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Ross Hunter

High-Precision W-Boson Studies with LHCb

Measurements of the W Boson's Mass and Lepton Flavour Universality, and Trigger Development for the LHCb Upgrade

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Ross Hunter

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Measurements of the W Boson's Mass and Lepton Flavour Universality, and Trigger Development for the LHCb Upgrade

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Someone once told me that time was a predator that stalked us all our lives. But I rather believe that time is a companion who goes with us on the journey—reminds us to cherish every moment, because they'll never come again.

What we leave behind is not as important as how we've lived.

After all, Number One, we're only mortal.

—Captain Jean-Luc Picard

Supervisor's Foreword

Ross' Ph.D. project was on precision electroweak studies with the LHCb experiment and the real-time analysis system of the experiment. In his first year, Ross developed a method to calibrate muon tracking, identification and trigger efficiencies with a combination of Z boson and Quarkonium decays. This would become a critical ingredient in the first measurement of the W boson mass with the LHCb experiment, reported in JHEP 01 (2022) 036. Ross is a primary author of that analysis. During his second year, Ross was based at CERN and developed a new framework for measuring the performance of signal selections in the real-time analysis system for the LHCb upgrade. Ross presented this at the high-profile CHEP conference (EPJ Web Conf., 251 (2021) 04024), and the tool has now been used by several hundred members of the experiment. During Ross' second year, he made a major contribution to the review of two possible technologies for the first stage of the High-Level Trigger of the experiment. In Ross' third year, he focused on finalizing the W boson mass measurement. He was fully responsible for the design, implementation and validation of the efficiency corrections. His sharp attention to detail was crucial in realizing such a precise and challenging measurement. Ross was one of the first people to present the result in public, at a seminar in Warwick. As expected, he demonstrated a solid understanding of the wider context of the analysis and the details of the methodology, being able to confidently answer all questions. Soon after this, Ross presented the results at the very high-profile EPS conference. During his fourth year, Ross moved his attention to a test of lepton universality with W boson decays, which was an analysis that he had been developing over the previous two years. This is a challenging analysis, but Ross was able to bring it close to completion before the submission of his thesis.

The work presented in this thesis makes a significant impact on the program of electroweak physics at the LHC, and on the commissioning of the real-time analysis system of the upgraded LHCb experiment. Measurements of the W boson mass, and related parameters, by the LHCb experiment are now seen as being essential in realizing the full physics potential of the LHC machine in this area. With the upgraded LHCb experiment now being commissioned, the impact Ross' software developments had in making this process clearer and more efficient for the experiment is clear.

Coventry, UK
August 2023

Dr. Mika Vesterinen

Abstract

In the electroweak sector of the Standard Model (SM), comparing precise measurements with predictions built on the SM's assumptions offers one of the principal avenues for indirect discoveries of new physics. The W boson mass, m_W, is a key SM parameter that is notoriously difficult to measure at hadron colliders, and the lack of high-precision measurements of it limits the sector's discovery power. Meanwhile, the SM's fundamental property of lepton flavour universality (LFU) has been questioned by hints of discrepancy in recent measurements of rare B-meson decays and legacy tests of W-boson decays. This thesis presents two measurements using LHCb's 2016 data that address these important issues: first, a proof-of-principle extraction of m_W that paves the way for a competitive legacy measurement; and second, a test of the W boson's LFU in decays to tau leptons and muons that, when completed, will validate and complement other recent measurements shedding light on previous LFU anomalies.

The value of m_W was measured to be

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV},$$

which is consistent with previous direct measurements and indirect SM predictions. It is not consistent with the very recent CDF measurement, and therefore places LHCb in a prime position to address this high-profile disagreement with a future measurement using all available data.

LHCb is currently undergoing commissioning for a fresh period of data-taking, which features a brand-new detector, a factor of five more collisions and a fully redesigned trigger system. The development of the trigger validation tool `HltEfficiencyChecker` is also presented, which plays a crucial role in facilitating trigger optimization that fully exploits the new detector, whilst also conforming to its constraints. This tool helped the collaboration decide that the new first-level trigger should be implemented with GPUs, and is now widely used in LHCb, as exemplified in the development of trigger selections for electroweak processes in Run 3 presented here.

Acknowledgements

Like any Ph.D., completing this one has certainly been a journey, and I am grateful for the help of many along the way. It's not often one is allowed to acknowledge all this help, so I hope the reader will allow me a brief indulgence.

Firstly, I'm grateful to Mark Hadley for the style template of this thesis. I'd like to thank my supervisor, Mika Vesterinen, for imparting huge amounts of wisdom and steering the ship so well. My trigger work would not have been possible without Olli Lupton, Rosen Matev and Sascha Stahl. The W mass measurement team is, in my opinion, a shining example of scientific collaboration, and I count myself extremely lucky to have fallen in with such a formidable bunch. The Warwick EPP group is a great environment for research, and I am especially grateful to Flavia Cicala, Eleanor Jones, Andy Morris and Bryn Roberts for their emotional support, physics expertise and for many a wholesome and hilarious dinner party at CERN and various locations across the West Midlands. I could not forget another Warwick EPP alumnus and a key culinary influence, Arnau Brossa Gonzalo: we kept each other going and saw each other's Ph.Ds. through those dark days of the second national COVID-19 lockdown. When COVID struck Europe, I was in danger of spending months doing very little work alone in my flat in Meyrin, so I thank the Hobson family for taking me in, for their love and for providing an excellent home-working atmosphere that led to a remarkably productive first few months of the pandemic.

The journey in fact began a long time before October 2018 however, and I am grateful to every inspiring teacher and every wonderful friend that has helped a council estate lad realize his professional dream. Nathan Ritson and Che Nabeta deserve special mention; you are truly tremendous people. Thank you to the Alexander Duckham Memorial Schools Trust for keeping me afloat financially during my undergraduate degree. I'd like to thank my family for instilling good values in me, delivering a constant supply of Henderson's Relish in the flavourless South, and for providing a welcoming home every time I'm back in the city I love. Mum, you were and still are a fundamental part of any success I have. Dad, I'm very sad you couldn't be here to see this, as you deserve so much credit. I would've loved to see the smile on your face, although I think this one might be a bit heavy to put on the wall. Finally, I save the biggest thanks for Alice: you're the best partner a person could

have and indeed, there were many times over the last eight years when the wheels could've come off were it not for you. To those I didn't mention, I apologize, but know that no matter how big or small your contribution, I am immensely grateful. In your own way, you're helping to further the noble pursuit of particle physics. I hope that isn't too shocking a revelation for you.

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Chapter 1
Introduction

Particle physics is the field that studies the smallest building blocks of the universe and how they interact with one another via the fundamental forces. Although the objects of interest are infinitesimally small, almost everything else about particle physics is remarkably large. The field is a colossal endeavour that features tens (perhaps hundreds) of thousands of scientists around the globe–a field of cathedral-sized detectors, that surround atom-smashers of tens of kilometres in length which produce conditions similar to the moments after the Big Bang. The goals of the field are suitably lofty as well: particle physics is really trying to understand how *everything* works, at least on the most basic scale. What could be more grand a pursuit?

Although humans have always been curious about the universe and what it is made of, modern particle physics emerged at the turn of the 20th century. Experiments began to peer into the atom and to question the duality of waves and particles, and suddenly humanity's understanding of the microscopic world was revolutionized by the nascent theories of quantum mechanics. Particle physics since then has always been a highly predictive field; innovations in the mathematical theories give precise predictions of what particles should be seen and when they should be seen–it is then up to the experimentalists to devise an experiment to find them. Throughout the mid-late 20th century, this back-and-forth between theorists and experimentalists was extremely productive. Dozens of particles discoveries from the 1930s to 1950s lead theorists to the quark model, which says that the protons and neutrons that make up the nuclei of all the atoms in the human body are in fact made of *quarks*, and that these–along with the electron, a *lepton*—are the true fundamental particles. As the century came to a close more quarks and more leptons arrived on the scene at particle physics experiments, and the field's theorists were able to bookkeep them all together into one coherent and beautiful theory: the "Standard Model" of particle physics.

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The Standard Model is arguably the biggest theoretical achievement of the field. It describes, in just a few lines of mathematics, how all the fundamental particles interact with each other. Its equations have had staggering success at predicting the outcomes of experiments. Besides a few hints of discrepancy—some of which this thesis will go into—every result from every particle physics experiment[1] over the last half-century has aligned with the expectations of the SM. The discovery of the Higgs boson [2, 3] in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) was the cherry on the cake—proof of the Higgs mechanism that holds the SM together and gives mass to the fundamental particles. This discovery—although expected—was spectacular, and can count the author of this thesis as among the many it inspired into particle physics.

Today, the SM stands unfazed by the ceaseless and painstaking examinations physicists have devised to unearth its flaws. However, for all its predictive power in atom-smashing experiments, there are several important features of the universe it cannot describe. Gravity—one of the four fundamental forces of the universe—is conspicuously absent. It has no answer for the origin or particle content of the "dark matter" that is theoretically necessary to explain both the formation of galaxies and their observed patterns of rotation. To the best of humanity's knowledge, the universe is dominated by *matter* rather than *antimatter*, yet the SM predicts that they should've been created in equal measure by the Big Bang, and gives no mechanism to yield the observed matter-antimatter asymmetry. There are further theoretical problems, all clearly showing that something is missing, and that the SM cannot be the ultimate theory of the universe's fundamental interactions.

So where to go next? A fine question, and if you get the correct answer you will surely get a call from the Royal Swedish Academy of Sciences that you do not want to miss. There are a plethora of theories around describing how to extend, generalize or modify the SM to solve the problems listed above, but to prove any of them requires experimental confirmation of their beyond-the-Standard-Model (BSM) phenomena. Another angle to take is to test the SM's predictions at ever higher precision, hoping to see a significant-enough deviation to suggest what theoretical direction should be followed—a foot in the door. A large portion of the field is dedicated to this angle of attack, and it is the trajectory that is taken here. The electroweak (EW) part of the SM (responsible for the everyday force of electromagnetism, and the nuclear weak force that keeps the stars shining) is a fertile ground for such high-precision tests: relatively-speaking, it is extremely well-understood theoretically; the physics processes involved are comparatively simple; and it is at the centre of the SM formalism. For these reasons however, there is a long history of electroweak precision measurements at particle colliders, and increasing the level of precision requires supreme effort in understanding the potential experimental biases, and constant innovation in theoretical predictions to match.

---

[1] The discovery of neutrino oscillations in 1998 [1] provided evidence that neutrinos have mass, which is not strictly predicted by the SM. However, it can be easily incorporated, and as such it is debatable whether this is truly a beyond-the-Standard-Model phenomenon.

This thesis describes two high-precision tests of the EW sector of the SM: a measurement of the W boson mass, and a test of the W boson's property of "lepton flavour universality". The meaning of the latter property will be described in due course, as will the motivations for making these particular measurements. Both take place using data collected in 2016 by the LHCb [4] experiment at the LHC. LHCb was primarily designed as an experiment for studying the physics of hadrons containing charm and beauty quarks in the aim of shedding light on the aforementioned matter-antimatter asymmetry, but has broadened since its inception into a general-purpose physics experiment. The measurements here contribute to an increasingly impressive catalogue of EW precision measurements. At the time of writing, LHCb is emerging from a major upgrade designed to vastly increase its physics reach. A notable part of that upgrade is a complete redesign of its trigger system to fully exploit the new detector's capabilities and the larger rate of data that it will collect in the coming years. The author has played a part in this upgrade, first by developing tools to facilitate optimization of the new trigger system, and then in writing trigger "selections" to pick out those collision events that involve EW processes. The latter work ensures the data will be collected to allow further high-precision EW tests in the future.

The structure of the thesis is as follows. To fully understand the measurements introduced, a brief primer of the required theoretical background is presented in Chap. 2. It was mentioned that supreme understanding of the experimental apparatus is required, so Chap. 3 describes the LHCb experiment. The author's work on the upgraded trigger system is the subject of Chap. 4. The thesis then goes into further depth on the theoretical modelling aspects of precision EW physics in Chap. 5, followed by the detector modelling strategies in Chap. 6. The author's primary contribution to the W mass measurement was the study of muon reconstruction efficiencies, which is presented by Chap. 7. This is followed directly by description of the W mass measurement in its entirety in Chap. 8. Chapter 9 concerns the test of the W boson's lepton flavour universality. Finally, conclusions of the thesis are presented in Chap. 10.

1.1 Conventions and Coordinates

Before diving deep into the theory of the SM, the reader should be aware of a number of conventions used throughout the thesis:

- In the electroweak process $\mathrm{q\overline{q}} \to \mathrm{Z}/\gamma^* \to \ell\ell$ (ℓ is a lepton, q and $\overline{\mathrm{q}}$ are a quark and an antiquark respectively), where the interaction can be mediated by either a Z boson or a photon, only Z will be used to denote both,
- In particle decays, the charge of the particles will usually be omitted, both for brevity and because the inclusion of both charges is usually implied, e.g. $\mathrm{W} \to \mu\nu$ is used in place of both $\mathrm{W}^+ \to \mu^+\nu_\mu$ and $\mathrm{W}^- \to \mu^-\overline{\nu}_\mu$. The slightly more complex case of $\mathrm{W} \to (\tau \to \mu\nu\nu)\,\nu$ corresponds to both $\mathrm{W}^+ \to (\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau)\nu_\tau$ and $\mathrm{W}^- \to (\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)\overline{\nu}_\tau$,