Study of Expected Sensitivities for $t\bar{t}H$, tbH^+ and Leptoquark Production with Run-3 and HL-LHC in the 2lSS1tau Channel – Summer Student Project

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Abstract

Higher luminosity data at the LHC can significantly enhance the sensitivity of already discovered particles and also have the potential for discovering new particles or interactions. This study evaluates the expected sensitivity at higher luminosities for the production measurement of $t\bar{t}H$, tbH^+ and Leptoquarks decaying into two same-sign light leptons and one hadronically decaying tau. This analysis uses the statistical and systematic uncertainties from several analyses and scales the values to obtain expected uncertainty values for higher luminosity data. An additional study is also performed to validate the applied scaling formula.

1 Introduction

This project addresses measuring the $t\bar{t}H$ process, and the search for tbH^+ and Leptoquark reactions. The 2lSS1tau final state, two leptons of the same electric charge and one hadronically decaying tau is a well-established channel that is used for measurements and searches. This channel has proven in the past to provide excellent sensitivity.

This project reviews the current state of the art of these three analyses and illustrates the developments of statistical and systematic uncertainties of various research results. Using the existing research results, extrapolations of the predicted statistical uncertainties are made from LHC Run-2 luminosities, to LHC Run-3 luminosities and to HL-LHC luminosities.

Currently, LHC Run-2 analyses are based on about 140 fb^{-1}. For the predictions, a total of 300 fb^{-1} is assumed for LHC Run-3, and a total of 3000 fb^{-1} for HL-LHC.

1.1 Processes of Interest

There are three processes of interest $t\bar{t}H$, tbH^+, and Leptoquark pair production. Their characteristic signature is very similar in the 2lSS1tau final state. Therefore, in practice, these three analyses have recently been studied in different thesis projects, $t\bar{t}H$ [1], tbH^+ [2], and Leptoquarks [3] using the same simulated background reactions. These analyses' results are used to extrapolate higher luminosities regarding the statistical uncertainties. For the $t\bar{t}H$ analyses, the Standard Model Higgs boson mass of 125 GeV is assumed, while for the tbH^+ and Leptoquark searches, different masses are studied.

1.1.1 $t\bar{t}H$

The top quark is the heaviest elementary particle. The measurement of its interactions with the other particles of the Standard Model is an important objective of modern particle physics. The production of a top-antitop pair and a Higgs boson from two gluons in a proton-proton collision is a process known as $t\bar{t}H$. The final state of this process which this study focuses on is the 2lSS1tau while also considering analyses that consider a combination of multileptonic final states. The sensitivities of the following analyses are considered:

- ATLAS-CONF-2019-045. Analysis of $t\bar{t}H$ and $t\bar{t}W$ production in multilepton final states with the ATLAS detector [4].
- Phys Rev D 97 (2018) 072003. Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector [5].
- Eur Phys J. C 81 (2021) 378. Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt{s} = 13$ TeV [6].
- Vladyslav Yazykov (2023). Optimization of the $t\bar{t}H$ Selection Including Systematics Using Machine Learning with ATLAS Data [1].

1.1.2 tbH^+

A hypothetical elementary particle, the charged Higgs boson, is predicted by some extensions of the Standard Model (SM). If the charged Higgs boson exists, the Large Hadron Collider (LHC) should also be able to produce it. A process that indicates the presence of a charged Higgs boson involves the production of a charged Higgs boson paired with a top quark and bottom quark from a proton-proton collision in the LHC. Due to the different decay modes of the top quark and the charged Higgs boson, there are several final states in which this interaction can be observed. While focusing on the 2lSS1tau final state, this study will also consider combined multileptonic final states. The sensitivities of the following analyses are considered:

- JHEP11(2018)085. Search for charged Higgs bosons decaying into top and bottom quarks at $\sqrt{s} = 13$ TeV with the ATLAS detector [7].
- JHEP06(2022)145. Search for charged Higgs bosons decaying into a top quark and a bottom quark at $\sqrt{s} = 13$ TeV with the ATLAS detector [8].
- Martin Rameš (2023). Search for the tbH^+ with Performance Optimization for Signal and Background Separation using Machine Learning with ATLAS data [2].

1.1.3 Leptoquarks

Leptoquarks are hypothetical particles proposed beyond the Standard Model. They combine the properties of both leptons and quarks. They are supposed to be color triplet bosons with fractional charges that interact with quarks and leptons [9].

The sensitivities of the following analyses are considered:

- JHEP 06 (2021) 179. Search for pair production of third-generation scalar Leptoquarks decaying into a top quark and a τ-lepton in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector [10].
- Janick Böhm (2023). Optimization of Machine Learning for the Leptoquark Search using CERN ATLAS Data: A thesis on the search for Leptoquarks with 140.0 fb^{-1} [3].

2 Systematic versus Statistical Uncertainties Comparison

2.1 $t\bar{t}H$

As shown in Figure 1, the uncertainty values from combined final states generally have lower uncertainty than the values from the 2lSS1tau final state. The statistical and systematical uncertainties have about equal contribution to the total uncertainty in the combined final state. The statistical uncertainties are much larger than the systematic uncertainties for all analyses with low luminosity (i.e. 36.1 fb^{-1} and 79.9 fb^{-1}).

2.2 tbH^+

A general trend from the $tbH^+(tbtb)$, [8] and [7], analyses suggests that higher masses have less uncertainty (statistical and systematic). The higher luminosity analysis at 139.0 fb^{-1} [8] does have a marginally lower uncertainty than [7] which is based on a luminosity of 36.1 fb^{-1}. Although systematics is much larger than statistical uncertainties for all masses and luminosities, the difference between systematics and statistics is much less at higher mass (800 GeV) than at lower mass (200 GeV), as shown in Figure 2.

For the $tbH^+(H^+ \rightarrow WH, H \rightarrow \tau\tau)$ analysis, [2], Figure 3 and 4[1] show that there is no clear trend on the sensitivity to masses as given in the thesis [2]. The updates of this analysis

[1] The difference between Figure 3 and Figure 4 is the version of the signal simulation.

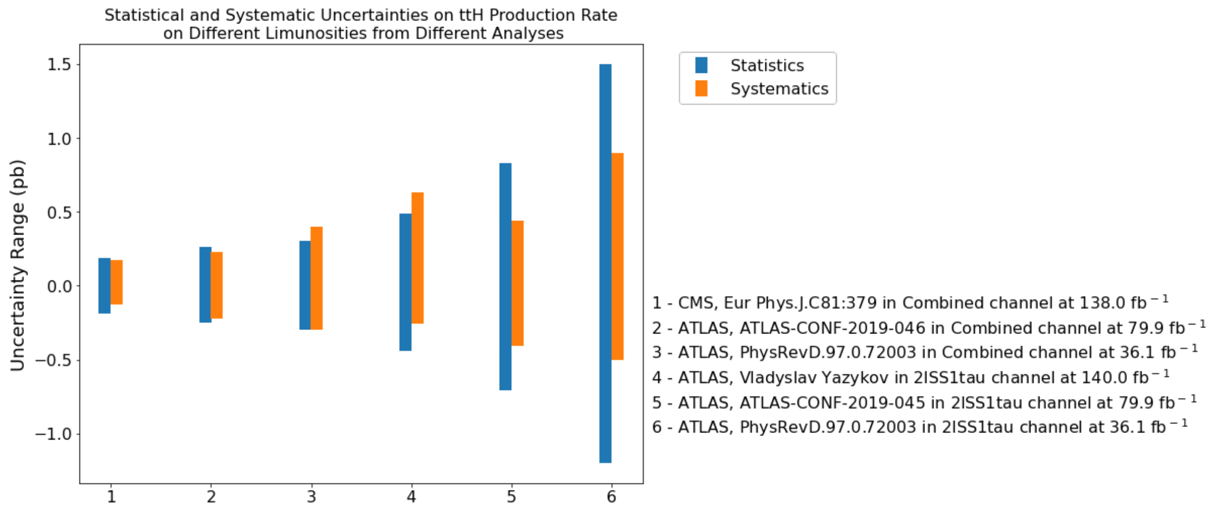

Figure 1: Comparison of systematic and statistical uncertainties from different $t\bar{t}H$ analyses. The first three analyses use a set of final states and combine the uncertainties of each channel to obtain the given uncertainties. The last three analyses only focus on the 2lSS1tau channel.

including systematics given in the internal note [11] indicate statistical uncertainties dominate the systematic uncertainties.

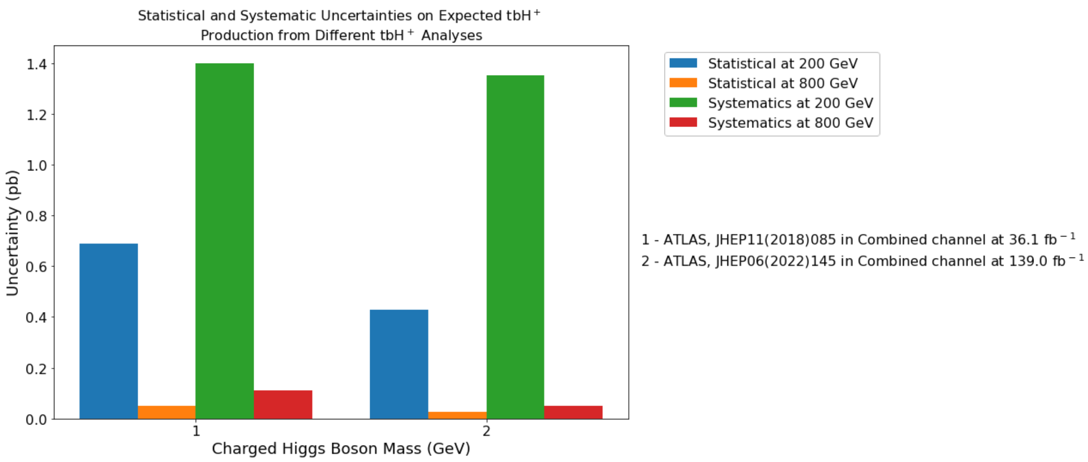

Figure 2: Systematic versus statistical uncertainties from $tbH^+(tbtb)$ analyses. Both analyses consider a combined multileptonic final state.

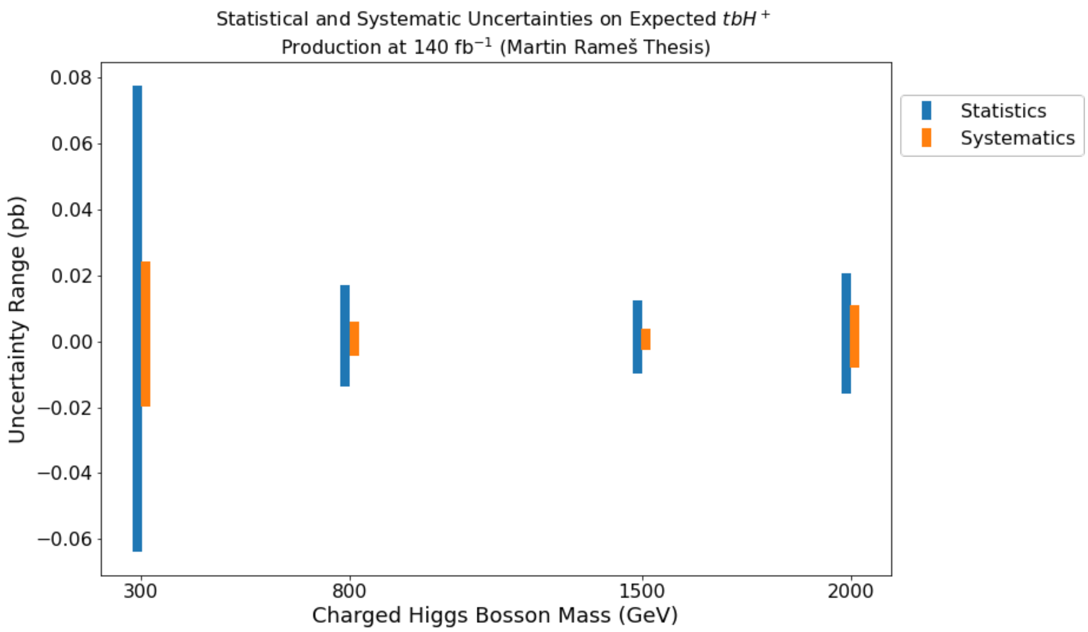

Figure 3: Systematic versus statistical uncertainties from [2] and the update including systematics given in the internal note [11].

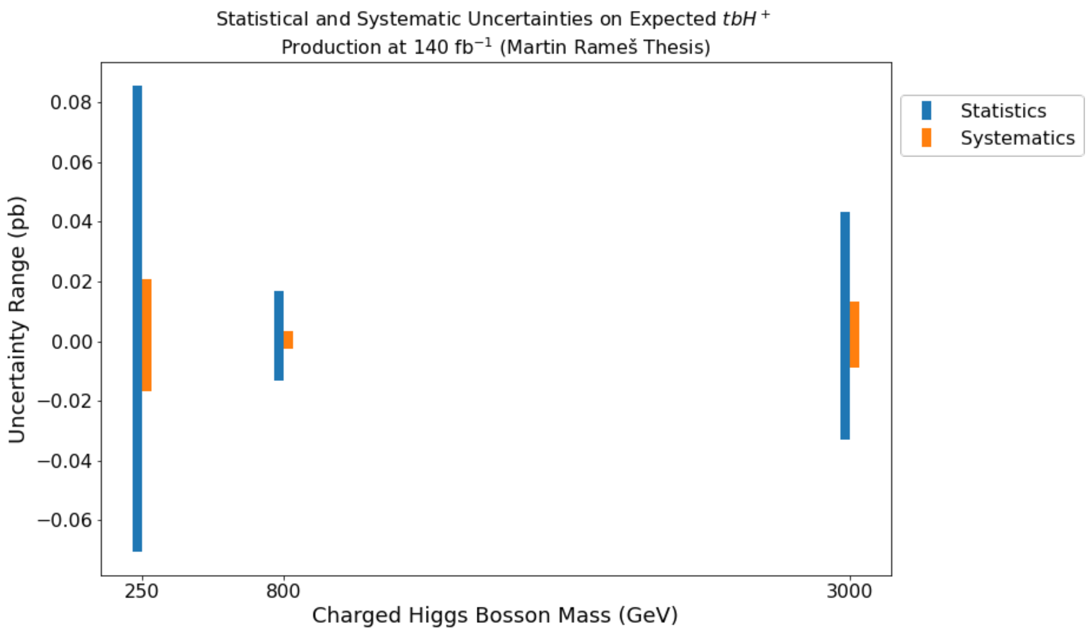

Figure 4: Systematic versus statistical uncertainties from [2] and the update including systematics given in the internal note [11].

2.3 Leptoquarks

The Leptoquark analyses ($t\tau t\tau$) discussed here have an opposite trend of uncertainty values to the particle mass. The ATLAS collaboration analysis (Figure 5) shows that the systematic uncertainties are larger than the statistical uncertainties at lower masses, however, for higher masses the statistical uncertainties become dominant, specifically for masses larger than 1100 GeV. Moreover, both the systematic and statistical uncertainties are increasing with mass. The uncertainties from [3] (Figure 6) clearly show that statistical uncertainties are more dominant than the systematics.

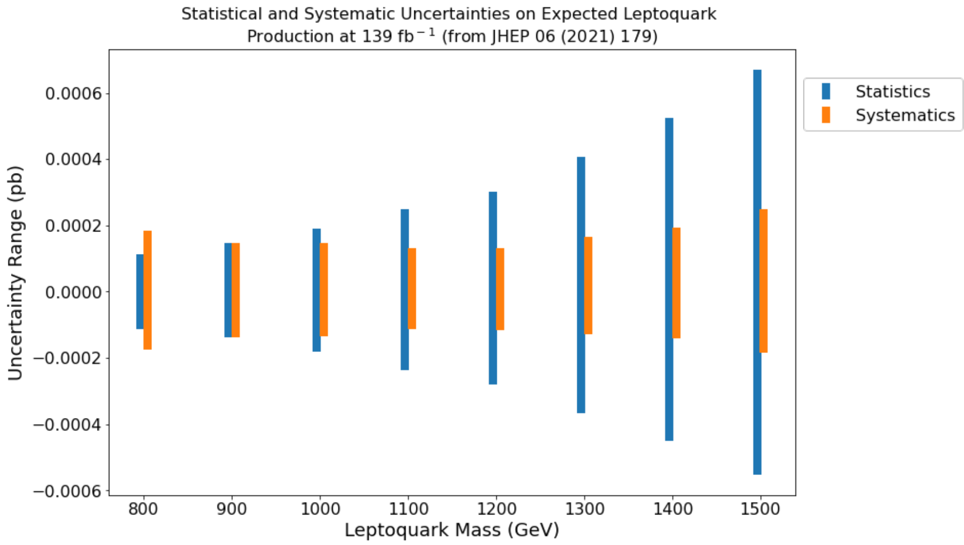

Figure 5: Systematic versus statistical uncertainties on expected Leptoquark production sensitivity. [10] evaluates the uncertainties for the given mass on the expected upper limits. It also considers a multileptonic final state.

Contrary to the general trend of the ATLAS collaboration analysis shown in Figure 5, the bachelor's thesis by Janick Böhm concludes that as the masses increase the statistical uncertainty decreases, as shown in Figure 6.

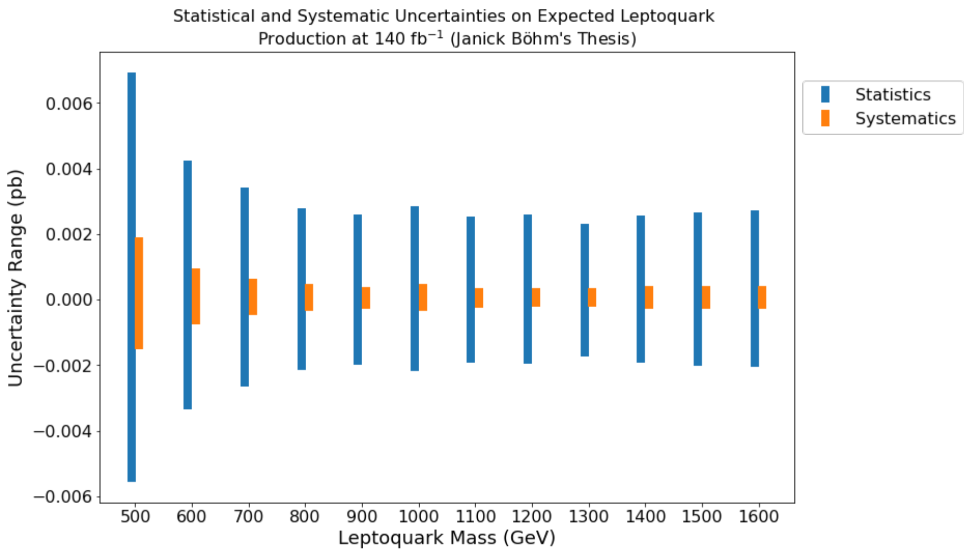

Figure 6: Systematic versus statistical uncertainties on expected Leptoquark sensitivities. The uncertainties of this thesis are given for the respective Leptoquark masses on the expected upper limits for the 2lSS1tau channel [3], and the update detailed in the internal note [11].

3 Higher Luminosity Statistical Uncertainty

This section will briefly discuss the formula used to calculate the statistical uncertainty at higher luminosities. Furthermore, the expected values of the statistical uncertainties of all the analyses will be discussed for every process of interest.

3.1 Formula for Obtaining High Luminosity Statistical Uncertainty

Scaling the number of events, for both the signal and background, gives the expected yield at a specific luminosity. This scaling can be approximated using the luminosity on which the analysis is based and a new luminosity (a luminosity we want to scale the analysis to). Hence, to obtain the statistical uncertainty at higher luminosity the following formula is used:

$$\texttt{new uncertainty} = \texttt{old uncertainty} \times \sqrt{\frac{\texttt{old luminosity}}{\texttt{new luminosity}}} \tag{1}$$

To evaluate the accuracy of the approximation (1), the uncertainty from Vladyslav Yazykov's thesis [1] is computed again at a higher luminosity of 300 fb^{-1} and 3000 fb^{-1} The results align very closely with the result found from applying the approximation (1) on the same analysis (detailed in the internal note [11]).

3.2 $t\bar{t}H$

Figure 7 shows all analyses that consider combined channels have almost the same statistical uncertainty at 300 fb^{-1} and 3000 fb^{-1} regardless of the original luminosity they are scaled from. Similarly, the analyses in the 2lSS1tau channel also show that with higher luminosities, the value of the statistical uncertainty is similar.

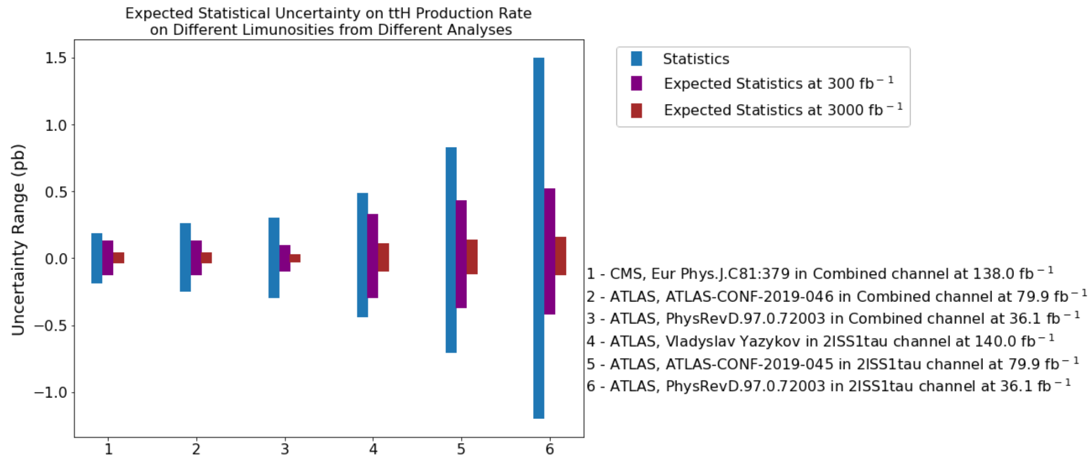

Figure 7: Statistical uncertainty on $t\bar{t}H$ production rate on original luminosity the analyses are based on, and the expected statistical uncertainty at 300 fb^{-1} and 3000 fb^{-1} obtained using equation (1).

3.3 tbH^+

Comparing the two analyses, [8] and [7], for tbH^+, [7] achieves a slightly lower statistical uncertainty at higher luminosity for all masses. Nevertheless, the expected statistical uncertainty is similar for both 300 fb^{-1} and 3000 fb^{-1}, as shown in Figure 8. Additionally, [2] achieves higher sensitivities at higher luminosities of 300 fb^{-1} and 3000 fb^{-1}, as shown in Figures 9 and 10.

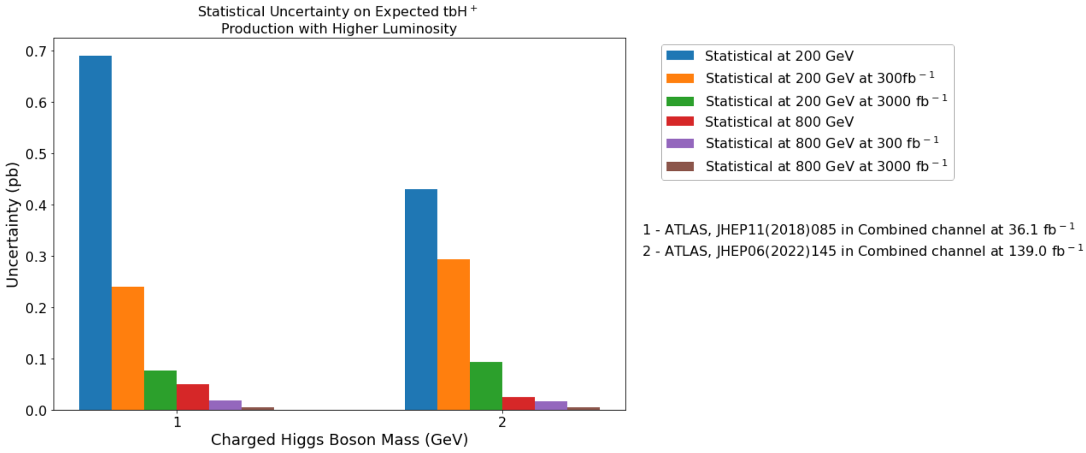

Figure 8: Statistical uncertainty on expected $tbH^+(tbtb)$ production rate from [7] and [8], and the extrapolations for the expected statistical uncertainties at 300 fb^{-1} and 3000 fb^{-1} obtained using equation (1).

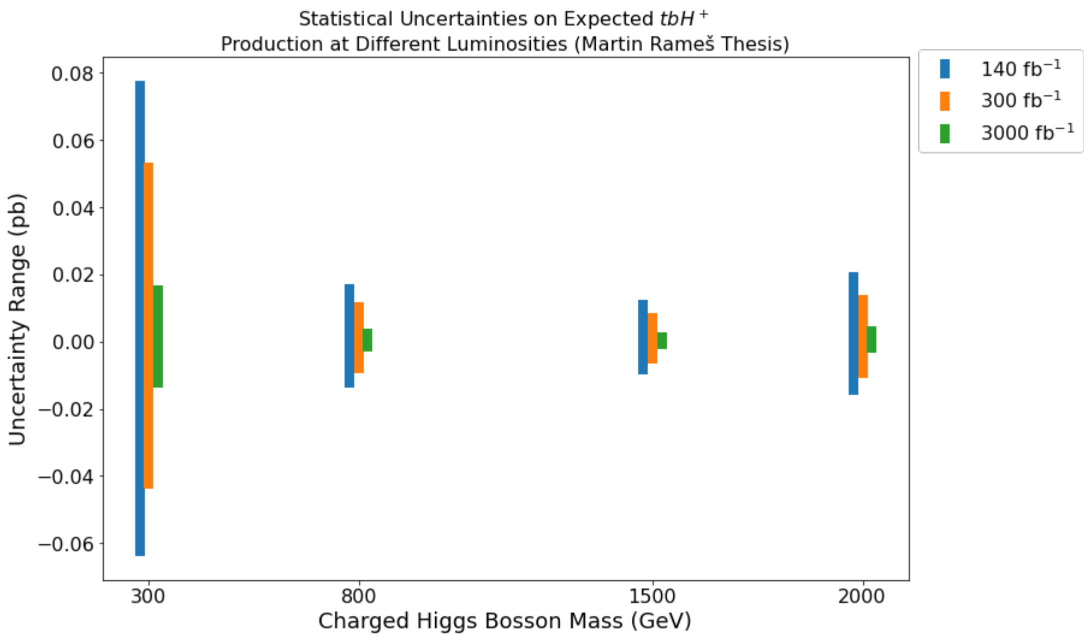

Figure 9: Statistical uncertainty on expected tbH^+ production rate from [2], and the update detailed in the internal note [11]. The expected statistical uncertainties at 300 fb^{-1} and 3000 fb^{-1} are obtained using equation (1).

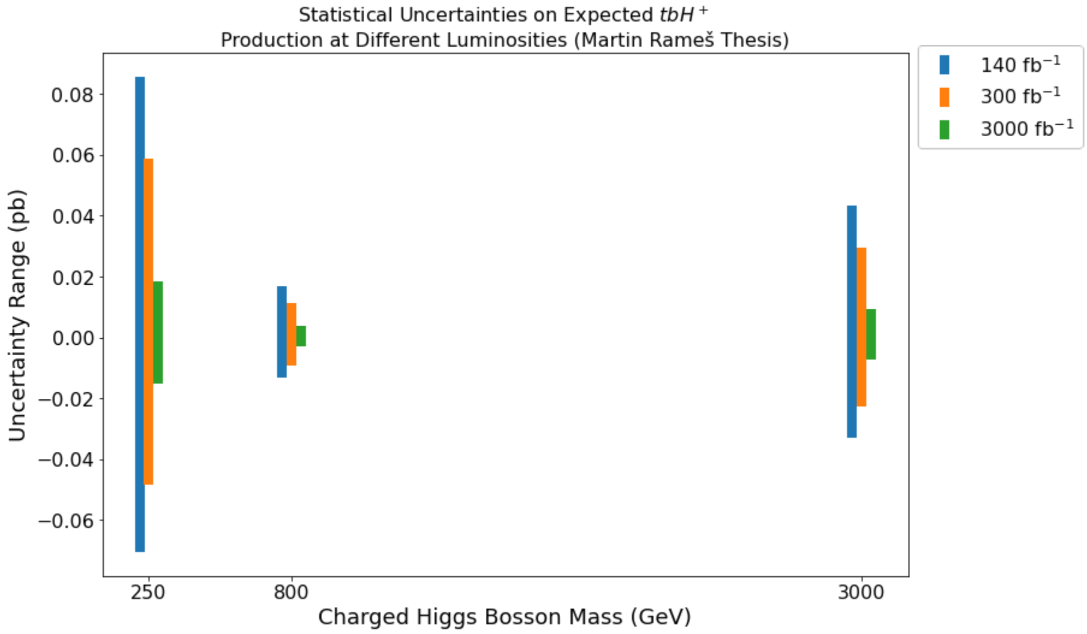

Figure 10: Statistical uncertainty on expected tbH^+ production rate from [2], and the update detailed in the internal note [11] . The expected statistical uncertainties at 300 fb^{-1} and 3000 fb^{-1} are obtained using equation (1).

3.4 Leptoquarks

Figures 11 and 12 show the uncertainties in the analyses, [10] and [3], for higher luminosities of 300 fb^{-1} and 3000 fb^{-1}. As the trend of the statistical uncertainty of those two analyses is very different, it is difficult to compare their statistical uncertainties for higher luminosities but a higher sensitivity can be obtained for some Leptoquark masses by increasing the luminosity.

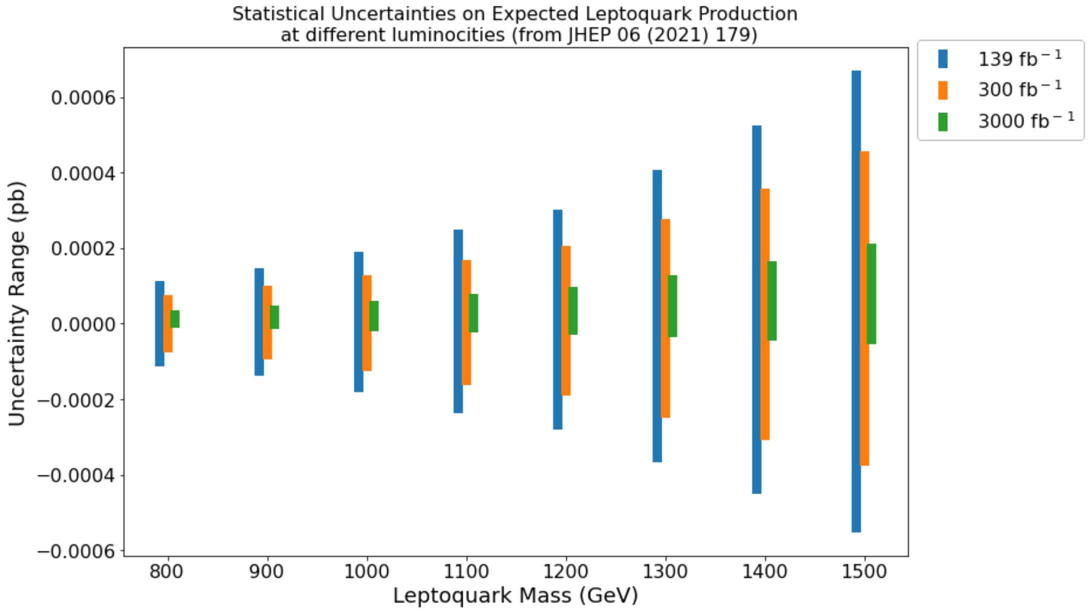

Figure 11: Statistical uncertainty on expected Leptoquarks production rate on original luminosity from [10]. The expected statistical uncertainties at 300 fb^{-1} and 3000 fb^{-1} are obtained using equation (1).

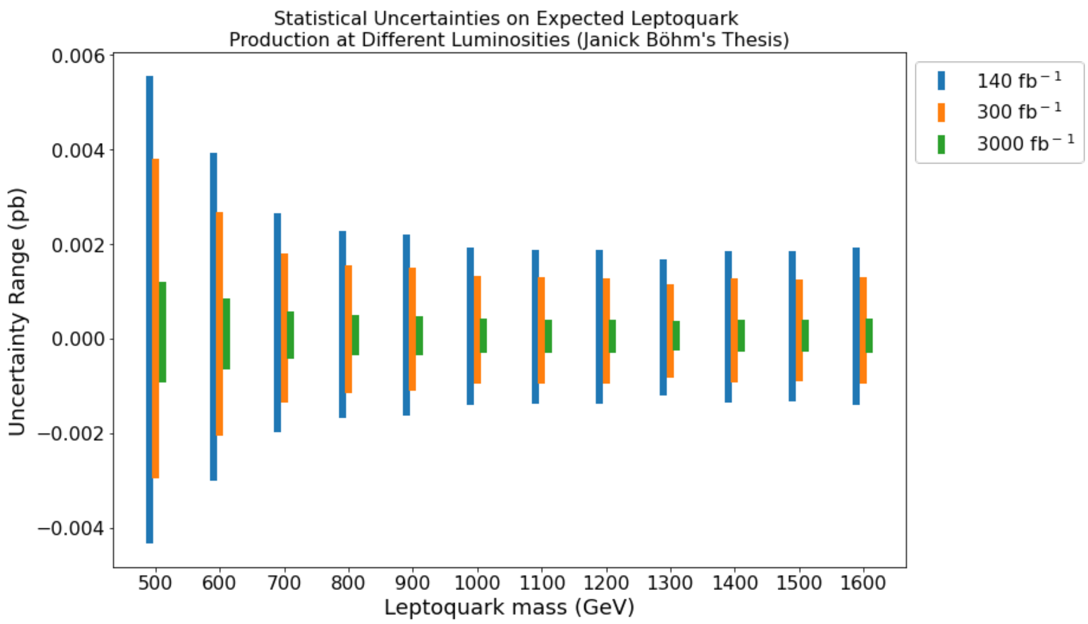

Figure 12: Statistical uncertainty on expected Leptoquark production rate from [3], and the update detailed in the internal note [11]. The expected statistical uncertainties at 300 fb^{-1} and 3000 fb^{-1} are obtained using equation (1).

4 Summary

This study shows how much smaller the statistical uncertainty will become with higher luminosity. The impact on the overall uncertainty depends on how much the statistical uncertainty contributes compared to the systematic uncertainty. In the $t\bar{t}H$ analyses, where the statistical uncertainty is dominant in all of the analyses presented here, higher luminosity would very much improve the sensitivity of those analyses. However, it has to be noted that on a combined channels scheme, the statistical and systematic have an equal contribution to the overall uncertainty hence a more significant improvement would be expected in the analyses that focus on the 2lSS1tau channel.

The uncertainties for $tbH^+(tbtb)$ in this study are based on the respective upper limit given in their respective analyses. For those respective upper limits, it is observed that the systematic uncertainties dominate the overall uncertainties of almost all analyses, which evaluate both statistical and systematic uncertainties. Although higher luminosity would lower the statistical uncertainty, improving the systematic uncertainties is more important to increase the sensitivity of those analyses. For the $tbH^+(WH, H \to \tau\tau)$ analysis [11], statistical uncertainties are dominant, and higher luminosities significantly improve the sensitivity.

As Figure 5 shows, for the analysis [10] while higher masses of Leptoquarks are dominated by statistical uncertainty, lower masses (<900 GeV) are dominated by systematic uncertainty. From this observation, for the upper limits given in the internal note [11], higher luminosity would greatly benefit the sensitivity for higher Leptoquark masses (>900 GeV) and additional improvement in systematic uncertainty would affect the sensitivity of low Leptoquarks mass (<900 Gev).

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References

[1] Vladyslav Yazykov. “Optimization of the ttH Selection Including Systematics Using Machine Learning with ATLAS Data”. Presented 05 Sep 2023. Prague, Tech. U., 2023. URL: https://cds.cern.ch/record/2871484.

[2] Martin Rames. “Search for tbH$^+(\tau\tau)$ with Performance Optimization for Signal and Background Separation Using Machine Learning with ATLAS Data”. Presented 14 Jun 2023. 2023. URL: https://cds.cern.ch/record/2862250.

[3] Janick Böhm. “Optimization of Machine Learning for the Leptoquark Search using CERN ATLAS. Data”. Presented 21 Jun 2023. URL: https://cds.cern.ch/record/2863280.

[4] ATLAS Collaboration. “Analysis of $t\bar{t}H$ and $t\bar{t}W$ production in multilepton final states with the ATLAS detector”. ATLAS-CONF-2019-045. Geneva, 2019. URL: https://cds.cern.ch/record/2693930.

[5] ATLAS Collaboration. “Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector”. Apr. 2018. DOI: 10.1103/PhysRevD.97.072003. URL: https://link.aps.org/doi/10.1103/PhysRevD.97.072003.

[6] CMS Collaboration. “Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt{s} = 13$ TeV”. *Eur. Phys. J. C* 81 (2021), p. 378. DOI: 10.1140/epjc/s10052-021-09014-x. URL: https://cds.cern.ch/record/2743741.

[7] ATLAS Collaboration. “Search for charged Higgs bosons decaying into top and bottom quarks at $\sqrt{s}$=13 TeV with the ATLAS detector”. *JHEP* 11 (2018), p. 85. DOI: 10.1007/jhep11(2018)085. URL: https://doi.org/10.1007%2Fjhep11%282018%29085.

[8] ATLAS Collaboration. “Search for charged Higgs bosons decaying into a top quark and a bottom quark at $\sqrt{\mathrm{s}} = 13$ TeV with the ATLAS detector”. *JHEP* 06 (2021), p. 145. DOI: 10.1007/JHEP06(2021)145. URL: https://cds.cern.ch/record/2752605.

[9] Lukas Vicenik. “Machine Learning for the Leptoquark Search Using CERN ATLAS Data”. Presented 14 Jun 2022. 2022. URL: https://cds.cern.ch/record/2812370.

[10] ATLAS Collaboration. “Search for pair production of third-generation scalar leptoquarks decaying into a top quark and a τ-lepton in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”. *JHEP* 06 (2021), p. 179. DOI: 10.1007/JHEP06(2021)179. URL: https://cds.cern.ch/record/2750498.

[11] Yaphet Elias Weldegebriel and André Sopczak. “Study of Expected Sensitivities for $t\bar{t}H$, tbH^+ and Leptoquark Production with Run-3 and HL-LHC in the 2lSS1tau Channel – Summer Student Project”. ATL-COM-PHYS-2023-1127. Geneva, 2023. URL: https://cds.cern.ch/record/2884768.