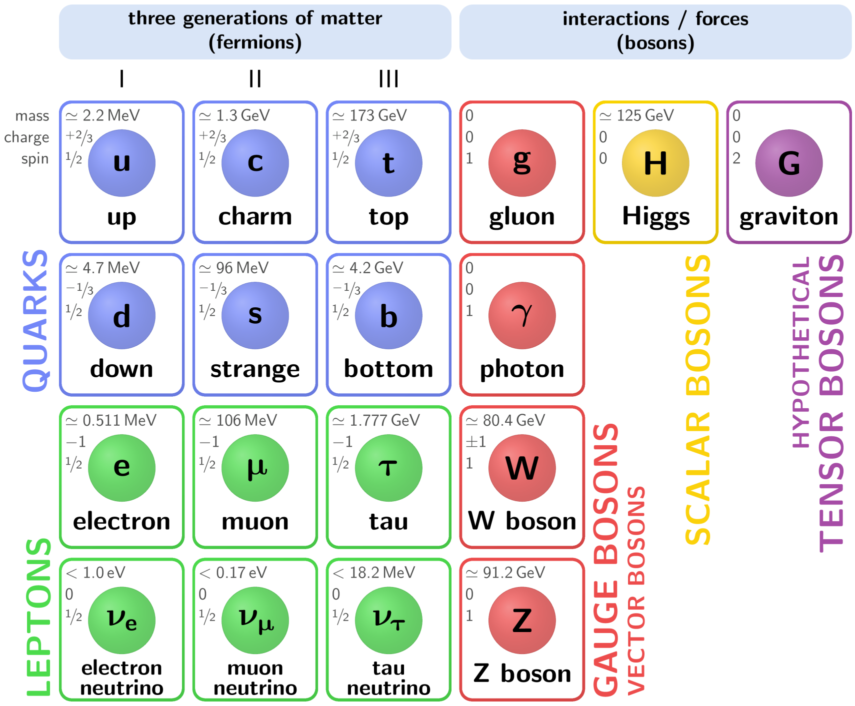

Figure 1: Standard Model.

The dileptonic final state is the main focus of this study. It produces two charged leptons, missing transverse momentum from neutrinos, and two b-jets. While this channel has a smaller branching ratio compared to the all-hadronic case, it offers a much cleaner signature with lower background contamination, making it particularly suitable for searches for new resonances in the 2HDM framework.

Searches for such signatures are performed using data from high-rate proton–proton collisions at the LHC. Only a tiny fraction of these events can be recorded, which makes a selective trigger system essential. Triggers are real-time decision algorithms that select potentially interesting events while rejecting the vast majority of uninformative ones. In the case of leptonic final states, both single-lepton and multi-lepton triggers are used. The efficiency of a trigger is defined as the fraction of signal events passing the trigger selection relative to the total number of signal events. Evaluating trigger efficiency is crucial, as it determines how much of the signal survives into the recorded dataset. In this work, we emulate such triggers at the truth level by applying transverse momentum cuts on leptons and study their effect on the dileptonic signal described above.

2 Background

The Large Hadron Collider (LHC) is the world's largest particle accelerator, built at CERN on the border of Switzerland and France. It is a 27-kilometer underground ring where beams of protons are accelerated close to the speed of light and then collided head-on. These collisions recreate conditions similar to the very early universe, allowing physicists to test fundamental theories and search for new phenomena. One of the most important outcomes of the LHC program was the 2012 discovery of the Higgs boson, which confirmed an essential piece of the Standard Model.

Around the LHC ring, there are four massive detectors designed to record what happens when particles collide: ATLAS, CMS, ALICE, and LHCb. ATLAS (A Toroidal LHC ApparatuS) is a general-purpose detector and also the largest of the four. CMS (Compact Muon Solenoid) is another general-purpose detector, similar in scope to ATLAS but with a different design philosophy. ALICE (A Large Ion Collider Experiment) is specialized for studying heavy-ion collisions and the properties of quark–gluon plasma. LHCb (Large Hadron Collider beauty experiment) is optimized for exploring rare decays and CP violation in beauty and charm quarks. Together, these experiments cover a broad range of physics goals at the LHC.

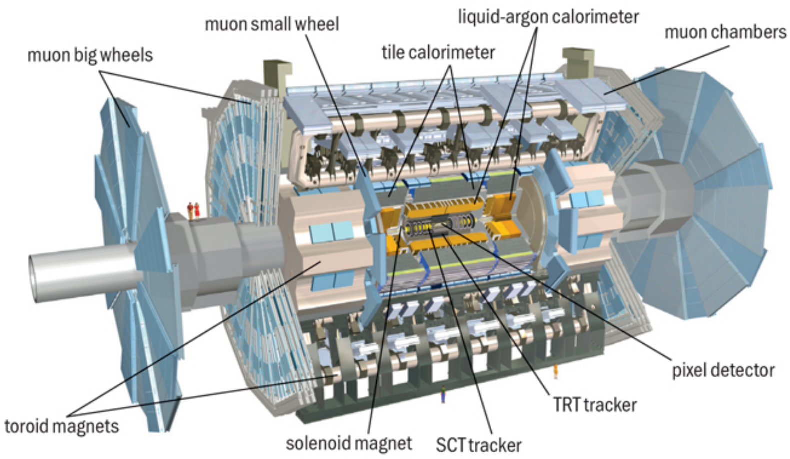

Figure 2: ATLAS Detector.

ATLAS is designed to capture as much information as possible from collisions, measuring the trajectories, energies, and identities of particles that fly out in every direction. It works like a giant 3D camera, made up of different layers of sub-detectors, each specialized for tracking or measuring certain types of particles. Thanks to its broad design, ATLAS can be used for many kinds of physics studies simultaneously—from precision tests of the Standard Model to searches for new physics such as supersymmetry, dark matter candidates, or extended Higgs sectors.

At the LHC, proton–proton collisions occur at a rate of billions per second, producing enormous numbers of particles inside ATLAS. Only a tiny fraction of these events contain signatures of rare or potentially new phenomena, while the overwhelming majority correspond to well-understood Standard Model processes. To handle this challenge, ATLAS employs a real-time decision system known as the trigger. The trigger reduces the event rate from billions per second to a manageable level by selecting only the most interesting events for storage and later analysis. It operates in two stages: a hardware-based first level that rapidly identifies coarse signatures such as energetic leptons or jets, and software-based levels that refine the selection using more detailed reconstruction.

Lepton triggers are especially important for analyses targeting leptonic final states, since high-momentum electrons and muons are rare in proton–proton collisions but often signal interesting physics. In this project, we emulate representative ATLAS trigger thresholds corresponding to the lowest un-prescaled paths: a single-electron trigger at 26 GeV, a single-muon trigger at 50 GeV, a dielectron trigger at 24 GeV, and a dimuon trigger at 14 GeV. Concretely, a statement such as "single-electron trigger at 26 GeV" means that we apply a cut at truth level requiring at least one electron with transverse momentum $p_T > 26$ GeV. Similarly, the dielectron and dimuon triggers require two leptons above the quoted p_T thresholds.

The performance of a trigger is usually quantified in terms of its *efficiency*, defined as the fraction of signal events passing the trigger relative to the total number of signal events generated. In addition to evaluating the efficiency of each trigger individually, it is often useful to consider *logical combinations* of triggers, such as requiring that an event passes either the single-electron *or* the dielectron trigger, or both muon triggers simultaneously. Studying such combinations allows us to maximize signal retention while keeping rates within manageable limits.

3 Materials and Methods

Monte Carlo Samples and Tools

The Monte Carlo signal samples used in this analysis were generated using `MadGraph5_aMC@NLO`, interfaced with `Pythia8` with the A14 tune. The UFO model used for the generation was the `2HDM_TypeI_EFF` model, available at `https://github.com/ycwu1030/2HDM_FR/tree/master/UFOs/Type-I/2HDM_CPC_Type-I_EFF_cba_UFO`

Several mass points were produced, corresponding to different values of m_{H^+} and m_A, allowing us to probe the trigger response across a broad parameter space.

It is important to emphasize that these are simulated samples at the truth level, not data recorded from ATLAS. Since our goal was to study trigger efficiencies in an unbiased way, we did not impose any pre-selection on the events beyond the truth-level kinematic requirements. This ensured that all generated events were included in the efficiency evaluation. List of all triggers used in the project is listed below in Table 1.

For the analysis, we relied on two main tools. `pyROOT` provided a structured way to access the simulation files, apply trigger emulation by imposing p_T cuts on leptons, and compute efficiencies. Python complemented this framework by automating the event loop, handling large-scale processing, and producing custom visualizations such as heatmaps of efficiency across different mass ranges. The combined use of these tools enabled us to efficiently study lepton trigger performance over the simulated parameter space.

	Name of the trigger
1	HLT$_{e}26_{l}htight_{i}varloose_{L}1eEM26M$
2	HLT$_{e}20_{l}htight_{i}varloose_{L}1ZAFB-25DPHI-eEM18M$
3	HLT$_{e}140_{l}hloose_{L}1eEM26M$
4	HLT$_{2}e17_{l}hvloose_{L}12eEM18M$
5	HLT$_{2}e24_{l}hvloose_{L}12eEM24L$
7	HLT$_{e}26_{l}htight_{e}14_{i}dperf_{t}ight_{p}robe_{5}0invmAB130_{L}1eEM26M$
8	HLT$_{m}u24_{i}varmedium_{L}1MU14FCH$
9	HLT$_{m}u50_{L}1MU14FCH$
10	HLT$_{m}u60_{0}eta105_{m}sonly_{L}1MU14FCH$
11	HLT$_{2}mu14_{L}12MU8F$
12	HLT$_{m}u20_{i}varmedium_{m}u8noL1_{L}1MU14FCH$
13	HLT$_{2}mu10_{l}2mt_{L}1MU10BOM$
14	HLT$_{e}7_{l}hmedium_{L}1eEM5_{m}u24_{L}1MU14FCH$
15	HLT$_{e}17_{l}hloose_{m}u14_{L}1eEM18L_{M}U8F$
16	HLT$_{e}26_{l}hmedium_{m}u8noL1_{L}1eEM26M$

Table 1: All triggers that were used in this project

Analysis Procedure

The analysis of the Monte Carlo simulation data was carried out step by step:

1. Lepton selection cuts. For each event, transverse momentum (p_T) thresholds were applied to electrons and muons. These cuts determine which leptons are kept for the next steps. The goal was to isolate the most relevant events for studying the triggers.

2. Calculating trigger efficiencies. After selecting the leptons, we evaluated the efficiency of different triggers. In this context, the efficiency was defined as the ratio of the number of events that passed a given p_T cut to the total number of generated events.

3. Trigger combinations. We applied a logical OR of the different emulated triggers. This allowed us to assess how efficiently events would be selected if multiple trigger requirements were considered together.

In short, our workflow followed a simple pattern: load and prepare the data, apply selection cuts, evaluate efficiencies for different triggers or their logical combinations, and then compare the results across the simulated mass points.

4 Results

The efficiency of the emulated lepton triggers was evaluated across all simulated mass points. For the single-electron trigger with $p_T > 24$ GeV, the efficiency ranges from 14.95% at the lowest mass point (300/200 GeV) to 20.39% at the highest studied mass point (700/400 GeV), showing a steady increase with heavier Higgs mass.

For the dilepton triggers, including the dielectron selection ($p_T > 24$ GeV) and dimuon selection ($p_T > 14$ GeV), the efficiency ranges from 36.51% at the smallest mass point (300/200 GeV) to 43.53% at the mass point (700/400 GeV). This reflects the larger transverse momentum of leptons produced in heavier resonance decays.

Combining all triggers using a logical OR—accepting events if any of the single- or dilepton thresholds is satisfied—produces the most inclusive selection. The efficiency of this OR combination ranges from 87.10% at the smallest mass point (300/200 GeV) to 97.76% at the mass point (700/300 GeV), demonstrating that broad, inclusive lepton triggers are particularly effective for capturing high-mass events.

The heatmap of trigger efficiencies for this OR combination is shown in Figure 3, and the corresponding maximum efficiencies for each mass point are listed in Table 2. On the vertical axis of the heatmap, the heavy scalar mass H is represented, while the horizontal axis corresponds to the pseudoscalar mass A. color scale, ranging from blue (low efficiency) to yellow (high efficiency), is displayed on the right side of the figure, covering values between 0 and 1. This heatmap provides a concise overview of the trigger performance across the parameter space of interest. It shows that the chosen trigger strategy is highly efficient, ensuring that a substantial portion of signal events is retained, with especially strong performance at higher mass scales.

5 Conclusion

The main goal of this work was to study the efficiency of different trigger selections using simulated Monte Carlo data. The results show a clear dependence on both mass and trigger choice: efficiencies rise with higher mass points and vary strongly across trigger strategies.

A single muon trigger alone proves insufficient, as it discards too many events. However, when combined with other options—such as dielectron or dimuon triggers, or higher-threshold single-lepton cuts—the efficiency increases substantially. The combined selection, which incorporates several trigger paths, achieves the most reliable performance, approaching full efficiency in many regions.

This highlights the central role of trigger design in high-energy physics experiments. An effective trigger strategy ensures that signal valuable events are preserved while keeping

Mass (A/H)	Max efficiency (in %)
300/200	87.10
400/200	93.59
500/200	95.94
600/200	96.98
700/200	97.66
400/250	92.42
500/250	95.63
600/250	96.94
700/250	97.60
400/300	90.30
500/300	95.16
600/300	96.91
700/300	97.76
500/350	94.36
600/350	96.61
700/350	97.68
500/400	92.89
600/400	96.47
700/400	97.71
600/450	95.73
700/450	97.54

Table 2: Summary of trigger efficiencies for selected inclusive cut: any electron > 26 GeV OR any muon > 50 GeV OR any dielectron > 24 GeV OR any dimuon > 14 GeV..

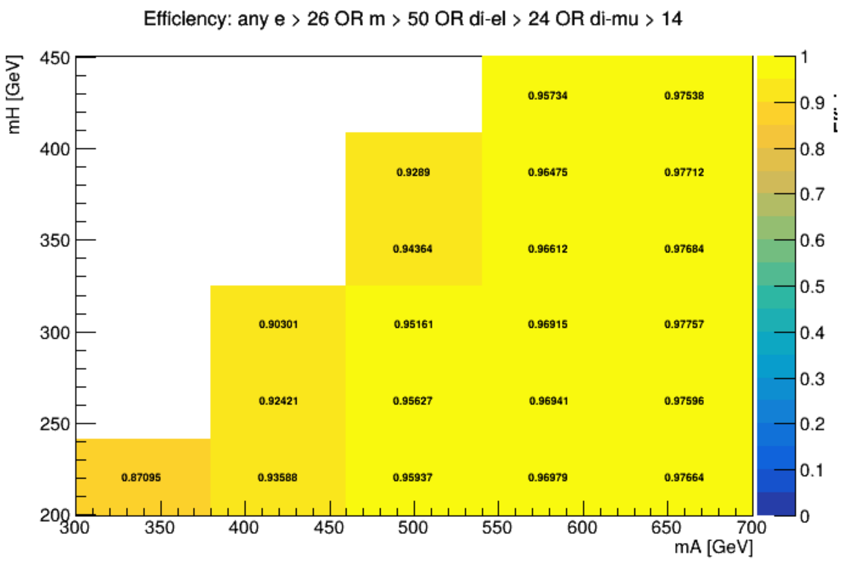

Figure 3: Trigger Efficiency: any electron > 26 GeV OR any muon > 50 GeV OR any dielectron > 24 GeV OR any dimuon > 14 GeV.

the recorded data manageable, ultimately making the difference between incomplete and

meaningful physics analyses.

I would also like to express my gratitude to Roshan Joshi for his valuable guidance and support throughout this project.

References

[1] D. Griffiths, *Introduction to Elementary Particles*, 2nd Edition, Wiley, 2008.

[2] M. Thomson, *Modern Particle Physics*, Cambridge University Press, 2013.

[3] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008) S08003.

A Example Code Snippets

Example of the pyROOT code

```
import ROOT
# Pass if: any single electron > 20 OR both muons > 26
files = [
    "523805.root", "523806.root", "523807.root", "523808.root", "523809.root",
    "523810.root", "523811.root", "523812.root", "523813.root", "523814.root",
    "523815.root", "523816.root", "523817.root", "523818.root", "523819.root",
    "523820.root", "523821.root", "523822.root", "523823.root", "523824.root",
    "523825.root"
]
tree_name = "analysis"
for file_name in files:
    df = ROOT.RDataFrame(tree_name, file_name)
    total_events = df.Count().GetValue()
 # Pass if: any single electron > 20 OR both muons > 26
    df_cut = df.Filter(
        "( (el_1_pt.size() > 0 && el_1_pt[0] > 20.0) "
        "|| (el_2_pt.size() > 0 && el_2_pt[0] > 20.0) )"
        " || "
        "( (mu_1_pt.size() > 0 && mu_2_pt.size() > 0) "
        "&& (mu_1_pt[0] > 26.0) && (mu_2_pt[0] > 26.0) )"
    )
    passed_events = df_cut.Count().GetValue()
    efficiency = passed_events / total_events if total_events > 0 else 0.0
    print(f"{file_name}: Efficiency={efficiency:.4f}")
```