**FEASIBILITY STUDY FOR MEASURING DRELL-YAN ANGULAR
COEFFICIENTS IN THE ATLAS DETECTOR USING LOW-PILEUP DATA SETS**

By

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ABSTRACT

W and Z bosons are the mediators of the fundamental weak force and are some of the particles produced using proton-proton collisions with the Large Hadron Collider at CERN. Proton-proton interactions producing Z bosons, which subsequently decay into leptonic particles, like electrons, are known as the Drell-Yan process. Its differential cross-section expresses the probability for this process to occur depending on the Z bosons' and decay products' kinematic variables. It can be separated into eight spin-related ratios, known as the Drell-Yan angular coefficients. This thesis is a feasibility study to explore if there is sufficient statistical sensitivity to measure the coefficients with special data sets. Taken with the ATLAS detector, these sets have a lower average number of interactions per proton bunch crossing. This thesis includes predictions of the coefficients and comparisons of MC simulations to the data; this is the first look at these data sets.

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INTRODUCTION

In order to better understand the universe, physicists model what is observed in nature to best describe it and to make further predictions. These models are used to describe the four fundamental forces: gravity, electromagnetism, the weak force, and the strong force. Gravity is the most apparent force in everyday life and describes the attraction of particles with mass. Electromagnetism describes how particles with electric charge interact and is responsible for light. Nuclear beta decay is a result of the weak force, where an electron and neutrino are emitted from the nucleus of an atom. Lastly, the strong force is responsible for how the nucleus of an atom is bound together.

Currently, the Standard Model (SM) describes the elementary particles and the interactions through electromagnetism, the weak force, and the strong force. In order to improve the SM and the understanding of nature, experiments are carried out at CERN, the European Organization for Nuclear Research. CERN is an international research facility located on the Swiss-French border outside of Geneva that holds the largest particle accelerator in the world, the Large Hadron Collider (LHC), a 27 km circumference ring. The LHC is used to accelerate bunches of protons in opposite directions around the ring and collide them, in order to observe their interactions. The interactions can produce new matter, where the products of the collisions are observed at several experiments, most notably ATLAS and CMS. In 2009, the LHC first took data at centre-of-mass energies, $\sqrt{s} = 0.9, 2.36$ TeV. Then in 2010-12, data at $\sqrt{s} = 7, 8$ TeV was collected before a long shut down occurred to upgrade the beamline. From 2015-18, the centre-of-mass energy was again increased, to $\sqrt{s} = 13$ TeV. From 2021 onwards, the LHC is to run at the design energy of $\sqrt{s} = 14$ TeV.

Protons are used in the colliding beams because they do not radiate much energy when accelerated compared to electrons, have a large mass, and are easily obtained. Protons are comprised of quarks, q , which are bound within the proton by exchange of gluons, g , as

Figure 1: Protons are comprised of three quarks, q , which are bound together by exchange of gluons, g . Quark-antiquark pairs, $q\bar{q}$, be created and destroyed inside the protons.

seen in Figure 1. Quarks come from a group of particles called fermions which have half-integer spin. When the protons collide, multiple different interactions can occur ($q\bar{q}$, qg , $\bar{q}g$, and gg), as seen in Figure 2. These interactions can produce new forms of matter such as bosons which have integer spin. Some bosons that can be created are W and Z bosons which are the mediators of the weak force. One of the ways for W and Z bosons to decay is into leptons, ℓ . Electrons are an example of leptons, another type of fermion. The process of $q\bar{q} \rightarrow Z \rightarrow \ell\ell$, called the Drell-Yan process, is important to this thesis.

The Drell-Yan process has the interaction of two fermions ($S = 1/2$) to a vector boson ($S = 1$) to two fermions ($S = 1/2$) as seen in Figure 2a. The spin dependence of all three components allows the process to be described by eight spin-dependent coefficients A_i where $i \in \{0 - 7\}$. Using the ATLAS detector located at CERN, the decay leptons can be observed and used to measure the A_i coefficients.

The SM has free parameters, meaning that the theory does not provide these values. By measuring the A_i coefficients, one of these free parameters is able to be constrained. Namely, the coefficients A_3 and A_4 are related to the weak mixing angle - $\sin^2 \theta_W$, a free parameter. The weak mixing angle relates the masses of the W and Z bosons through:

$$\sin^2 \theta_W = 1 - \left(\frac{m^W}{m^Z} \right)^2, \quad (1)$$

Figure 2: Examples of three Feynman diagrams of different ways protons can interact when collided at the LHC. a) A quark and antiquark from each proton annihilate to form a Z boson via the weak force before it decays. b) A quark from one of the protons can interact with an emitted gluon from another proton via the strong force. c) Two emitted gluons can interact via the strong force and in this case, create a quark-antiquark pair.

where m^W and m^Z are the masses of the W and Z bosons, respectively. Measuring the mass of the W boson is difficult, as not all of the particles it can decay into are detectable. One way to measure the W mass is through measuring the $\sin^2 \theta_W$ and Z mass.

ATLAS is one of the major experiments located at CERN using the LHC proton-proton collisions which happen in the centre of the detector. It reconstructs as many interactions from the proton-proton collisions as possible through the use of semiconductors - to track particle trajectories, calorimeters - to measure their energy, and a muon spectrometer - to measure muons. By reconstructing detected events, ATLAS is able to validate the SM by measuring processes such as the Drell-Yan process. Any deviations can point towards

new physics beyond the SM. This thesis uses Monte Carlo (MC) simulations of the Drell-Yan process in the ATLAS detector for a feasibility study to examine if there is sufficient statistical sensitivity to measure the Drell-Yan angular coefficients with special data sets taken in 2017-18. After predictions are made, the particle kinematic distributions of the simulation are compared to data to confirm the agreement.

The thesis is outlined as follows: the first chapter introduces the theoretical considerations of the Drell-Yan process and the angular coefficients. The second chapter discusses the LHC and the ATLAS detector and how ATLAS detects particles and reconstructs them. The methodology used for the measurement of the Drell-Yan angular coefficients, utilizing a statistical folding method, is covered in chapter three. This methodology was used previously for the $\sqrt{s} = 8$ TeV measurement [1], so my work towards it was to make it usable for this special data set. Chapter four covers results of the predictions of the Drell-Yan angular coefficients and the comparison between the MC simulation and data. The results presented are all my original work with the exception when compared to published ATLAS results, where mentioned. Chapter five concludes the thesis and gives an outlook of the potential direction of related research. More detail on the folding method derivation can be found in Appendix A. Appendices B and C provide information for MC simulation files used and additional plots, respectively. Lastly, a list of acronyms used and brief explanations can be found in Appendix D.

I joined the SM analysis team in ATLAS in 2018, when I traveled to CERN in June and July. Traveling to CERN allowed for my introduction to relevant ATLAS analysis software and techniques to measure the Drell-Yan angular coefficients. I then worked towards making predictions of the Drell-Yan angular coefficients and comparisons of particle distributions between simulation and data. I presented my work to my colleagues at an ATLAS workshop in Paris in February, 2019. My results have also been presented to physicists outside of ATLAS at the Winter Nuclear and Particle Physics Conference in February, 2019 and the Ottawa-Carleton Institute for Physics symposium in April, 2019.

CHAPTER 1

THEORETICAL CONSIDERATIONS

This thesis focuses on making predictions of the Drell-Yan angular coefficients for special data sets taken during 2017-18 in the ATLAS detector. To understand the physical meaning of the Drell-Yan angular coefficients, an understanding of the theoretical framework is important. This theoretical framework will be presented with a brief explanation of the SM that describes the elementary particles and their interactions. Next, the Drell-Yan process, $q\bar{q} \rightarrow Z \rightarrow \ell\ell$, will be explained including where the Drell-Yan angular coefficients appear from. Then, simulation of the kinematic distributions of the Z boson at $\sqrt{s} = 13$ TeV to demonstrate the expected distributions. Lastly, the Drell-Yan angular coefficients measurement, by ATLAS, at centre-of-mass energy, $\sqrt{s} = 8$ TeV [1], will be presented.

1.1 Standard Model

The SM is the theory that best describes the observed interactions between elementary particles via three of the four fundamental forces: electromagnetism, the weak force, and the strong force. Electromagnetism and the weak force were found to be unified with the discovery of interactions mediated by the Z boson in 1973 at CERN [2]. The strong force, described by quantum chromodynamics (QCD), has shown indications to be unified with electroweak theory at higher energies but there has not been any experimental evidence so far. The SM is incomplete. There are many observed phenomena that the SM does not include, such as the asymmetry between matter and antimatter, dark matter, and dark energy.

The SM is constructed with free parameters that do not have a theoretically prescribed value. Knowing these free parameters to higher precision is important for validating the

SM. If discrepancies are found, they can help improve the SM. This section will cover a brief overview of the relevant material of how the SM describes the particles and their interactions, as seen in nature. This section is based upon textbooks [3, 4, 5, 6] where more in-depth explanations can be found.

1.1.1 Particles and Interactions

The particles seen in nature are grouped, based upon their spin, into fermions and bosons. Fermions are what matter is made of and have half-integer spin $S = 1/2$. Bosons have integer spin $S = 0, 1, 2$ and are the mediators of the fundamental forces. They are able to interact with fermions and other bosons. Fermions are further split into two groups, leptons ℓ and quarks q .

Six leptons have been observed: electron e , muon μ , and tau τ which have charge $Q = -1e$ ¹ and their corresponding neutral neutrinos ν_e , ν_μ , and ν_τ . Neutrinos have been observed to only interact via the weak force because they do not have electric charge. The other leptons can interact via both the electromagnetic and weak force described by the electroweak theory.

There are six observed quarks: up, down, strange, charm, bottom, and top. The quarks carry fractional elementary charge of either $Q = 2/3e$ or $Q = -1/3e$. They also have an additional quantum number called colour, which has three states: red, green, and blue. A difference between quarks and leptons is that quarks can interact via the strong interaction while leptons do not. Most particles (x) will have antiparticles ($\bar{x}$) which have the same mass and lifetime but opposite electric charges. A summary of all known fermions and some of their properties can be found in Table 1.1.

¹ e is the elementary charge and taken to be positive.

Fermion	Generation	Flavour	Charge (e)	Mass (MeV)
Leptons	First	e	-1	$0.5109989461 \pm 0.0000000031$
		ν_e	0	
	Second	μ ν_μ	-1 0	$105.6583745 \pm 0.0000024$
Quarks	Third	τ ν_τ	-1 0	1776.86 ± 0.12
	First	u (up)	2/3	$2.2^{+0.5}_{-0.4}$
		d (down)	-1/3	$4.7^{+0.5}_{-0.3}$
	Second	s (strange)	-1/3	95^{+9}_{-3}
		c (charm)	2/3	1275^{+25}_{-35}
	Third	b (bottom) t (top)	-1/3 2/3	4180^{+40}_{-30} $(173.1 \pm 0.9) \times 10^3$

Table 1.1: Table of known fermions summarizing their charge and mass, grouped by leptons and quarks and further sub-grouped by generation based on mass. Mass values are in natural units where $c = 1$ and charges in units of the elementary charge e . The neutrinos mass are much smaller than the other fermions and are not included as in most cases they can be treated as massless. Taken from PDG [7].

There are two different types of observed elementary bosons, vector ($S = 1$) and scalar ($S = 0$). There is only one known elementary scalar boson, the Higgs boson, which was experimentally discovered in 2012 by ATLAS and CMS [8, 9]. The Higgs boson is the excitation of the Higgs field which gives particles their mass. Vector bosons are the mediator particles of the interactions between particles. The electromagnetic interaction is the interaction between charged particles and is mediated by the photon, γ , described by quantum electrodynamics (QED). The strong force is the interaction between coloured particles: quarks, antiquarks, and the gluon, g . The interactions are described by QCD and are mediated by the gluon. The weak interaction is mediated by the $W^\pm$ and Z bosons and is unique because it interacts with all fermions. A summary of the known bosons can be found in Table 1.2.

Force	Boson	Charge (e)	Mass (GeV)
Gravity	Graviton*	-	-
Electromagnetic	Photon γ	0	0
Weak	W^+	1	80.379 ± 0.012
Weak	W^-	-1	80.379 ± 0.012
Weak	Z	0	91.1876 ± 0.0021
Strong	Gluon g	0	0
-	Higgs H	0	125.18 ± 0.16

Table 1.2: Table of known bosons where mass values are in units of GeV and charge in units of the elementary charge e , taken from PDG [7]. *The graviton has not been observed and would be the boson of a field theory that describes gravity with a boson of spin ($S = 2$).

1.1.2 Electroweak Theory

This electroweak discussion is based on sources [10, 11, 12] and covers the unification of QED and the weak force. The weak force is mediated by three massive bosons W^+ , W^- , and the Z boson. Unlike QED, the weak force does not interact equally with all particles. Instead, the Z boson has a different coupling strength for left and right-handed particles, while the W boson only couples to left-handed fermions or right-handed anti-fermions. For massless particles chirality is equal to the helicity, which relates the spin to the momentum of the particle. In the context of this thesis the mass of the particles is negligible to their energy so they can be approximated as massless. Therefore, if the spin is in the same direction as the momentum it is right-handed and if the spin is in the opposite direction it is left-handed.

The electroweak interaction Lagrangian, which expresses the rules for how fermions electroweakly can interact, is²:

$$\mathcal{L}_{EW}^{int} = g \vec{J}_\mu \cdot \vec{W}^\mu + g' J_\mu^Y B^\mu. \quad (1.1)$$

In Equation 1.1, g and g' give the strengths of the interaction, $\vec{W}^\mu$ are the weak isospin bosons ($W_1^\mu, W_2^\mu, W_3^\mu$), and B^μ is the hypercharge boson. The weak isospin, T , is a quan-

²The convention used is the Einstein summation convention where contracted indices are summed over in the range $\mu = 0, 1, 2, 3$.

tum number with three components. The third component, T^3 , and the quantum number hypercharge, Y , combine to give the electric charge through the relation $Q = T^3 + \frac{Y}{2}$. The currents, $\vec{J}_\mu$, are the isospin currents:

$$\begin{aligned} J_\mu^+ &= \frac{1}{2} \bar{\nu}_e \gamma^\mu (1 - \gamma^5) e, \\ J_\mu^- &= \frac{1}{2} \bar{e} \gamma^\mu (1 - \gamma^5) \nu_e, \\ J_\mu^3 &= \frac{1}{2} \bar{e} \gamma^\mu (v - a \gamma^5) e. \end{aligned} \quad (1.2)$$

J_μ^{EM} is the electromagnetic current $J_\mu^{EM} = Q \bar{e} \gamma^\mu e$, where Q is the electric charge of the particle. J_μ^Y is the hypercharge current, where $J_\mu^{EM} = J_\mu^3 + \frac{J_\mu^Y}{2}$. In the definitions of the currents, v and a are the vector and axial-vector couplings, respectively. Operators³ e and ν_e are associated to the electrons and neutrinos being created and destroyed. Lastly, γ^μ and γ^5 are the Dirac matrices defined in the Bjorken and Drell basis [3] as:

$$\gamma^0 = \begin{pmatrix} \mathbb{1} & \mathbb{0} \\ \mathbb{0} & -\mathbb{1} \end{pmatrix}; \quad \gamma^i = \begin{pmatrix} \mathbb{0} & \tau_i \\ -\tau_i & \mathbb{0} \end{pmatrix}; \quad \gamma^5 = \begin{pmatrix} \mathbb{0} & \mathbb{1} \\ \mathbb{1} & \mathbb{0} \end{pmatrix}. \quad (1.3)$$

In these instances $i = \{1, 2, 3\}$, $\mathbb{1}$ is the 2×2 unit matrix, $\mathbb{0}$ is a 2×2 matrix of zeros, and τ_i are the Pauli matrices:

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}; \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}; \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (1.4)$$

The physical bosons, W^+ , W^- , Z , and the photon, are mixed states of the weak isospin

³All currents presented in Equation 1.2 and J_μ^{EM} are just for the electron, e , and the electron neutrino, ν_e , interactions for simplicity. The currents are similar for other fermions by replacement of particles with the exception being quarks and antiquarks. They gain a mixing factor but do not change the functional form of the current.

and the hypercharge bosons:

$$\begin{aligned}
W^{\pm,\mu} &= \frac{1}{\sqrt{2}} (W_1^\mu \mp iW_2^\mu), \\
Z^\mu &= W_3^\mu \cos \theta_W - B^\mu \sin \theta_W, \\
A^\mu &= W_3^\mu \sin \theta_W + B^\mu \cos \theta_W,
\end{aligned} \tag{1.5}$$

where A^μ is the photon field and θ_W is the weak mixing angle, a free parameter of the SM.

QED and electroweak theory strengths are related through:

$$g \sin \theta_W = g' \cos \theta_W = e. \tag{1.6}$$

The electroweak Lagrangian from Equation 1.1 for interactions between fermions is more commonly expressed in terms of the physical bosons as:

$$\mathcal{L}_{EW}^{int} = \frac{g}{\sqrt{2}} (J_\mu^- W^{+,\mu} + J_\mu^+ W^{-,\mu}) + \frac{g}{\cos \theta_W} (J_\mu^3 - \sin^2 \theta_W J_\mu^{EM}) Z^\mu + e J_\mu^{EM} A^\mu. \tag{1.7}$$

To better understand how the interaction Lagrangian in Equation 1.7 works, examples of the boson interactions will be given. An example of the weak charged current, J_μ^- in Equation 1.2, can be seen in nuclear beta decay in Figure 1.1. The down quark changes flavour to an up quark by emitting a W boson, which decays into an electron and an anti-neutrino. The coupling of the W^- , electron, and anti-neutrino is the $\frac{g}{\sqrt{2}} J_\mu^+ W^{-,\mu}$ term in Equation 1.7.

Figure 1.1: Feynman diagram of nuclear beta decay where a down quark in a neutron emits a W boson to change flavour into an up quark. The W boson then decays into an electron and an anti-neutrino. This W boson emission is an example of one of the weak charged currents.

An example of the Z interaction can be seen in Figure 1.2, the Drell-Yan process of $q\bar{q} \rightarrow Z \rightarrow e^+e^-$. The middle term in Equation 1.7, using the J_3^μ current in Equation 1.2, is the current for the Z decaying to e^+e^- .

Figure 1.2: Feynman diagram of the Drell-Yan process of quark-antiquark pair annihilation into a Z boson before decaying into an electron-positron pair.

Lastly, the electromagnetic current, which can be seen in Figure 1.3, has a very similar diagram to Figure 1.2. This comes from the last term of Equation 1.7 in the coupling of the photon field, A^μ , to the e^+e^- pair.

Figure 1.3: Feynman diagram of a quark-antiquark pair annihilation into a photon before decaying into an electron-positron pair.

The mixing of the weak and electromagnetic currents in the middle term for the Z boson in Equation 1.7 allows for coupling both left and right-handed fermions, while the W bosons can only couple to the left-handed fermions. For the Z boson, the total coupling strength is different for both left and right-handed fermions. They can be expressed in terms of T^3 and the charge through the relations:

$$\begin{aligned} g_L &= T^3 - Q \sin^2 \theta_W, \\ g_R &= -Q \sin^2 \theta_W. \end{aligned} \tag{1.8}$$

These are usually expressed in terms of vector and axial-vector couplings v and a , respectively, for the Z which are:

$$\begin{aligned} v &= g_L + g_R = T^3 - 2Q \sin^2 \theta_W, \\ a &= g_L - g_R = T^3. \end{aligned} \tag{1.9}$$

How the left and right-handed couplings for W and Z bosons change for different fermions as well as the vector and axial-vector couplings can be seen in Table 1.3.

Fermion	T^3	Charge (e)	Z boson		W $^\pm$ boson	
			g_L	g_R	g_L	g_R
e, μ, τ	$-1/2$	-1	$-1/2 + \sin^2 \theta_W$	$\sin^2 \theta_W$	$-1/2$	0
ν_e, ν_μ, ν_τ	$1/2$	0	$1/2$	0	$1/2$	0
u, c, t	$1/2$	$2/3$	$1/2 - 2/3 \sin^2 \theta_W$	$-2/3 \sin^2 \theta_W$	$1/2$	0
d, s, b	$-1/2$	$-1/3$	$-1/2 + 1/3 \sin^2 \theta_W$	$1/3 \sin^2 \theta_W$	$-1/2$	0

Table 1.3: List of all fermions, the third component of weak isospin T^3 , and charge Q . The left and right-handed coupling strength for $W^\pm$ and Z bosons are compared.

Since the couplings vary with fermion type, understanding them is important for understanding the production and decay of the Z boson.

1.1.3 Quantum Chromodynamics

An additional quantum number in quarks, called colour, comes in three types: red, green, and blue. The theory behind the exchange of colour through gluons, which simultaneously carry colour and anticolour, is known as QCD. Quarks and gluons have been observed to only be in bound states, called hadrons. This notion of no free quarks or gluons is known as confinement. The bound states have no net colour, which can be achieved by having a bound system of three quarks, called a baryon, such as a proton (uud) or a neutron (udd) each with one of the colours. Another bound system is a quark-antiquark pair, called a meson, such as a π^+ ($u\bar{d}$) having colour and anticolour. Other more exotic bound systems, called pentaquarks [13, 14], have been observed by another experiment at CERN, LHCb, with minimum quark content $uudc\bar{c}$. The quarks and antiquarks that form bound states are called valence quarks, which stay bounded by colour exchange through gluons.

The strong coupling constant, α_S , between quarks and gluons depends on the momentum transfer⁴, Q^2 . When two quarks are at very short distances, they exchange gluons with a large momentum transfer and behave as approximately free particles which is called asymptotic freedom. When two quarks are separated, Q^2 decreases which results in α_S increasing as the two quarks try to pull back together like a spring. There comes a point when the potential between the quarks becomes so strong it becomes more energetically favourable to produce a quark-antiquark pair to reduce the energy in the hadron. This process is called hadronization. This notion of the strong coupling constant being a function of Q^2 , $\alpha_S(Q^2)$, is called a running coupling constant and can be seen in Figure 1.4.

⁴Not to be confused with the electric charge, Q .

Figure 1.4: Running strong coupling constant α_s which decreases with increased momentum transfer Q^2 and separation distance. Plot taken from PDG [7].

Other than valence quarks, pairs of quarks and antiquarks can come into and out of existence within hadrons. They are called sea quarks and can come from gluon emission from valence quarks before being reabsorbed as seen in Figure 1.5. Valence quarks, sea quarks, and gluons are the constituent particles that make up hadrons, referred to as partons.

Figure 1.5: An example of a Feynman diagram where a gluon is emitted within a proton to form sea quarks before reabsorbed.

1.2 Drell-Yan Process

In a proton-proton interaction, multiple different processes can occur. Each process has a unique probability, known as the cross-section denoted by σ . One of these processes is the Drell-Yan process. This is when a $q\bar{q}$ annihilates producing a Z boson, which decays

into a $\ell^+\ell^-$ in the final state [12]. An example of $q\bar{q} \rightarrow Z \rightarrow \ell^+\ell^-$ can be seen in Figure 1.6 with protons, carrying momenta P_i , interact via partons carrying fractional momenta $x_i P_i$ where $x_i < 1$.

Figure 1.6: Example of a Drell-Yan process where protons, with momenta P_i , have partons with momenta $x_i P_i$, annihilate into a Z boson which decays into two leptons.

Within hadrons, partons follow Parton Distribution Functions (PDF), $f_i(x)$, for the probability of particle i having momentum fraction x_i . PDFs have to be obtained experimentally as they cannot be obtained from first principles. Since the different partons contribute to similar processes, the total cross-section is the sum over all of the partons and associated cross-sections. The individual similar processes are approximated through an expansion [15]:

$$\sigma = \sum_{i,j} \int dx_a dx_b f_i(x_a; \mu_F^2) f_j(x_b; \mu_F^2) [\hat{\sigma}_0 + \alpha_S(\mu_R^2) \hat{\sigma}_1 + \alpha_S^2(\mu_R^2) \hat{\sigma}_2 \cdots]_{ab \rightarrow X}. \quad (1.10)$$

μ_F is the factorization scale, which the hard interaction of the process can be factorized from the non-perturbative dynamics. μ_R is the renormalization scale, which sets the strength of the strong coupling constant. Usually, both scales are set to the dilepton resonance mass, $\mu_F = \mu_R = m^{\ell\ell}$. The expansion of $\alpha_S^i \hat{\sigma}_i$ is the order of perturbative QCD used. An example of each order can be seen in Figure 1.7. $\hat{\sigma}_0$ is Leading Order (LO), $\alpha_S(\mu_R^2) \hat{\sigma}_1$ is Next to Leading Order (NLO), $\alpha_S^2(\mu_R^2) \hat{\sigma}_2$ is Next to Next to Leading Order

(NNLO), and etc. For each order added, a better precision to the calculation is achieved but with a cost of complexity and computation time, as the number of processes increases rapidly with each order.

Figure 1.7: Examples of a) LO, b) NLO, and c) NNLO Feynman diagrams for the Drell-Yan process. The order is determined by the number of QCD vertices on the left. With increased order, the number of Feynman diagrams increases.

1.3 Drell-Yan Angular Coefficients

The Drell-Yan process $q\bar{q} \rightarrow Z \rightarrow \ell\ell$ can be described by a differential cross-section as a function of variables p_T^Z , m^Z , y^Z , $\cos\theta$, and φ where p_T^Z , m^Z , and y^Z are the transverse momentum, mass, and rapidity of the Z boson, respectively. Rapidity is defined as $y = \ln[(E + p_z)/(E - p_z)]$, where E and p_z are the energy and the z component of the momentum vector, respectively. The angles $\cos\theta$ and φ are angles of the lepton in the centre-of-mass frame of the Z. Since there are two spin 1/2 particles going to a spin 1 particle and then decaying to two spin 1/2 particles, the differential cross-section can be expressed as an angular decomposition related to the spherical harmonics $Y_l^m(\theta, \varphi)$. The

differential cross-section correct to all orders of QCD [16] can be expressed as:

$$\frac{d\sigma}{dp_T^Z dy^Z dm^Z d\cos\theta d\varphi} = \frac{3}{16\pi} \sum_{\alpha \in M} g_\alpha(\theta, \varphi) \frac{d\sigma^\alpha}{dp_T^Z dy^Z dm^Z}, \quad (1.11)$$

where $M = \{U+L, L, T, I, P, A, 7, 8, 9\}$ is the set of spin cross-sections $d\sigma^\alpha$ and g_α are the second-order harmonic polynomials. Examples of $d\sigma^\alpha$ are $d\sigma^L$, $d\sigma^T$, and $d\sigma^I$ are the longitudinal-polarized, transverse-polarized, and transverse-longitudinal interference cross-sections, respectively. The polynomials, $g_\alpha(\theta, \varphi)$, are [16]:

$$\begin{aligned} g_{U+L} &= 1 + \cos^2 \theta; & g_L &= 1 - 3 \cos^2 \theta; & g_T &= 2 \sin^2 \theta \cos 2\varphi; \\ g_I &= 2\sqrt{2} \sin 2\theta \cos \varphi; & g_P &= 2 \cos \theta; & g_A &= 4\sqrt{2} \sin \theta \cos \varphi; \\ g_7 &= 2 \sin^2 \theta \sin 2\varphi; & g_8 &= 2\sqrt{2} \sin 2\theta \sin \varphi; & g_9 &= 4\sqrt{2} \sin \theta \sin \varphi. \end{aligned} \quad (1.12)$$

The cross-sections are related to the vector v_x and axial-vector a_x coupling coefficients of $x = \{\ell, q\}$ to the Z boson in the following way [16]:

$$\begin{aligned} \sigma^{U+L, L, T, I} &\sim (v_\ell^2 + a_\ell^2) (v_q^2 + a_q^2). \\ \sigma^{P, A} &\sim v_\ell a_\ell v_q a_q. \\ \sigma^{7, 8} &\sim (v_\ell^2 + a_\ell^2) (v_q a_q). \\ \sigma^9 &\sim (v_\ell a_\ell) (v_q^2 + a_q^2). \end{aligned} \quad (1.13)$$

By factoring out the unpolarized cross-section $d\sigma^{U+L}$ from Equation 1.11, unitless ratios of the helicity dependent cross-sections can be expressed as coefficients denoted by A_i . These are known as the Drell-Yan angular coefficients:

$$\begin{aligned} A_0 &= 2d\sigma^L/d\sigma^{U+L}; & A_1 &= 2\sqrt{2}d\sigma^I/d\sigma^{U+L}; & A_2 &= 4d\sigma^T/d\sigma^{U+L}; \\ A_3 &= 4\sqrt{2}d\sigma^A/d\sigma^{U+L}; & A_4 &= 2d\sigma^P/d\sigma^{U+L}; & A_5 &= 2d\sigma^7/d\sigma^{U+L}; \\ A_6 &= 2\sqrt{2}d\sigma^8/d\sigma^{U+L}; & A_7 &= 4\sqrt{2}d\sigma^9/d\sigma^{U+L}. \end{aligned} \quad (1.14)$$

This results in a simplification of the differential cross-section and allows for expressing it in terms of the Drell-Yan angular coefficients, A_i , and polynomials, P_i , given in Table 1.4:

$$\frac{d\sigma}{dp_T^Z dy^Z dm^Z d\cos\theta d\varphi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z dy^Z dm^Z} \left\{ (1 + \cos^2\theta) + \sum_{i=0}^7 A_i(p_T^Z, y^Z, m^Z) P_i(\cos\theta, \varphi) \right\}. \quad (1.15)$$

An interesting thing to note is that the A_i coefficients are dependent on just the Z boson kinematics, while the P_i are dependent just on the lepton kinematics. Although the differential cross-section equation is correct to all orders of perturbative QCD, the A_i 's can be zero at some orders. The orders at which each A_i contributes can be found in Table 1.4.

P_i	$Y_l^m(\theta, \varphi)$	A_i	Coupling	Non-Zero
$1/2(1 - 3\cos^2\theta)$	Y_2^0	A_0		$\mathcal{O}(\alpha_S^1)$
$\sin 2\theta \cos \varphi$	$(Y_2^{-1} - Y_2^1)$	A_1	$(v_\ell^2 + a_\ell^2)(v_q^2 + a_q^2)$	$\mathcal{O}(\alpha_S^1)$
$1/2 \sin^2\theta \cos 2\varphi$	$(Y_2^{-2} + Y_2^2)$	A_2		$\mathcal{O}(\alpha_S^1)$
$\sin\theta \cos\varphi$	$(Y_1^{-1} - Y_1^1)$	A_3	$v_\ell a_\ell v_q a_q$	$\mathcal{O}(\alpha_S^1)$
$\cos\theta$	Y_1^0	A_4	$\sim \sin^2\theta_W$	$\mathcal{O}(\alpha_S^0)$
$\sin^2\theta \sin 2\varphi$	$(Y_2^{-2} - Y_2^2)$	A_5	$(v_\ell^2 + a_\ell^2)(v_q a_q)$	$\mathcal{O}(\alpha_S^2)$
$\sin 2\theta \sin \varphi$	$(Y_2^{-1} + Y_2^1)$	A_6		$\mathcal{O}(\alpha_S^2)$
$\sin\theta \sin \varphi$	$(Y_1^{-1} + Y_1^1)$	A_7	$(v_\ell a_\ell)(v_q^2 + a_q^2)$	$\mathcal{O}(\alpha_S^2)$

Table 1.4: Summary of polynomials, how the polynomials relate to the spherical harmonics, Drell-Yan angular coefficients, the vector and axial-vector couplings, and order at which they become non-zero.

1.4 Collins-Soper Frame

The Drell-Yan angular coefficients are reference frame dependent because they are dependent on the Z boson kinematics. The Collins-Soper (CS) frame [17] compared to the lab frame can be seen in Figure 1.8. The CS frame is the rest frame of the Z boson with the z-axis along the direction of the Z boson and create a bisecting angle between the initial protons. The y-axis is then defined as the normal vector to the proton-proton plane. To have a right-handed Cartesian coordinate system, the x-axis is orthogonal to both the y and z axes.

Figure 1.8: On the left is the lab frame with protons coming from opposite directions resulting in the Z boson, in an arbitrary direction. The Collins-Soper (CS) frame [17], is the rest frame of the Z boson with the z axis along the direction of the Z boson. This creates a bisecting angle, α , from the protons. The y axis is normal to the plane that the protons are in. The x axis is orthogonal to the yz-plane. The CS angles are defined so that θ_{CS} is the angle between the negatively charged lepton and z-axis and φ_{CS} is the angle between the xz-plane and the lepton plane.

The angles θ_{CS} and φ_{CS} are used to define the direction of the leptons in the CS frame. θ_{CS} is the angle between the negatively charged lepton and the z-axis and φ_{CS} is the angle in the xy-plane between the lepton and xz-plane. The angles are calculated with the outgoing lepton momenta in the laboratory frame, where $\cos \theta_{CS}$ is defined such that:

$$\cos \theta_{CS} = \frac{p_z^{\ell\ell}}{|p_z^{\ell\ell}|} \frac{2}{m^{\ell\ell} \sqrt{m^{\ell\ell 2} + p_T^{\ell\ell 2}}} (P_1^+ P_2^- - P_1^- P_2^+), \quad (1.16)$$

with

$$P_i^\pm = \frac{1}{\sqrt{2}} (E_i \pm p_{z,i}). \quad (1.17)$$

E_i and $p_{z,i}$ are the energy and longitudinal momentum of the lepton, respectively, such that $i = 1$ for the lepton and $i = 2$ for the anti-lepton. $p_z^{\ell\ell}$ is the longitudinal momentum of the dilepton system.

1.5 Z Boson Simulated Kinematic Distributions

The differential cross-section depends on p_T^Z , m^Z , y^Z , $\cos \theta_{CS}$, and φ_{CS} . These distributions, as seen in Figure 1.9, are MC simulation of the process $pp \rightarrow Z \rightarrow ee$, where no event selection criteria nor detector effects are applied. The m^Z distribution, on a logarithmic scale in the top-left, shows the mass resonance at the expected 91 GeV [7]. In the top-right, the p_T^Z distribution on a logarithmic scale shows that most simulated events have low p_T^Z . The rapidity distribution, in the middle-left, has most of the distribution at low rapidity. This means there are not as many simulated events with a large amount of momentum along the z-axis. The $\cos \theta_{CS}$ distribution, in the middle-right, is parabolic with most of the events having $\cos \theta_{CS}$ close to ± 1 . This happens when the lepton is traveling in a similar direction as the Z boson in the CS frame. Lastly, φ_{CS} in the bottom-left follows a W-shape distribution where it is largest around 0, π , and 2π .

Figure 1.9: Kinematic distributions of the Z boson derived from MC simulation of the process $q\bar{q} \rightarrow Z \rightarrow ee$ using Powheg+Pythia8. More information about Powheg+Pythia8 will be discussed in Section 4.2.1. These distributions assume no selection criteria and no detector effects. In the top-left and right are the mass and transverse momentum respectively on a logarithmic scale. The middle-left is the rapidity of the Z boson and the middle-right is the $\cos \theta_{CS}$ distribution. Lastly, on the bottom-left is the φ_{CS} distribution.

1.6 $\sqrt{s} = 8$ TeV Drell-Yan Angular Coefficients

The results from ATLAS at $\sqrt{s} = 8$ TeV [1] will be presented in order to show the distributions for the Drell-Yan angular coefficients. Preliminary results from ATLAS of $\sin^2 \theta_W$ from the Drell-Yan angular coefficients are also presented [18]. The data sets taken with the ATLAS detector in 2012 during Run 1 correspond to an integrated luminosity of 20.3 fb^{-1} . These results are a combination of both the electron and the muon channels in the central part of the detector. From the $\sqrt{s} = 8$ TeV paper [1] and from Table 1.4, it is expected that at LO in QCD there is only $q\bar{q}$ annihilation and only A_4 is non-zero. At NLO in QCD, other diagrams start to contribute such as gq , $g\bar{q}$, and gg , and as a result A_{0-3} are non-zero. At NNLO and higher orders in QCD, gluon loops contribute. This means A_{5-7} , while remaining small, are expected to be non-zero.

In Figure 1.10, Drell-Yan angular coefficients A_0 and A_2 are shown to both increase with p_T^Z . The difference between A_0 and A_2 is also shown to be non-zero. This difference between these two coefficients, known as the Lam-Tung relation [19, 20, 21] is of interest because, at NLO in perturbative QCD theory, this difference is expected to be zero from the gluon having spin 1 in $qg \rightarrow Zq$ and $q\bar{q} \rightarrow Zg$ diagrams. Including higher order diagrams, such as NNLO, this difference is allowed to be non-zero.

Figure 1.10: Experimental results for coefficients A_0 , A_2 , and $A_0 - A_2$ from ATLAS, taken at $\sqrt{s} = 8$ TeV [1]. The results are a combination of the electron (ee_{CC}) and muon ($\mu\mu_{CC}$) channels integrated over all rapidity values.

Figure 1.11 shows Drell-Yan angular coefficients A_1 , A_3 , and A_4 in the combined electron and muon channels integrated in rapidity. Both A_1 and A_3 increase with p_T^Z like A_0 and A_2 , however, not at the same rate. This difference, which are an order of magnitude different, can be seen in the y-axis scales of Figures 1.10 and 1.11. However, unlike the first four coefficients, A_4 decreases with p_T^Z . In the $\sqrt{s} = 8$ TeV paper [1], A_{5-7} were found to be non-zero with a significance of 3.0 standard deviations.

Figure 1.11: Experimental results for coefficients A_1 , A_3 , and A_4 from ATLAS, taken at $\sqrt{s} = 8$ TeV [1]. The results are a combination of the electron (ee_{CC}) and muon ($\mu\mu_{CC}$) channels integrated over all rapidity values.

From Table 1.4, A_3 and A_4 are linearly related to the vector and axial-vector couplings for both the quarks and the leptons. This means that the weak mixing angle, $\sin^2 \theta_W$, can be extracted from measuring these two coefficients. With this in mind, ATLAS performed a measurement⁵ using the A_4 measurement with the $\sqrt{s} = 8$ TeV data sets resulting in $\sin^2 \theta_{eff}^\ell = 0.23140 \pm 0.00036$ [18]. This result, shown in Figure 1.12, has a sensitivity comparable to, and in agreement with, the overall LEP-1/SLD: Z-pole average [7] denoted by the vertical band. This result is also in agreement with the $\sqrt{s} = 8$ TeV results from CMS, which has the most comparable data set.

⁵The measurement was of the effective leptonic weak mixing angle, $\sin^2 \theta_{eff}^\ell$. At the Z-pole it is related to the weak mixing angle through a flavour-dependent electroweak form factor, K_Z^ℓ by the relation $\sin^2 \theta_{eff}^\ell = K_Z^\ell \sin^2 \theta_W$.

Figure 1.12: Comparison of the effective lepton weak mixing angle, $\sin^2 \theta_{eff}^l$, of the ATLAS $\sqrt{s} = 8$ TeV measurement to previous measurements [18]. The ATLAS results at the bottom are in agreement to the vertical band corresponding to the LEP-1/SLD average.

A goal of measuring the Drell-Yan angular coefficients is to measure $\sin^2 \theta_W$ to constrain the SM. This is because $\sin^2 \theta_W$ is one of the free parameters in the SM and knowing its value to higher precision will help improve the model. The goal of this thesis is a feasibility study of measuring the Drell-Yan angular coefficients with special data sets taken with the ATLAS detector in 2017-18, during special runs. This is also the first look at this data set.

CHAPTER 2

LHC AND THE ATLAS DETECTOR

The measured properties of particles are dependent on how the particles are detected, so it is important to understand the LHC and ATLAS detector and what effects they can have on the measured data. This chapter will cover the LHC and how it accelerates protons that are collided in the ATLAS detector. It will also cover how the subdetectors of the ATLAS detector operate and how the triggering system in ATLAS detector works.

2.1 LHC

The LHC [22] is a 27 km circumference ring, operated by CERN, that can accelerate and collide protons at a centre-of-mass energy, up to $\sqrt{s} = 14$ TeV. It is located on the border of France and Switzerland, outside of Geneva. Every 25 ns, bunches of approximately 10^{11} protons are collided in four experiments located along the ring. The LHC started collecting data at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 2.36$ TeV, for beam and detector calibration, in 2009. During 2010-12, data sets were taken at $\sqrt{s} = 7, 8$ TeV before a long shut down from 2013-15, to upgrade the accelerator. This upgrade of the accelerator allowed the LHC to operate at higher centre-of-mass energy of $\sqrt{s} = 13$ TeV during Run 2, from 2015-18. Currently, the LHC is in another long shut down where the accelerator and some of the experiments are being upgraded again to be able to operate at the designed centre-of-mass energy of $\sqrt{s} = 14$ TeV, from 2021 onwards. The LHC has also accelerated heavy ions, Pb and Xe, at energies of $\sqrt{s} = 2.76, 5.02, 5.44,$ and 8.16 TeV per nucleon, where a nucleon is a proton or neutron. The heavy ion program is not further considered in this thesis.

The experiments at the interaction points of the LHC include ALICE [23], ATLAS [24], CMS [25], and LHCb [26]. ATLAS and CMS are the largest experiments at the LHC and are multipurpose detectors located on opposite sides of the ring. Both experiments record

as much information available from each collision for analysis. These analyses cover a range of physics, from precision physics to validate the SM to searching for new physics processes. ALICE is designed for precision measurements of heavy ion collisions as it is able to reconstruct up to several thousand tracks per event. To study hadrons comprised of b quarks, LHCb is a single-arm spectrometer, which allows for better positional tracking close to the beamline. It has the interaction point displaced by 11.25 m from the centre, to detect particles at a low angle close to the beamline as $b\bar{b}$ mesons are usually produced at low angles. There are also two other experiments, LHCf [27] and TOTEM [28], which detect particles in regions of very small angles from the beamline, by being placed further away from the interaction points. This thesis will focus on ATLAS as the predictions are for simulation and data taken with the ATLAS detector.

The proton beams go through acceleration steps before they are injected into the LHC, as seen in Figure 2.1. First, hydrogen gas is ionized to isolate protons. The protons are then accelerated to an energy of 50 MeV using radiofrequency cavities in a linear accelerator. They are sent to the proton synchrotron booster, which accelerates the protons up to an energy of 1.4 GeV using four superimposed synchrotron rings. The 1.4 GeV proton beam is then sent to the Proton Synchrotron (PS), which accelerates the beam up to 25 GeV. Before being sent to the LHC ring, the proton beam is accelerated using the Super Proton Synchrotron (SPS) up to an energy of 450 GeV. Lastly, the beam is injected into the LHC ring, where it is accelerated up to a maximum energy of 7 TeV.

Due to their small physical size, protons rarely physically collide. Instead, bunches of approximately 10^{11} protons are used to increase their chance to interact. The SPS is responsible for bunching the protons when injecting into the LHC. The protons are divided between two beam pipes until there are approximately 2800 bunches per beam pipe for a spacing of 25 ns between each bunch as they circulate around the LHC. The two beam lines in the LHC accelerate the bunches in opposite directions in order to maximize the centre-of-mass energy at collision.

CERN's accelerator complex

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Figure 2.1: Schematic overview of CERN complex [29]. To have proton-proton collisions, hydrogen atoms are ionized to produce protons before being accelerated through the path LINAC2, BOOSTER, PS, SPS, and LHC. Beams are then collided in experiments such as ATLAS.

The LHC was built to look for rare processes, so a large data set is required to increase the likelihood of observing these processes. The expected rate of events, dN_x/dt for process x , that the ATLAS detector would observe is expressed as:

$$\frac{dN_x}{dt} = \sigma_x \mathcal{L}. \quad (2.1)$$

In Equation 2.1, σ_x is the production cross-section and $\mathcal{L}$ is the instantaneous luminosity, which acts as a proportionality factor. The calculation for instantaneous luminosity involves the number of protons in the bunch, LHC circulation frequency, beam crossing angle, and density of the beam in all directions [30]. The LHC has exceeded the original designed instantaneous luminosity of $1.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ by a factor of two during Run 2 [31]. Data sets are usually reported in terms of the integrated luminosity, which is the time integral of the instantaneous luminosity. For ATLAS Run 2 (2015-18), the integrated luminosity that is useful for physics measurements is approximately 140 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$ [31].

When the bunches of protons are collided, only a fraction of protons interact while the rest pass through and continue to circulate. The purpose of having a high instantaneous luminosity is to increase the number of protons interactions at each 25 ns crossing of the LHC proton beams. For each data set, an average number of interactions per bunch crossing, $\langle\mu\rangle$, is also recorded. From 2015-18, $\langle\mu\rangle$ increased from 13.4 to 36.1 as a result of the instantaneous luminosity increasing. This increase in $\langle\mu\rangle$ leads to a pileup of events in the detector and makes reconstruction harder but allows for more data to be recorded. There are two forms of pileup: in-time and out-of-time pileup. In-time pileup is from the interactions occurring during the same bunch crossing. Since some subdetectors take up to several hundred ns to record the signals from the collisions, there can be overlaps of the signal called out-of-time pileup [32].

2.2 ATLAS Detector

The ATLAS detector (**A** Toroidal **L**HC **A**pparatu**S**) is one of the main experiments at CERN using the LHC ring. It is a multipurpose detector, which means that it tries to measure as much information as possible from each interaction. This provides flexibility to have a broad physics programme, such as precision measurements of SM physics and searching for new physics. It follows as a cylindrical geometry, as seen in Figure 2.2, which is divided into three different regions: the barrel, which is the central part, and the

two endcaps. The ATLAS detector is divided into subdetectors: the inner detector - closest to the beamline and identifies charged particle trajectory, the calorimeters - surrounds the inner tracker and measures the energy of the particles, and the muon spectrometer - furthest outside and is used to detect muons.

The Cartesian coordinate system, used by the ATLAS Collaboration for particle position, has the origin at the centre of the detector with the z-axis along the beamline. The x-axis points towards the centre of the ring, and the y-axis orthogonal to both, which is upwards. Cylindrical coordinates (r, ϕ) in the transverse plane are also used, where r is the radius and ϕ is the angle around the z-axis. To compliment the cylindrical coordinates, the pseudorapidity, η , is used. It is defined as $\eta = -\ln [\tan (\theta/2)]$, where θ is the polar angle between the trajectory and the positive z-axis. The pseudorapidity is equal to the Lorentz invariant rapidity, y , when the mass of the particle is negligible. This is approximately the case for particles that are light compared to their energy, such as electrons. The coordinate systems overlaying the ATLAS detector can be seen in Figure 2.2. The transverse momentum, p_T , is in the transverse plane along r .

Figure 2.2: Schematic of the ATLAS detector with labeled subdetector and magnet locations [33]. From inside out: the inner detector, the calorimeters, and the muon spectrometer. Cartesian coordinate system used by ATLAS: the z -axis is along the beamline, the x -axis points towards the centre of the LHC ring, and the y -axis consequently points upwards where the origin is at the centre of the detector (displaced from the origin for readability). Also used are r , θ , and ϕ where r is the radius in the xy -plane, θ is the polar angle from the z -axis, and ϕ is the azimuthal angle measured from the x -axis. A Lorentz invariant quantity pseudorapidity, $\eta = -\ln [\tan (\theta/2)]$, is used. The transverse momentum, p_T , is in the transverse plane along r .

2.2.1 Inner Detector

The Inner Detector (ID) [34, 35] is used to measure charged particle trajectories with high precision and reconstruct vertices of the interaction. There are two types of vertices: primary vertices - the original interaction location and secondary vertices - the location of longer-lived particle decay (such as τ leptons and some hadrons). The ID is divided into three subdetectors and covers a pseudorapidity range of $|\eta| < 2.5$ or $\sim 10^\circ \leq \theta \leq 170^\circ$ because of how close it is to the beamline. The order of subdetectors from inside out: the Pixel Detector, the Semiconductor Tracker, and the Transition Radiation Tracker, can be seen in Figure 2.3.

Figure 2.3: Cut away view of the ATLAS Inner Detector [36]. Closest to the beamline are the Insertable B-Layer (IBL) and the three layers of Pixel detector. Outside of that are the four layers of Semiconductor Tracker (SCT). Lastly, is the Transition Radiation Tracker (TRT) which is constructed out of straws with polypropylene fibers between them.

To construct trajectories, multiple detected points from charged particles interacting with layers of the subdetector are used. To aid in particle reconstruction, the ID uses a solenoid magnet located outside of the Transition Radiation Tracker, which provides a magnetic field strength of 2 T. By applying a magnetic field, the charged particles curve with the relation:

$$p_T = qBr, \quad (2.2)$$

where B is the magnetic field, p_T is the transverse momentum, q is the electric charge, and r is the radius of curvature. All three subdetectors combined have a transverse momentum resolution [37] as a function of p_T ¹:

$$\frac{\sigma_{p_T}}{p_T} \sim 0.05\% \frac{p_T}{\text{GeV}} \oplus 1\%. \quad (2.3)$$

¹In this thesis $\oplus$ denotes two quantities being added in quadrature ie. $a \oplus b = \sqrt{a^2 + b^2}$

Pixel Detector

The Pixel Detector is comprised of four barrel and three endcap layers, which make up $\sim 80\%$ of the readout channels in the ATLAS detector and has the finest position resolution of all ID subdetectors. The Pixel Detector is made of silicon semiconductors, which read out if a charged particle passes through. The innermost barrel layer, called the Insertable B-Layer (IBL) [38], was added during the upgrade period between Run 1 and 2 and is located at 33.25 mm from the beamline. The IBL has granularity $50\ \mu\text{m} \times 250\ \mu\text{m}$ with resolution of $10\ \mu\text{m}$ in $r\phi$ -plane and $75\ \mu\text{m}$ in the z direction. All the other layers of the Pixel Detector have granularity $50\ \mu\text{m} \times 400\ \mu\text{m}$ with resolution of $10\ \mu\text{m}$ in $r\phi$ -plane and $40\ \mu\text{m}$ in the z direction [37].

Semiconductor Tracker

The Semiconductor Tracker (SCT) works in a similar way as the Pixel Detector with silicon semiconductors. However, being further from the detector it is impractical to have such small detection elements. The SCTs are strips with pitch $80\ \mu\text{m}$ and length 6 or 13 cm. This gives them a resolution of $17\ \mu\text{m}$ in $r\phi$ -plane and $580\ \mu\text{m}$ in the z direction for the barrel layers [24]. The layers have strips that are set up back to back with an angle of 40 mrad between them. For the barrel there are four layers while each endcap has nine layers.

Transition Radiation Tracker

The Transition Radiation Tracker (TRT) [39, 40, 41] is the outermost subdetector for the ID. It utilizes straws that are 4 mm in diameter. The cathode is the straw, while the anode is a wire running through the centre of the straw. They are filled with a gaseous mixture of xenon (70%), carbon dioxide (27%), and oxygen (3%) [39], which is ionized when a charged particle passes through the straw. This ionization drifts towards the anode of the detector. The TRT also uses transition radiation to help with identifying charged particles.

Transition radiation comes from the charged particles interacting with polypropylene that is placed between the straws. When the charged particles interact with the polypropylene, photons are emitted and interact with the straws which emit a signal. Electrons provide more transition radiation, allowing for more charge to be accumulated on the anode. There are over 100,000 straws in the barrel and approximately 250,000 straws in the endcaps. The straws have a combined spatial resolution $130\ \mu\text{m}$ in the $r\phi$ -plane.

2.2.2 Calorimeters

Outside of the ID and the surrounding solenoid magnet, are the calorimeters, as seen in Figure 2.4. ATLAS has two calorimeter systems: the electromagnetic (ECAL) [42] and hadronic (HCAL) [42, 43]. They are sampling calorimeters, which utilizes a denser material called the absorber - that showers the particles - and an active material - to measure the energy deposited. For a sampling calorimeter, the absorber and active materials alternate, making the particles come to a stop in a more compact space with the entire energy deposited in the calorimeters. However, the absorber can have energy deposited in it that is not measured by the active material component. The calorimeters are segmented for position and shower shape reconstruction to identify the particles that are showering.

The energy resolution of calorimeters is dependent on the energy of the particle and follows the quadratic sum of terms of the form [45]:

$$\frac{\sigma_E}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c. \quad (2.4)$$

In Equation 2.4, a is the term dependent on the electronic noise and pileup in the detector, b is the term dependent on stochastic sampling uncertainty, and c is a constant term from the response of the detector and reconstruction of particles.

Figure 2.4: The schematic diagram of the calorimeter systems in the ATLAS detector [44]. On the inside is the electromagnetic calorimeter (ECAL) which is comprised of the liquid argon (LAr) electromagnetic barrel (EMB), electromagnetic endcap (EMEC), and the first layer of the Forward Calorimeter (FCal). Outside of it is the hadronic calorimeter (HCAL) comprised of the Tile barrel and extended barrel calorimeter, LAr hadronic endcap (HEC), and the last two layers of the FCal.

ECAL

The ECAL is the innermost calorimeter and is designed to detect the particles that shower electromagnetically by emitting $e^\pm$ and γ . Muons also interact electromagnetically and leave some energy in the ECAL system. However, they pass through the system to the rest of the detector. Electromagnetic showers come from cascades of bremsstrahlung radiation (emitted photons from motion through matter) and e^+e^- pair creation from an emitted photon, until they come to a stop in the detector. The energy deposited follows the form $E(x) = E_0 e^{-x/X_0}$, where x is the number of radiation lengths traveled and X_0 is the material dependent radiation length. The ECAL is constructed so particles travel through a minimum $24X_0$.

Seen in Figure 2.4, the ECAL is made of subdetector sections: the Electromagnetic Barrel (EMB), the Electromagnetic Endcap (EMEC), and the first layer of the Forward Calorimeter (FCal). The EMB and EMEC use lead absorbers and liquid argon (LAr) as the active material. In order to keep the LAr at a constant thickness, the lead absorbers are layered in an accordion shape. Before the EMB and EMEC is the presampler layer, which corrects for energy lost by the particle before it got to the calorimeter. The presampler has a granularity of $\eta \times \phi = 0.025 \times 0.1$. The EMB and EMEC have three layers, where the first layer discriminates between charged particles by using strips 4 mm wide in the η direction and has a granularity of $\eta \times \phi = 0.0031 \times 0.1$. A majority of the shower occurs in the second layer and it has a granularity of $\eta \times \phi = 0.025 \times 0.025$. Lastly, the third layer measures the remaining energy not deposited in the other layers and has a granularity of $\eta \times \phi = 0.05 \times 0.025$. The EMB and EMEC cover a range of $|\eta| < 1.475$ and $1.375 < |\eta| < 3.2$ respectively. The overlap region of $1.37 < |\eta| < 1.52$ has inefficiency from the separation between the EMB and the EMEC. The coefficients for Equation 2.4 for the EMB and EMEC resolution are $a \approx 0.4 \text{ GeV}$ [42], $b \approx 10\% \sqrt{\text{GeV}}$, and $c = 0.7\%$ [24].

The ECAL portion of the FCal uses copper as the absorber and follows a cylindrical geometry covering a pseudorapidity range of $3.0 < |\eta| < 4.9$. The FCal has worse resolution compared to the EMB and EMEC with terms $b \approx 29\% \sqrt{\text{GeV}}$ and $c = 3.5\%$ [24]. The electronic noise term, a , remains the same for the FCal.

HCAL

The HCAL [42, 43] is the calorimeter for detecting mostly hadronic particles, usually traveling further into the detector. Seen in Figure 2.4, the HCAL is made of three subdetectors: the Tile Calorimeter (covering up to $|\eta| < 1.7$), the Hadronic Endcap (HEC) (covering from $1.5 < |\eta| < 3.2$), and the last two layers of the FCal (covering from $3.1 < |\eta| < 4.9$). The Tile calorimeter consists of alternating steel plates as the absorber and polystyrene scintillator tiles as the active material. It has three layers, where the first two have granular-

ity $\eta \times \phi = 0.1 \times 0.1$ and the outermost layer has granularity $\eta \times \phi = 0.2 \times 0.1$. The Tile calorimeter has resolution coefficients of $a \approx 0.5 \text{ GeV}$, $b \approx 50\% \sqrt{\text{GeV}}$, and $c = 3\%$ [43].

The HEC is positioned behind the EMEC using copper as the absorber and LAr as the active material. The HECs are comprised of two wheels, where each wheel has two layers. It has a granularity of $\eta \times \phi = 0.1 \times 0.1$ for $|\eta| < 2.5$ and $\eta \times \phi = 0.2 \times 0.2$ for the rest. The HEC has worse resolution with coefficients a that ranges between $0.5 - 1.5 \text{ GeV}$ as a function of η , $b \approx 60\% \sqrt{\text{GeV}}$, and $c = 2\%$ [24]. Lastly, the FCal part of the HCAL uses tungsten as the absorber.

2.2.3 Muon Spectrometer

The Muon Spectrometer (MS) [46] is the outermost subdetector in the ATLAS main detector. Due to the large mass and long lifetime of the muons, they usually escape the other subdetectors and need their own subdetector to measure them. The MS is comprised of four subdetectors: the Monitored Drift Tube (MDT), Cathode Strip Chamber (CSC), Resistive Plate Chamber (RPC), and the Thin Gap Chamber (TGC). A schematic of the MS can be seen in Figure 2.5. The MS also has a barrel and endcap geometry, where the barrel has three layers and covers a range of $|\eta| < 1.05$ and the endcaps are comprised of three wheels covering a range of $1.05 < |\eta| < 2.7$. Like in the ID, a magnetic field is needed to measure the momentum and charge of the muons. This magnetic field comes from toroid magnets that are in the barrel and endcap in the MS. Since the toroid magnets in the barrel and endcap provide magnetic fields in different locations, the MS magnetic field is split into three regions: the barrel $|\eta| < 1.4$, the transition region $1.4 < |\eta| < 1.6$, and the endcap $1.6 < |\eta| < 2.7$.

All of the subdetectors of the MS use gas that is ionized when a charge particle passes through. The MDTs, found in the barrel and the two outermost wheels, are tubes filled with a gas mixture of Ar (91%), N₂ (4%), and CH₄ (5%). The CSCs are located in the small inner endcaps and instead of tubes they are comprised of strips with a mesh anode giving

Figure 2.5: Schematic of the muon spectrometer (MS) [47]. The barrel is comprised of Monitored Drift Tubes (MDT), Resistive Plate Chambers (RPC), and the barrel toroid magnets. For each endcap there is the smaller wheel of Cathode Strip Chambers (CSC) and Thin Gap Chambers (TGC), the endcap toroid magnets, and the larger two wheels comprised of MDTs and TGCs.

a two dimensional position measurement. RPCs are located in the barrel and are used for the muon triggering system. They are constructed of two plastic resistive plates with gas between the 2 mm gap. Lastly, the TGCs are used in the endcap for triggering and also use a mesh anode and strips similar to the CSCs. All four subdetectors work together so that the MDTs and CSCs give precision measurements for position and transverse momentum while RPCs and TGCs are used for triggering. The MS has momentum resolution [46]:

$$\frac{\sigma_{p_T}}{p_T} \sim \begin{cases} 2 - 3\% \frac{p_T}{\text{GeV}} & \text{most of the kinematic range,} \\ 10\% \frac{p_T}{\text{GeV}} & p_T \geq 1 \text{ TeV.} \end{cases} \quad (2.5)$$

2.2.4 Triggering

On average, 33.7 interactions occurred every 25 ns during Run 2 at $\sqrt{s} = 13$ TeV, which corresponds to an event rate of ~ 1.3 GHz. The read-out for a single event from all detectors in ATLAS is approximately 1.5 MB of data, so every event cannot be saved. Most interactions are not of much physical interest, so selection criteria must be applied to reduce the event rate. There are two levels of triggers that are applied: the Level-1 Trigger and the High Level Trigger. The Level-1 Trigger at the hardware level uses custom electronic hardware [48] utilizing information from the calorimeters and MS. If the event passes the Level-1 Trigger, all subdetectors are read out in the regions of interest. The High Level Trigger is at the software level and uses reconstruction algorithms to further reduce the event rate. After the Level-1 and High Level Trigger the event rate is reduced to approximately 1 kHz, which is then recorded for further analysis.

CHAPTER 3

A_i THEORY AND MEASUREMENT METHODOLOGY

This chapter will go over the methodology used to extract the Drell-Yan angular coefficients from the differential cross-section in Equation 3.1. It was first introduced in Section 1.3:

$$\frac{d\sigma}{dp_T^Z dy^Z dm^Z d\cos\theta d\varphi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z dy^Z dm^Z} \left\{ (1 + \cos^2\theta) + \sum_{i=0}^7 A_i(p_T^Z, y^Z, m^Z) P_i(\cos\theta, \varphi) \right\}. \quad (3.1)$$

Most of this research involves a common MC file tuned to ATLAS conditions, which will be discussed in more detail in Section 4.2. This MC simulates 5×10^6 $pp \rightarrow Z \rightarrow e^+e^-$ interactions in the ATLAS detector at $\sqrt{s} = 13$ TeV. It was used with the following procedure to make predictions of the Drell-Yan angular coefficients over all rapidity values in the mass range $80 \leq m^{\ell\ell} \leq 100$ GeV. There are three steps to extract the Drell-Yan angular coefficients. First, taking the moment to isolate each coefficient in the full phase space is necessary, where full phase space means no selection requirements to events are applied. Second, the coefficients are then extracted from the simulated events with the same selection criteria as data taken in the ATLAS detector. This selection criteria creates a reconstructed phase space, which is different than the full phase space. Finally, a statistical method, called folding, performs a fit of the likelihood for matching the reconstructed and full phase spaces. This fit allows for extracting the Drell-Yan angular coefficients, which otherwise cannot be extracted alone in the reconstructed phase space.

The Drell-Yan angular coefficients are important to measure for a few reasons. Firstly, the coefficients allow better understanding of Z boson production in hadronic collisions through the angular decomposition of Z boson production and decay. The second reason is to extract two of the coefficients A_3 and A_4 that are linearly proportional to the vector and

axial-vector couplings of both the leptons and quarks. This makes both of these coefficients sensitive to the weak mixing angle, $\sin^2 \theta_W$. Measuring $\sin^2 \theta_W$ constrains the SM, which has several free parameters. Constraining the SM allows for a more directed search of new physics by looking for deviations. Lastly, because the Z boson production involves the interaction of quarks and gluons, it allows for probing of the parton structure of the proton.

3.1 Moments Method

In the full phase space of the variables p_T , m , y , θ , and φ , extraction of each Drell-Yan angular coefficient can be performed using a technique called the moments method [49]. This is done in a similar manner as getting the first moment of a probability distribution function which gives the mean [50]:

$$\mu = \langle x \rangle = \int_{-\infty}^{\infty} x f(x) dx. \quad (3.2)$$

This isolation occurs by taking the moment to exploit the orthogonality of the trigonometric polynomials $P_i(\theta, \varphi)$, listed in Table 1.4. The moment is then:

$$\langle P_i(\theta, \varphi) \rangle = \frac{\int d\sigma(p_T, m, y, \theta, \varphi) P_i(\theta, \varphi) d\cos\theta d\varphi}{\int d\sigma(p_T, m, y, \theta, \varphi) d\cos\theta d\varphi}. \quad (3.3)$$

Comparing Equations 3.2 and 3.3, x is the polynomial P_i and the probability distribution function $f(x)$ is the differential cross-section $d\sigma$. In the denominator of Equation 3.3, the moment is normalized by the total unpolarized cross-section. For example, when $i = 4$ this results in:

$$\langle \cos\theta \rangle = \frac{1}{4} A_4. \quad (3.4)$$

Similarly, the rest of the A_i 's in Equation 3.5 can be obtained by taking the moments of their respective polynomials:

$$\begin{aligned}
\left\langle \frac{1}{2} (1 - 3 \cos^2 \theta) \right\rangle &= \frac{3}{20} \left(A_0 - \frac{2}{3} \right); & \langle \sin 2\theta \cos \varphi \rangle &= \frac{1}{5} A_1; \\
\langle \sin^2 \theta \cos 2\varphi \rangle &= \frac{1}{10} A_2; & \langle \sin \theta \cos \varphi \rangle &= \frac{1}{4} A_3; \\
\langle \cos \theta \rangle &= \frac{1}{4} A_4; & \langle \sin^2 \theta \sin 2\varphi \rangle &= \frac{1}{5} A_5; \\
\langle \sin 2\theta \sin \varphi \rangle &= \frac{1}{5} A_6; & \langle \sin \theta \sin \varphi \rangle &= \frac{1}{4} A_7.
\end{aligned} \tag{3.5}$$

Using this method allows for extracting all eight coefficients individually in the full phase space of the MC.

3.2 A_i 's Extracted from MC in Full Phase Space

In order to use the moments method from Section 3.1, the full phase space must be obtained through the following steps. First, the Z boson is reconstructed from the dilepton pair by adding their four-vectors. An example of the reconstructed dielectron mass spectrum can be seen in Figure 3.1, showing the expected Breit-Wigner Z mass resonance at 91 GeV [7].

Figure 3.1: Reconstructed dielectron mass spectrum from MC simulation of $Z \rightarrow ee$ of events ranging $66 \leq m^{ee} \leq 116$ GeV using Powheg+Pythia8. More information about Powheg+Pythia8 will be discussed in Section 4.2.1. The mass resonance is at the expected peak at 91 GeV [7].

Using the Z boson and the lepton pair, the CS angles - $\cos \theta_{CS}$ and φ_{CS} - are calculated from the angle definitions in Section 1.4. The total phase space is demonstrated through an 8×8 two dimensional histogram of $\cos \theta_{CS}$ ranging from $[-1, 1]$ and φ_{CS} bins ranging from $[0, 2\pi]$, as seen in Figure 3.2. The number of bins in $\cos \theta_{CS}$ and φ_{CS} follows what was used in the $\sqrt{s} = 8$ TeV measurement [1]. In this measurement they explored other binning configurations and found this binning was closest to optimal. As seen in Figure 3.2, the $\cos \theta_{CS}$ distribution follows a parabolic shape, where it is most frequent as $|\cos \theta_{CS}| \rightarrow 1$. The φ_{CS} distribution follows a W-shape, where it is most frequent at $\varphi_{CS} = \{0, \pi, 2\pi\}$. The $\cos \theta_{CS}$ and φ_{CS} plots in Section 1.5 show this can be expected.

Figure 3.2: Distribution of $\cos \theta_{CS}$ vs. φ_{CS} in the full phase space for $Z \rightarrow ee$ where no selection criteria nor detector effects are applied. The $\cos \theta_{CS}$ distribution follows a parabolic shape while the φ_{CS} distribution follows a W-shape.

The distributions of $\cos \theta_{CS}$ and φ_{CS} , like Figure 3.2, are created to form templates in each p_T^Z bin, which form the denominator in the moments method in Equation 3.3. There are also templates corresponding to the numerator from the moment method. These are templates of the full phase space as a function of each trigonometric polynomial, so in total

there are $9 \times N_{p_T}^{bins}$ templates. The templates are denoted by $T_{ij}(\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth}, p_T^{Truth, Z})$ for the i th polynomial in the j th p_T^Z bin. The A_i 's are then calculated from Equations 3.5 for each p_T^Z bin, denoted by A_i^{ref} . An example of A_4^{ref} can be seen in Figure 3.3.

Figure 3.3: Reference coefficient A_4 in 23 $p_T^{\ell\ell}$ bins extracted using the moments method from Equation 3.3. This is done using the full phase space of $Z \rightarrow ee$ MC simulation at $\sqrt{s} = 13$ TeV. The points are denoted by ee_{CC} , which refers to two electrons in the central region ($|\eta| < 2.4$).

3.3 A_i 's Extracted from MC in Reconstructed Phase Space

The reconstructed phase space demonstrates the realistic issues that are faced when trying to extract the Drell-Yan angular coefficients. The first issue is that the full phase space is not accessible from the limited acceptance and range in the detector. Another issue is that there can be some mismodeling in the MC of the instrumental inefficiencies as observed in data. Lastly, there are other processes that can mimic the Drell-Yan process, so this also needs to be corrected for. To correct for some of these issues, selection criteria are applied to remove data deemed unacceptable.

Some of the selection criteria come from the limited acceptance in the ATLAS detector, such as restrictions in η values that can be measured. One of these limitations is between the central and endcap sections of the ECAL, where there are cracks in the range $1.37 < |\eta^e| < 1.52$ and results in a limited acceptance. Since muons are measured in their

own subdetector, they do not have this same selection criteria applied to them. Another limitation is that the hardware triggers have a threshold on accepted particle p_T . Lastly, there is a finite resolution in all kinematic distributions resulting in a difference between measured and simulated values in these distributions. The selection criteria applied to both MC and data can be seen in Table 3.1, where loose LH electron [51] and medium muons [52] refer to selection criteria in the identification of these particles.

Electrons	Muons
Loose LH electron	Medium muon
$p_T^\ell > 25 \text{ GeV}$	$p_T^\ell > 25 \text{ GeV}$
$ \eta^\ell < 2.4$	$ \eta^\ell < 2.4$
$1.37 < \eta^\ell < 1.52$	
$80 < m^{\ell\ell} < 100 \text{ GeV}$	$80 < m^{\ell\ell} < 100 \text{ GeV}$

Table 3.1: Table of selection criteria for p_T^ℓ , η^ℓ , and $m^{\ell\ell}$ used for A_i calculations.

Since the detector efficiencies and particle identification are not perfectly modeled in the MC, weights are applied to correct for this mismodeling. The total weight is constructed from the product of individual particle scale factors for inefficiencies, such as: identification, isolation, reconstruction, pileup, and triggering. This total weight can be written as:

$$w_{event} = \prod_{i \in SF} w_i, \quad (3.6)$$

where SF is the set of scale factors.

The selection criteria from Table 3.1 removes events in the full phase space from Figure 3.2, which can be seen when compared to Figure 3.4. The most visible difference is a decrease in the number of events in the region $|\cos \theta_{CS}| \rightarrow 1$ which corresponds to $\theta_{CS} \approx 0$. Figure 1.8 of the Collin-Soper frame definition, shows that $\theta_{CS} \approx 0$ occurs when the leptons are close to the z-axis in the CS frame. Comparing Figures 3.2 and 3.4, the φ_{CS} distribution does not change much as both follow the W-shape.

Figure 3.4: Distribution of $\cos \theta_{CS}$ vs. φ_{CS} in the reconstructed phase space after selection criteria and detector effects are applied to $Z \rightarrow ee$ MC. The most noticeable effect is that as $|\cos \theta_{CS}| \rightarrow 1$ there is a decrease in events.

In order to better understand the effect that the selection criteria have on the full phase space, the CS angles are plotted versus p_T^ℓ and η^ℓ in the full phase space. This can be seen in Figures 3.5 and 3.6. Dashed lines are plotted to visually demonstrate what portion of the phase space is removed with the selection criteria from Table 3.1. From Figure 3.5, the effect on $\cos \theta_{CS}$ is largest with the selection $p_T^\ell > 25$ GeV, where a majority of the events with low p_T^ℓ correspond to $|\cos \theta_{CS}| \rightarrow 1$, as seen in a) and b). The effect of η^ℓ selection criteria on $\cos \theta_{CS}$ is not as noticeable compared to p_T^ℓ . This is because there is not a preferred $\cos \theta_{CS}$ value removed with the η^ℓ selection criteria. In Figure 3.6, there is not a preferred φ_{CS} value removed with the selection criteria. One interesting feature is the areas lost in Figures 3.6a and 3.6b are complimentary.

Figure 3.5: $\cos \theta_{CS}$ distribution vs. a) $p_T^{e^+}$, b) $p_T^{e^-}$, c) η^{e^+} , and d) η^{e^-} . The dashed lines are the selection criteria: $p_T^\ell > 25$ GeV, $1.37 < |\eta^\ell| < 1.52$, and $|\eta^\ell| < 2.4$.

Figure 3.6: φ_{CS} distribution vs. a) $p_T^{e^+}$, b) $p_T^{e^-}$, c) η^{e^+} , and d) η^{e^-} . The dashed lines are the selection criteria: $p_T^\ell > 25$ GeV, $1.37 < |\eta^\ell| < 1.52$, and $|\eta^\ell| < 2.4$.

Within data, there are other non-Drell-Yan signals that are occasionally misinterpreted as $Z \rightarrow \ell\ell$, which are known as background and fakes. Background is when non-Drell-Yan processes result in two leptons plus other particles and the two leptons pass the selection criteria. The three most dominant backgrounds are: $t\bar{t}$, $Z \rightarrow \tau\tau$, and VV - where $V = \{W, Z\}$. The combination of all three backgrounds is $< 1\%$ of the desired signal of $Z \rightarrow \ell\ell$. Fakes, which occur rarely, are when a particle other than a lepton passes the identification criteria and is mistakenly identified as a lepton. Before the Drell-Yan angular coefficients can be extracted, the amount of background and fakes must be estimated. Background estimates will be discussed further in Section 4.5.

The distortion of the phase space, from the p_T and η selection criteria, results in a breaking of the orthogonality of the polynomials in the moments method in Equation 3.3. This leads to signal templates $T_{ij} \left(\cos \theta_{CS}^{Reco}, \varphi_{CS}^{Reco}, p_T^{Reco,Z} \right)$ comparable in construction as the full phase space templates. In addition to the breaking of the orthogonality, there are other considerations, such as background and fakes. The background and fake signals are not expected to have the same $\cos \theta_{CS}$ and φ_{CS} distributions as the $Z \rightarrow \ell\ell$ signal. To account for backgrounds and fakes, they need to have their own templates, $T_B \left(\cos \theta_{CS}^{Reco}, \varphi_{CS}^{Reco}, p_T^{Reco,Z} \right)$ and $T_{Fakes} \left(\cos \theta_{CS}^{Reco}, \varphi_{CS}^{Reco}, p_T^{Reco,Z} \right)$, respectively.

To match the templates from simulation to those from data, the full simulation is folded into the templates from data that are reconstructed through a likelihood fit. In the likelihood fit, the templates are scaled with two parameters. The first is the i th coefficient in the j th bin, A_{ij} . The second, is a floating normalization parameter, μ_j , that scales the templates T_{ij} independently in the j th p_T bin. The likelihood fit is then:

$$\mathcal{L}(A_{ij}, \mu_j | N) = \prod_{events}^N \left\{ \sum_{j=1}^{N_{p_T}^{bins}} \mu_j \left[T_{8,j} + \sum_{i=0}^7 A_{ij} \times T_{ij} \right] + \sum_B^{bkgs} T_B + T_{Fakes} \right\}, \quad (3.7)$$

where $T_{8,j}$ refers to the template for the polynomial $P_8 = 1 + \cos^2 \theta$ from Equation 3.1 associated to the unpolarized cross-section. Since the data are counted, they should follow

a Poisson distribution in each p_T^Z bin of the likelihood. This implies that the expected mean in each bin is expected to be the sum of the templates. This likelihood fit results in values of coefficients A_{ij} and the associate statistical uncertainties.

3.4 Folding

A technique called unfolding is most often used in particle physics, which takes the measured phase space and unfolds into the full phase space [53]. The inverse of this is called folding, which takes the true variables in the full phase space and folds it into the measured variables in the reconstructed phase space. Given an understanding of the relation between the two phase spaces, folding or unfolding should give the same results. In general, truth observables - t - distributed in function - $f(t)$ - are folded through a probability distribution - $p(r|t)$ - into the reconstructed observables - r - and are distributed in function $g(r)$. This can be seen in Figure 3.7.

Figure 3.7: The truth distribution, $f(t)$, can be folded into the reconstruction distribution, $g(r)$, through the probability distribution $p(r|t)$. This methodology can also be used for the polynomials P_i .

The probability distribution, $p(r|t)$, must be constructed through simulation, as there is no analytical solution. This is done by finding the probability of measuring the reconstructed observables $r = (\cos \theta_{CS}^{\text{Reco}}, \varphi_{CS}^{\text{Reco}}, p_T^{\text{Reco}, \ell\ell})$, given the truth observables $t = (\cos \theta_{CS}^{\text{Truth}}, \varphi_{CS}^{\text{Truth}}, p_T^{\text{Truth}, Z})$. The truth observables come from the reference coefficients and templates from Section 3.2, while the reconstructed observables come from the templates in Section 3.3. Creating the probability distribution, as further explained in

Appendix A, results in the relation for the reconstructed templates:

$$T_{ij} = \sum_{event \in \Delta_j} \frac{P_i(\cos \theta_{CS}^{Reco}, \varphi_{CS}^{Reco}) w_{event}(r, t)}{\sigma_j \left\{ P_8(\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth}) + \sum_{i=0}^7 A_{ij}^{ref} P_i(\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth}) \right\}}, \quad (3.8)$$

where $\Delta_j = \left(\Delta p_T^{Z, Truth} \right)_j, \left(\Delta p_T^{\ell\ell, Reco} \right)_j, \left(\Delta \cos \theta_{CS}^{Reco} \right)_j$, and $\left(\Delta \varphi_{CS}^{Reco} \right)_j$. In this instance Δ_j is the j th bin width. In Equation 3.8, σ_j is the differential cross-section in the j th p_T^Z bin and w_{event} is the product of event scale factors, as described in Equation 3.6. Examples of templates $T_{4,j}$ can be seen in Figure 3.8, showing the evolution of the template in 11 p_T^Z bins from Equation 4.1.

Figure 3.8: Templates $T_{4,j}$ for coefficient A_4 in the j th p_T^Z bin in a set of 11 p_T^Z bins which will be discussed in Section 4.3. Along the x-axis is $\cos \theta_{CS}$, along the y-axis is φ_{CS} , and along the z-axis the number of events.

The statistical method of folding compared to unfolding has the advantage of easier-to-obtain statistical uncertainties. Unfolding data does not follow Poisson statistics, so a covariance matrix is required to be applied to the reconstructed data in order to get the proper statistical uncertainty. Folding has the statistical uncertainty built into the likelihood and follows Poisson statistics, making it easier to determine. Statistical uncertainty is important, as the primary goal of this study is to determine if there is sufficient statistical sensitivity to make a measurement. In the $\sqrt{s} = 8$ TeV paper [1], it was determined that the systematic uncertainty is most often negligible compared to the statistical uncertainty. The systematic uncertainty is not expected to change much between centre-of-mass energies and is assumed to be at a comparable level.

CHAPTER 4

WORK TOWARDS A_i PREDICTIONS AT $\sqrt{s} = 5, 13$ TeV WITH LOW $\langle\mu\rangle$ DATA AND COMPARISONS BETWEEN MC SIMULATION AND DATA

With the methodology described in Chapter 3, predictions for the Drell-Yan angular coefficients are made using MC simulation. This chapter will focus on predictions for special data sets taken in 2017 and 2018, where the average number of interactions per bunch crossing, $\langle\mu\rangle$, is much lower than what is normally taken in the ATLAS detector. The special data sets were taken at two different centre-of-mass energies, $\sqrt{s} = 5$ TeV and $\sqrt{s} = 13$ TeV. Predictions are compared between energies and between both electron and muon channels. Due to the low statistics of this special data set, a reduced number of p_T^Z bins - compared to the $\sqrt{s} = 8$ TeV measurement [1] - are needed in order to improve statistical sensitivity. Comparisons between two different MC generators are also done at $\sqrt{s} = 13$ TeV. In order to validate the data sets, comparisons between data and MC at $\sqrt{s} = 13$ TeV are done for their kinematics distributions including: p_T , η , and ϕ of the leading lepton and p_T , mass, rapidity, $\cos\theta_{CS}$, and φ_{CS} of the dilepton pair. The results from this chapter are original work and include a first look at these data sets with low $\langle\mu\rangle$.

4.1 Low $\langle\mu\rangle$ Data

Run 2, taken from 2015-18, had an average $\langle\mu\rangle = 33.7$, resulting in a total integrated luminosity of 146.9 fb^{-1} . The data sets used in this analysis were taken with a much lower average of $\langle\mu\rangle = 2$. The data sets were taken for the purpose of precision measurements, such as for W boson measurements, by having lower ambient energy associated to pileup. This analysis was performed as an exploratory study to see if a measurement of the Drell-Yan angular coefficients was feasible with this data set.

The first special runs, were performed during period M in Fall 2017, were taken at

$\sqrt{s} = 5$ TeV and resulted in an integrated luminosity of 258.4 pb^{-1} . The other special runs were taken at $\sqrt{s} = 13$ TeV, which occurred over multiple periods. The first was during period N in Fall 2017 with integrated luminosity of 146.6 pb^{-1} . Additional $\sqrt{s} = 13$ TeV data sets were taken during periods G4+J in Summer 2018, which resulted in an integrated luminosity of 193.2 pb^{-1} . This results in a total luminosity of 339.8 pb^{-1} taken at $\sqrt{s} = 13$ TeV. How this low $\langle\mu\rangle$ data set compares in size to the total data taken in Run 2 by the ATLAS detector can be seen in Figure 4.1. The small peak on the left corresponds to this special data set, which makes up less than 1% of the total Run 2 data.

Figure 4.1: Integrated luminosity vs. mean number of interactions per bunch crossing, $\langle\mu\rangle$, taken with the ATLAS detector during Run 2 at $\sqrt{s} = 13$ TeV. The small peak on the left hand side corresponds to the integrated luminosity of the low $\langle\mu\rangle$ data set used in this analysis [31].

4.2 Low $\langle\mu\rangle$ MC

This analysis used MC samples, listed in Appendix B, in order to simulate data taken in the special runs. To simulate the $\sqrt{s} = 5, 13$ TeV data, the MC generator, Powheg,

with showering software, Pythia8, are used for $Z \rightarrow ee, \mu\mu$. A second MC generator, Sherpa 2.2.1, was also used to simulate $\sqrt{s} = 13$ TeV data and to compare to the predictions made by Powheg+Pythia8. The Powheg+Pythia8 $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ samples at $\sqrt{s} = 5$ TeV were equivalent in data set size to an integrated luminosity of 9545.5 pb⁻¹ and 2178.0 pb⁻¹, respectively. This is equivalent to approximately 37 and 8 times the amount of $\sqrt{s} = 5$ TeV data taken. For Powheg+Pythia8 $Z \rightarrow ee, \mu\mu$ samples at $\sqrt{s} = 13$ TeV, the integrated luminosity was equivalent to 2630.1 pb⁻¹ for both electron and muon channels. This is equivalent to approximately 8 times the amount of $\sqrt{s} = 13$ TeV data taken. The Sherpa samples had 5041.0 pb⁻¹ integrated luminosity for both electron and muon channels at $\sqrt{s} = 13$ TeV, which is approximately 15 times the amount of data taken. Since this is a sensitivity study all of the MC samples, they are reweighted to the integrated luminosity of the special data sets.

4.2.1 Powheg+Pythia8

The Powheg+Pythia8 $Z \rightarrow ee, \mu\mu$ samples have events for low $\langle\mu\rangle$ generated from Powheg [54, 55, 56, 57] using the CT10 [58] PDF. The samples are then showered using Pythia8 [59] by using an ATLAS tune, which was first used in an $\sqrt{s} = 7$ TeV measurement [60]. The samples then have final state QED radiation simulated, through software Photos++ [61]. Lastly, the samples are renormalized to the NNLO calculation, performed using the DYTURBO program. DYTURBO is an optimized version of DYNNLO [62, 63] using the MMHT2014nnlo [64] PDF set. This methodology was done for $\sqrt{s} = 5, 13$ TeV in order to simulate the data sets. Background samples $Z \rightarrow \tau\tau$ and $t\bar{t}$, were also generated with Powheg+Pythia8. More information on all Powheg+Pythia8 samples can be found in Appendix B.

4.2.2 Sherpa 2.2.1

The Sherpa samples were generated with Sherpa 2.2.1 [65] at $\sqrt{s} = 13$ TeV using the NNPDF3.0NNLO [66] PDF set. Sherpa 2.2.1 merges Z+0,1,2 partons at NLO and Z+3,4 partons at LO by using the MEPS@NLO scheme. The samples were also renormalized with the same DYNNLO technique discussed with Powheg+Pythia8. The production of samples is divided by ranges of p_T^Z and used selection criteria that were applied during MC generation. This removed or limited events with an associated b or c quark. For this analysis, b and c vetoes were chosen because they best describe the selection criteria. The diboson background samples were generated with Sherpa 2.2.1 and Sherpa 2.2.2, as discussed in Appendix B.

4.3 Optimizing A New p_T^Z Binning

Due to the low statistics of this small data set after passing the selection criteria in Table 3.1, it was determined that the 23 p_T^Z bins used in the $\sqrt{s} = 8$ TeV measurement [1] would not give the necessary statistical sensitivity and that a new binning would be required. Certain criteria had to be met with the new p_T^Z binning. The criteria included: increasing statistical sensitivity, there are at least three bins below 10 GeV to ensure it was not susceptible to the shape of the p_T^Z distribution, and there are enough p_T^Z bins to not lose shape information of the A_i distributions. Since A_3 and A_4 are the coefficients of interest for a $\sin^2 \theta_W$ measurement, the binning was done to optimize their statistical uncertainty. A_3 is most sensitive at high p_T^Z , while A_4 is most sensitive at low p_T^Z ; therefore, new binning had to be created in two different regions and then stitched together. This is a challenge because the cross-section decreases as a function of p_T^Z , resulting in irregular p_T^Z binning. The last consideration was to minimize bin migration, which is the likelihood related to an event being in the wrong bin.

The same Powheg+Pythia8 MC file for the process $Z \rightarrow ee$ at $\sqrt{s} = 13$ TeV was used

for optimizing the binning derivation to ensure consistency during the process. The first test was to take the binning from the $\sqrt{s} = 8$ TeV measurement and remove every second bin boundary, resulting in 12 p_T^Z bins. This was not effective because it had too few bins below 10 GeV. There was also a significant uncertainty increase in the middle of the p_T^Z spectrum, as a result of too many bins being allocated in that region. After a few different binning options that were considered, the final binning used 11 p_T^Z bins and had the following bin boundaries:

$$p_T^Z [\text{GeV}] = \{0, 3, 6, 9, 12, 18, 30, 55, 85, 120, 200, 4000\}. \quad (4.1)$$

The comparison of the statistical uncertainty for A_4 can be seen in Figure 4.2 with binning: Equation 4.1, nominal 23 bins in the $\sqrt{s} = 8$ TeV measurement, and the previously mentioned 12 bins where every second boundary was removed.

Figure 4.2: Comparison of the statistical uncertainty for three binning configurations for A_4 . The circles are the 23 bins from the $\sqrt{s} = 8$ TeV measurement, the squares are every second p_T^Z boundary removed, and the triangles are the binning from Equation 4.1.

This binning was used for this analysis for a few reasons. Firstly, it allowed for approximately constant statistical uncertainty for events with $p_T^Z < 120$ GeV. This reduced the uncertainty in the region of $p_T^Z > 50$ GeV, where other binning configurations were too

fine. Secondly, it reduced the migration uncertainty in the region of $p_T^Z > 10$ GeV, where a lot of the other binning configurations had issues of increased uncertainty in this region. Lastly, the only way to reduce the uncertainty would be to have fewer bins in the low p_T^Z region. However, this would make the distribution too susceptible to the shape of the p_T^Z distribution, which would increase other statistical uncertainties.

The total statistical uncertainty of coefficient i in the j th p_T^Z bin, $\sigma_{A_{ij}}$, is comprised of three different components: data, migration, and non-migration - as seen in Figure 4.3. The data uncertainty corresponds to the Poisson statistical uncertainty of the amount of events in each bin. The migration uncertainty can be further decomposed, which will be discussed in Section 4.3.1. Lastly, non-migration uncertainty is the uncorrelated statistical uncertainty in the likelihood fit from Equation 3.7.

Figure 4.3: Decomposition of the statistical uncertainty for A_4 by type. The circles correspond to the total statistical uncertainty which is the same as the triangles in Figure 4.2 and is the addition in quadrature of the other uncertainties. The squares correspond to the Poisson statistical uncertainty of the number of events per bin. The upright triangles are the migration uncertainty which is the correlation between p_T^Z bins. Lastly, the downward triangles are the uncorrelated statistical uncertainty from the likelihood fit in Equation 3.7.

4.3.1 Migration

The statistical uncertainty for each coefficient is partially comprised of the migration uncertainty, which itself can be broken into pieces. These separate pieces are identified as self, shape, and norm-migration - as seen in Figure 4.4. Each column corresponds to a particular p_T^Z bin, while each row corresponds to a particular coefficient. Self-migration is the migration between p_T^Z bins and is dependent on the number of bins. Shape-migration is the uncertainty between different coefficients within the same p_T^Z bin. The same measurements are done for the norm - the denominator in Equation 3.3 - within each p_T^Z bin, which is labeled by norm-migration.

Figure 4.4: Migration uncertainty is split into three types: self, shape, and norm. Self-migration is the uncertainty attributed to the correlation between p_T^Z bins for the same coefficient. Shape-migration is the uncertainty for different coefficients within the same p_T^Z bin. Norm-migration is the self-migration for the norm in each p_T^Z bin. Based on image from [1].

An example of the migration uncertainty can be seen in Figure 4.5. For all of the coefficients, self-migration is the dominant migration uncertainty. Thus, appropriate binning is essential for minimizing this uncertainty.

Figure 4.5: Decomposition of migration uncertainty for coefficient A_4 . The circles correspond to the total migration uncertainty which is the addition in quadrature of the other shapes and is the same as the upright triangles in Figure 4.3. The squares correspond to the migration between p_T^Z bins, the upright triangles correspond to the correlation between coefficients, and the downward triangles correspond to the migration between p_T^Z bins for the norm.

A comparison of the migration uncertainty for the three binning configurations, discussed in Section 4.3, can be seen in Figure 4.6. The uncertainty in the region $p_T^Z < 10$ GeV is where the final binning has the largest comparative migration uncertainty. This is caused by the amount of bins in that region and an increased self-migration. However, this could not be avoided to ensure enough resolution in that region to not be susceptible to the shape of the p_T^Z distribution. Compared to the $\sqrt{s} = 8$ TeV paper p_T^Z bins, there is a significant reduction in migration uncertainty for the mid p_T^Z range.

Figure 4.6: A comparison of the migration uncertainty for A_4 . The 23 p_T^Z bins from $\sqrt{s} = 8$ TeV measurement are denoted by the circles, 12 p_T^Z bins, which is every second boundary removed denoted by the squares, and Equation 4.1 denoted by the triangles.

4.4 MC Predictions

Predictions are made with the MC samples in order to test for sufficient statistical sensitivity to measure the Drell-Yan coefficients with the low $\langle\mu\rangle$ data sets. This is done with the methodology presented in Chapter 3, by creating the reference coefficients with the truth information from the MC. Since these are predictions, reconstructed events in the MC are used in place of data. This allows the full statistics of the MC sample to be used before it is scaled down to the statistics of the data luminosity. Predictions are first done with the Powheg+Pythia8 $Z \rightarrow ee$ at $\sqrt{s} = 13$ TeV MC sample. Once the binning is chosen and predictions are established for this sample, the binning is tested with the Powheg+Pythia8 $Z \rightarrow \mu\mu$ sample at $\sqrt{s} = 13$ TeV. For both electrons and muon channels, only the Central Central (CC) events are used, which is defined as both leptons being in the central part of the detector bounded by $|\eta| < 2.4$. In the $\sqrt{s} = 8$ TeV measurements [1], Central Forward (CF) electrons were also used. However, the CF cross-section is smaller resulting in lower statistics. Due to the lower cross-section, the expected number of events in the CF region is expected to be an order of magnitude smaller, so it will not be used for this analysis.

4.4.1 Powheg+Pythia8 Predictions for $\sqrt{s} = 13$ TeV

Predictions of A_{0-4} are first made with the Powheg+Pythia8 $Z \rightarrow ee$ sample, which can be seen in Figure 4.7. This figure compares the $\sqrt{s} = 13$ TeV predictions, on the left, to the $\sqrt{s} = 8$ TeV results [1], on the right. All of the A_i distributions are in good agreement of their expected shapes from the $\sqrt{s} = 8$ TeV measurements [1]. However, A_0 has negative values for $p_T^Z < 10$ GeV, which is a known issue for the version of Powheg used. Due to the low statistics of the samples, A_1 and A_3 are expected to not have the required sensitivity, other than potentially in a few bins for A_1 . It is important to note at high p_T^Z A_1 fluctuates downwards. A_4 is expected to decrease as centre-of-mass energy increases, which will be discussed more in Section 4.4.3. The Powheg+Pythia8 samples were constructed at NLO, so the expected values for A_{5-7} will be 0 - previously mentioned in Section 1.3 in Table 1.4.

Figure 4.7: Prediction and comparison of coefficients $A_{0,2}$ (top) and $A_{1,3,4}$ (bottom) in electron channel for Powheg+Pythia8 at $\sqrt{s} = 13$ TeV (left) and combined channels for the $\sqrt{s} = 8$ TeV measurements [1] (right). Each A_i is denoted by the same symbol for both the Powheg+Pythia8 prediction and the $\sqrt{s} = 8$ TeV measurement for easier comparison. All predicted A_i 's are shifted to the right to avoid point and uncertainty bar overlap but all have the same uncertainty and position in p_T^Z .

The electron and muon channels are expected to be in agreement because there is no theoretical expectation for them to differ. Using the most precise coefficient, A_0 , the agreement between the two channels can be compared, as seen in Figure 4.8.

The electron and muon channels are in good agreement, which allows for a weighted average to combine the measurements. This will improve the overall precision of the measurement and - since the uncertainties are purely statistical - the samples can be treated as uncorrelated. In general, a weighted average and uncertainty for N measurements is [50]:

$$\hat{x} \pm \sigma_{\hat{x}} = \frac{\sum_{i=1}^N x_i / \sigma_i^2}{\sum_{j=1}^N 1 / \sigma_j^2} \pm \sqrt{\frac{1}{\sum_{j=1}^N 1 / \sigma_j^2}}. \quad (4.2)$$

Figure 4.8: Comparison of electron and muon channels at $\sqrt{s} = 13$ TeV for coefficient A_0 . The electron channel denoted by the circles is in good agreement with the muon channel denoted by the squares. The muon channel is shifted to the right to avoid point overlap and have the same p_T^Z position as the electron channel.

For the i th coefficient in the j th p_T^Z bin, A_{ij} , this simplifies to:

$$A_{ij} \pm \sigma_{A_{ij}} = \frac{A_{ij}^{ee} \sigma_{A_{ij}^{\mu\mu}}^2 + A_{ij}^{\mu\mu} \sigma_{A_{ij}^{ee}}^2}{\sigma_{A_{ij}^{\mu\mu}}^2 + \sigma_{A_{ij}^{ee}}^2} \pm \frac{\sigma_{A_{ij}^{\mu\mu}} \sigma_{A_{ij}^{ee}}}{\sqrt{\sigma_{A_{ij}^{\mu\mu}}^2 + \sigma_{A_{ij}^{ee}}^2}}. \quad (4.3)$$

Using Equation 4.3, the channels are combined for A_4 , as shown in Figure 4.9. This combination of channels increases the sensitivity for A_4 in all p_T^Z bins. A_4 is expected to have sufficient statistical uncertainty, which is constituted as having a majority of bins more than one standard deviation away from zero. Sensitivity to A_4 is expected so a measurement of $\sin^2 \theta_W$ might be possible with this data set with a limited statistical sensitivity. Predictions of coefficients A_{0-3} with combined channels can be found in Appendix C.

Figure 4.9: Combination of the predictions for coefficient A_4 in electron and muons channels for Powheg+Pythia8 at $\sqrt{s} = 13$ TeV using Equation 4.3 and is scaled down to the luminosity of data.

4.4.2 Powheg+Pythia8 Predictions for $\sqrt{s} = 5$ TeV

Predictions for $\sqrt{s} = 5$ TeV are also done to see the evolution of the coefficients with centre-of-mass energy. The same binning described in Section 4.3 is used. This is not an ideal choice, as this binning was designed for the $\sqrt{s} = 13$ TeV sample. The predictions for A_4 can be seen in Figure 4.10, which has the uncertainty increase faster in the region $p_T^Z > 100$ GeV compared to $\sqrt{s} = 13$ TeV. Since $\sqrt{s} = 5$ TeV has a lower cross-section, this results in fewer events at high p_T^Z and fewer overall. In order to do a measurement for the $\sqrt{s} = 5$ TeV sample, different binning would be needed and would include combining some of the higher p_T^Z bins.

Figure 4.10: Prediction at $\sqrt{s} = 5$ TeV for A_4 in electron channel for Powheg+Pythia8 which has the MC scaled down to the luminosity of the data.

4.4.3 Comparison Between Powheg+Pythia8 Predictions for $\sqrt{s} = 5, 13$ TeV

The differential cross-section - with respect to transverse momentum of the boson - is dependent on the centre-of-mass energy, so a difference is expected between predictions at $\sqrt{s} = 5, 13$ TeV. The A_i 's are also expected to change with the evolution of centre-of-mass energy, but not to the same degree because they are ratios of cross-sections. Coefficients A_0 and A_2 are not expected to change significantly with centre-of-mass energy, however, coefficients $A_{1,3,4}$ are expected to decrease with an increased centre-of-mass energy, which can be seen in Figure 4.11.

Figure 4.11: Comparison of the electron channel predictions made at $\sqrt{s} = 5$ TeV, denoted by squares, and $\sqrt{s} = 13$ TeV, denoted by circles, for coefficients A_{0-4} for MC generator Powheg+Pythia8. The $\sqrt{s} = 13$ TeV points are shifted to the right to avoid overlap and have the same p_T^Z position as the $\sqrt{s} = 5$ TeV predictions.

4.4.4 Sherpa Predictions for $\sqrt{s} = 13$ TeV

To see the effect of the MC generator on the predicted A_i values, predictions are made with another generator, Sherpa 2.2.1. Predictions of A_3 and A_4 can be seen in Figure 4.12, where both follow the expected distributions - similar to the $\sqrt{s} = 8$ TeV results [1].

Figure 4.12: Predictions at $\sqrt{s} = 13$ TeV of A_3 and A_4 in the electron channel for Sherpa 2.2.1 scaled down to the luminosity of the data.

4.4.5 Comparison Between Powheg+Pythia8 & Sherpa Predictions for $\sqrt{s} = 13$ TeV

Comparisons of the two MC generators is done only for $\sqrt{s} = 13$ TeV, as there are no samples generated at $\sqrt{s} = 5$ TeV with Sherpa. These comparisons are primarily done to better understand the difference in how events are simulated between the two MC generators. The comparison between Powheg+Pythia8 and Sherpa in the electron channel can be seen in Figure 4.13. The distributions both agree with the shapes of the $\sqrt{s} = 8$ TeV results [1] but there are still differences between the generators. An important difference for A_0 is that Sherpa does not have the same issues at low p_T^Z that Powheg+Pythia8 has. Another difference for A_0 and A_2 is that Sherpa fluctuates down at high p_T^Z but this could be from the low statistics. A_1 has the most difference between the MC, as Powheg+Pythia8 predicts A_1 to increase sooner compared to Sherpa. Lastly, A_3 and A_4 show the most agreement between the two generators and do not have the same

statistical fluctuations that the other coefficients see.

Another important difference between the two generators is that the uncertainty is different. This is unintuitive as they are both scaled to the same luminosity and are expected to have the same statistical uncertainty. However, different cross-sections are used when generating the MC samples. This same cross-section is used when scaling each MC generator to the luminosity of data. Using the cross-sections and filter efficiencies listed in Appendix B, Powheg+Pythia8 has $\sim 6.7 \times 10^5$ expected events, while Sherpa has $\sim 5.8 \times 10^5$ expected events.

The difference between expected events affects the expected Poisson statistical uncertainty slightly as the events are not spread uniformly between p_T^Z bins. This difference is increased with the difference in the number of events that pass selection criteria. The expected number of events also increases the other components of the total statistical uncertainty, as discussed in Sections 4.3. The migration uncertainty was also increased for Sherpa, as there are fewer events in each bin and results in them being more correlated. This is from having fewer events for constructing the templates. The difference in uncertainty is not an issue, however, as both MC generators expect the A_i 's to have sufficient statistical uncertainty.

Figure 4.13: Comparison of predictions that are made by Powheg+Pythia8 denoted by squares and Sherpa 2.2.1 denoted by circles in the electron channel at $\sqrt{s} = 13$ TeV. Powheg+Pythia8 is shifted to the right in order to avoid overlap but has the same $p_T^||$ position as Sherpa.

4.5 Kinematics Distributions with Data and MC at $\sqrt{s} = 13$ TeV

In order to test the agreement between MC and data, their kinematic distributions are compared. The presented kinematic distributions compare the $\sqrt{s} = 13$ TeV low $\langle\mu\rangle$ data and the MC sample Powheg+Pythia8 $Z \rightarrow ee$, denoted by PP8 $Z \rightarrow ee$ in the figures. Other processes, such as $WW \rightarrow e\nu e\nu$, can mimic the signal of $Z \rightarrow ee$ and must be accounted for. To compensate for the expected background signals, the presented kinematic distributions also contain MC simulation of the three most dominant backgrounds: $t\bar{t}$, diboson, and $Z \rightarrow \tau\tau$. The diboson background signal is the sum of the three combinations of VV signals, where $V = \{W, Z\}$. More details on these background samples can be found in Appendix B. The total background fraction is $< 0.5\%$. Table 4.1 gives the percentage breakdown of expected events for all processes.

Process	% of total events
$Z \rightarrow ee$	99.60
$Z \rightarrow \tau\tau$	0.04
<i>Diboson</i>	0.17
$t\bar{t}$	0.19

Table 4.1: Estimated fraction of events from MC simulation for a dilepton pair that pass the selection criteria in Table 3.1 and are within the mass window of $66 \leq m^{\ell\ell} \leq 116$ GeV.

All of the kinematic distributions presented are events that fall within the mass window of $66 \leq m^{\ell\ell} \leq 116$ GeV and satisfy the selection criteria presented in Table 3.1. The leading lepton kinematic distributions are shown in Figure 4.14, where leading lepton refers to the lepton with the larger p_T value. Next the dielectron kinematic distributions are shown in Figure 4.15. The p_T^{ee} distribution, from Figure 4.15, is compared to the same distribution from a total production cross-section paper [67] at $\sqrt{s} = 13$ TeV in Figure 4.16. The $\cos\theta_{CS}$ and φ_{CS} distributions integrated over p_T^Z , calculated from their definitions in Section 1.4, are shown in Figure 4.17. Figure 4.18 shows the p_T^Z dependence of the $\cos\theta_{CS}$ and φ_{CS} distributions in three different p_T^Z bins. The subleading lepton and additional dielectron kinematic distributions can be found in Appendix C. The kinematic distribu-

tions are displayed with a linear scale on the left and a logarithmic scale on the right for Figures 4.14, 4.15, and 4.17. Logarithmic scales are presented to show the distribution of the backgrounds which would otherwise not be visible. For Figure 4.18, it has $\cos \theta_{CS}$ on the left and φ_{CS} on the right for each p_T^Z bin. All of these distributions are discussed in more detail below.

The kinematic distributions have plots of the ratio of data/MC that show how well data and MC agree. The points that are not within a 15% agreement appear as arrows in the direction of the points. An exception is for p_T^{ee} and m^{ee} , where the ratio shows points that are within 30% agreement. The uncertainty on the points in the ratio plots is the statistical uncertainty of the data, while the band is the statistical uncertainty of the MC added in quadrature with an estimate of the systematic uncertainty. The estimate comes from a $\sqrt{s} = 7, 8, 13$ TeV Z cross-section measurement [68] and is taken to be a constant 1%. Some of the elements that contribute to this systematic uncertainty are lepton trigger, reconstruction, identification, and isolation. The p_T^{ee} distribution, however, uses a $p_T^{\ell\ell}$ dependent systematic uncertainty, which comes from an $\sqrt{s} = 8$ TeV differential cross-section measurement [69]. Neither systematic uncertainties contain a systematic uncertainty from data luminosity, which is approximately 2% but has not been released yet.

In Figure 4.14, the leading lepton p_T shows good agreement within 5% between MC and data in the peak region centred around the expected 45 GeV. In regions of low and high p_T , this difference could be attributed to the order of the MC that is not sufficiently high enough to correctly model the data. This disagreement at high p_T , where the missing higher orders contribute, was also seen in the early $\sqrt{s} = 13$ TeV cross-section paper [67]. However, a majority of the points are within 15% agreement as seen in the ratio plot. The leading lepton η distribution is in agreement of 5% but the ratio plot shows some modulation. This modulation can be attributed to the electron trigger, which has a similar modulation in η [51]. The crack region of the detector bounded by $1.37 < |\eta| < 1.52$ is visible with the significant drop in events in both MC and data. The ϕ distribution is also

in good agreement, where most points are also within 5% and the MC over estimates the number of events. The logarithmic plots in Figure 4.14 show that the background estimates follow a similar shape as the signal with the exception of $Z \rightarrow \tau\tau$, which is distributed mostly at low p_T .

Figure 4.14: Leading electron p_T (top), η (middle), and ϕ (bottom) distributions for $Z \rightarrow ee$ within $66 \leq m^{\ell\ell} \leq 116$ GeV mass window and passing selection criteria. The points represent the data and associated statistical uncertainties. The MC signal and background distributions are normalized to the data luminosity and are denoted by the filled histograms. The uncertainty band in the ratio plot is the MC statistical and systematic uncertainties added in quadrature.

In Figure 4.15, the dielectron distributions are in agreement to some extent between data and MC. The m^{ee} has most points agreeing within 10%, while there is some modulation around the central mass peak. This has been observed before in the $\sqrt{s} = 13$ TeV cross-section paper [67], and the $\sqrt{s} = 7, 8, 13$ TeV Z cross-section measurement [68]. This modulation could be an energy calibration issue for the electrons. Not all of the dielectron backgrounds follow the same distribution as the signal. The $Z \rightarrow \tau\tau$ signal is shifted to low mass because the τ leptons decays to $\tau \rightarrow e\bar{\nu}_e\nu_\tau$. Thus, it results in missing energy from the neutrinos and makes the dielectron mass shift downwards. The $t\bar{t}$ signal appears as a line, as this is just part of the smooth mass spectrum.

For p_T^{ee} , there is not much agreement between data and MC. This can be attributed to the NLO MC not being a high enough order to describe the data at high p_T^Z . This has also been observed in the early Z cross-section paper [67] and can be seen in Figure 4.16. For the low $\langle\mu\rangle$ data, there are three bins where there are no data events passing the selection criteria. The dielectron rapidity distribution is within a 3% agreement, other than the outermost bins.

Figure 4.15: Dielectron mass (top), p_T (middle), and rapidity (bottom) distributions for $Z \rightarrow ee$ within $66 \leq m^{\ell\ell} \leq 116$ GeV mass window and passing selection criteria. The points represent the data and associated statistical uncertainties. The MC signal and background distributions are normalized to the data luminosity and are denoted by the filled histograms. The uncertainty band in the ratio plot is the MC statistical and systematic uncertainties added in quadrature.

Figure 4.16: p_T^{ee} measurement from the Z cross-section paper [67] at $\sqrt{s} = 13$ TeV, which also sees a disagreement between data and MC at high p_T^{ee}

The detector has finite resolution and acceptance, which changes the shape of the kinematic distributions from the “truth” values from the MC in Figure 1.9. The truth values are what is generated by MC before smearing and detector effects are applied to the events. These effects are applied in order to better simulate what would be observed with data in reality. For instance, the dielectron mass spectrum has a much sharper peak in the truth distribution compared to the dielectron mass in Figure 4.15. This is because the detector has finite resolution and smears the data. However, the y^{ee} and p_T^{ee} distributions look similar to the truth level distributions.

The angular distributions, $\cos \theta_{CS}$ and φ_{CS} , are used to extract the A_i ’s, as discussed in Section 3.2. Figure 4.17 shows that both CS angles are within a 3% agreement and are well modeled by the MC. The $t\bar{t}$ and diboson backgrounds follow the same shape as the signal, while the $Z \rightarrow \tau\tau$ does not. This highlights the importance of having different templates for background in Equation 3.7. The $Z \rightarrow \tau\tau$ background does not have any events in the $\cos \theta_{CS}$ distribution in the edge bins and, for φ_{CS} , it does not follow the shape at all. Comparing to the truth level distributions in Figure 1.9, both $\cos \theta_{CS}$ and φ_{CS} distributions are flipped in shape. This flipping in shape is expected for $\cos \theta_{CS}$, as discussed in Section 3.3. However, for φ_{CS} , the flip in shape can be attributed to the amount

of low p_T^Z events that are removed with the selection criteria.

Figure 4.17: Angular distributions $\cos \theta_{CS}$ (top) and φ_{CS} (bottom) integrated over p_T^Z for $Z \rightarrow ee$ within $66 \leq m^{\ell\ell} \leq 116$ GeV mass window and pass selection criteria. The points represent the data and associated statistical uncertainties. The MC signal and background distributions are normalized to the data luminosity and are denoted by the filled histograms. The uncertainty band in the ratio plot is the MC statistical and systematic uncertainties added in quadrature.

The kinematics of the Z bosons determine the allowed phase space for the angular distributions. As p_T^Z increases, $\cos \theta_{CS}$ and φ_{CS} are expected to change, which was seen in the $\sqrt{s} = 8$ TeV measurement [1] and is why the A_i distributions are p_T^Z dependent. This can be seen in Figure 4.18, which has the $\cos \theta_{CS}$ and φ_{CS} distributions in three larger p_T^Z bins of $p_T^Z < 9.0$ GeV, $9.0 \leq p_T^Z < 55.0$ GeV, and $p_T^Z \geq 55.0$ GeV. These regions come from the 11 p_T^Z bins corresponding to the first three bins, middle three bins, and last four bins, respectively. This grouping was done in order to have close to equal number of events for each but still have the same boundaries as the 11 p_T^Z bins. The data/MC ratio plots are not meaningful, as most of the disagreement comes from the disagreement in the p_T^{ee} plot in Figure 4.15. For the region $p_T^Z < 9.0$ GeV, $\cos \theta_{CS}$ is mostly flat other than in the outermost bins and φ_{CS} is decreased around values $\pi/2$ and $3\pi/2$. The region of $9.0 \leq p_T^Z < 55.0$ GeV changes both distributions, such that $\cos \theta_{CS}$ has fewer events further from 0, while φ_{CS} has its shape flipped. For the last region of $p_T^Z \geq 55.0$ GeV, both of these effects become more pronounced.

Figure 4.18: Angular distributions $\cos \theta_{CS}$ (left) and φ_{CS} (right) of the dielectron system in p_T^Z bins: $p_T^Z < 9.0$ GeV (top), $9.0 \leq p_T^Z < 55.0$ GeV (middle), and $p_T^Z \geq 55.0$ GeV (bottom). The points represent the data and associated statistical uncertainties. The MC signal and background distributions are normalized to the data luminosity and are denoted by the filled histograms. The uncertainty band in the ratio plot is the MC statistical and systematic uncertainties added in quadrature. For top-right and middle-right plots for φ_{CS} , the y-axes are suppressed.

4.6 Conclusion

Predictions of the Drell-Yan angular coefficients were presented and the shapes are in agreement with the $\sqrt{s} = 8$ TeV measurements. As of now, the extraction of the A_i 's with data is not permitted due to the ATLAS Collaboration's blinding strategies because of their correlation to incomplete low $\langle\mu\rangle$ data analyses such as the W mass measurement. This is because the equivalent coefficients for the W boson have not been measured so the Z boson is used to model the structure instead. The correlation makes the A_i 's a systematic uncertainty for W boson measurements. Currently, it is unknown what the quantitative effect of the A_i 's measured with the low $\langle\mu\rangle$ data sets will be on the W boson measurements.

This analysis was done to test for the statistical sensitivity of the low $\langle\mu\rangle$ data sets with MC simulation. It was demonstrated that it is expected to have sufficient statistical sensitivity for a majority of the coefficients when the electron and muon channels are combined. This sensitivity is shown by A_0 , A_2 , and A_4 are different than zero in a majority of their bins. A_1 also has some bins that are non-zero but not a majority. This statistical sensitivity would allow for $\sin^2\theta_W$ to be inferred from A_4 , as it is linearly dependent on the vector and axial-vector couplings.

From Section 4.5, the kinematic distributions show sufficient agreement between simulation and data where most of the disagreement is attributed to the MC used not being of sufficiently high enough order. The Drell-Yan angular coefficients extracted from the low $\langle\mu\rangle$ data sets are expected to have sufficient statistical uncertainty because the MC and data are in agreement, the MC has sufficient statistical significance, and the shapes are in agreement when compared to the $\sqrt{s} = 8$ TeV measurement [1].

CHAPTER 5

CONCLUSION

The first goal of this thesis was to determine if there was sufficient statistical sensitivity to measure the Drell-Yan angular coefficients with the low $\langle\mu\rangle$ data set taken by the ATLAS detector in 2017 and 2018. A majority of the coefficients are expected to have sufficient statistical sensitivity to be measured by having a majority of bins different than zero by at least one standard deviation. The electron and muon channels are also expected to agree and combining them allows for an increase in the statistical sensitivity. The predicted coefficients are also found to be in agreement to the expected shapes from the $\sqrt{s} = 8$ TeV measurement [1].

The second goal, was to verify that the kinematic distributions of the MC and data were in agreement. A majority of the kinematic distributions are reasonably in agreement. However, some discrepancies are observed at high p_T that can be attributed to the MC not being of sufficiently high enough order. Since the MC and data are reasonably in good agreement and the MC demonstrates that there should be sufficient statistical sensitivity using 11 p_T^Z bins, it can be expected that the data will also have sufficient statistical sensitivity to measure the Drell-Yan angular coefficients.

5.1 Outlook

The measurement of the Drell-Yan angular coefficients with $\sqrt{s} = 13$ TeV data will not be restricted to the low $\langle\mu\rangle$ data set. Instead, the full $\sqrt{s} = 13$ TeV Run 2 data set will be used corresponding to an integrated luminosity of approximately 140 fb^{-1} . The low $\langle\mu\rangle$ data set is a small subset of this data as it corresponds to an integrated luminosity of 0.3 fb^{-1} . Using the full Run 2 data set will allow for the best statistical sensitivity. However, this analysis in this thesis will be useful because the low $\langle\mu\rangle$ data sets will need

to be treated differently.

The low $\langle\mu\rangle$ data could potentially be used in a different capacity. Instead of continuing with the Drell-Yan coefficients of the Z boson, the data sets could be used to measure the Drell-Yan angular coefficients of the W boson for the first time. These coefficients have not previously been measured before but there are theoretical predictions for them [16], as the W boson differential cross-section is similarly constructed to the Z boson. The difference between detection of the W and Z bosons is that the W boson decays into $\ell\nu_\ell$ instead of $\ell^+\ell^-$.

Measurement of the W boson angular coefficients is important for validating the SM and measuring the mass of the W boson but also comes with challenges. Most of these challenges are attributed to the neutrino and the reconstruction of the W boson. The transverse momentum of the system can be measured with the missing energy in the calorimeters and can be associated to the neutrino. However, there is ambiguity in the longitudinal direction since only the transverse plane is measurable. The low $\langle\mu\rangle$ data will be useful for this measurement because the low pileup allows for better isolation of the missing energy associated to the neutrino. Using the CS frame, only coefficients A_0 , A_2 , A_3 , A_5 , and A_7 are expected to be measured since there is ambiguity in $\theta \leftrightarrow \theta - \pi$ [16]. One benefit of measuring the W angular coefficients is that there is expected to be an increase in statistical sensitivity compared to the Z boson. This is because W bosons are produced approximately ten times as frequent when compared to the Z boson so the statistical sensitivity can increase up to a factor of $\sqrt{10}$. Measurement of the Drell-Yan angular coefficients for the W boson should be plausible with this low $\langle\mu\rangle$ data taken in the ATLAS detector.

Appendices

APPENDIX A

FOLDING

In general, truth observables - t - distributed in function - $f(t)$ - are folded through a probability distribution - $p(r|t)$ - into the reconstructed observables - r - and are distributed in function $g(r)$ given by Equation A.1:

$$g(r) = \int f(t) p(r|t) dt. \quad (\text{A.1})$$

The convolution, $p(r|t)$, is the probability to observe truth, t , from reconstructed, r . Similarly, the trigonometric polynomials can be folded. In this case the truth observables are $t = (\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth}, p_T^{Truth,Z})$ and are folded into the reconstructed observables - which are $r = (\cos \theta_{CS}^{Reco}, \varphi_{CS}^{Reco}, p_T^{Reco,\ell\ell})$. Using these elements, an expression for the i th folded polynomial in the j th p_T^Z bin $\tilde{P}_{ij}$ can be obtained:

$$\tilde{P}_{ij} \left(r | p_T^{Z,Truth} \in \left(\Delta p_T^{Z,Truth} \right)_j \right) = \int_{(\Delta p_T^{Z,Truth})_j} \int_{\cos \theta_{CS}^{Truth}} \int_{\varphi_{CS}^{Truth}} P_i (\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth}) p(r|t) dt. \quad (\text{A.2})$$

The folded polynomials, $\tilde{P}_{ij}$, are over a finite range of $p_T^{Truth,Z}$, expressed as $\left(\Delta p_T^{Z,Truth} \right)_j$. In order to get an expression for the templates, MC is used to estimate $p(r|t)$ since there is not an analytical solution for it. The moments derived in Section 3.2 are taken to help build the two dimensional phase space of $\cos \theta_{CS}$ and φ_{CS} in the j th bin of p_T , similar to the phase space in Figure 3.2 - denoted by $f_j (\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth})$, which has the form:

$$f_j (\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth}) = \sigma_j \left\{ P_8 (\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth}) + \sum_{i=0}^7 A_{ij}^{ref} P_i (\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth}) \right\}. \quad (\text{A.3})$$

In Equation A.3: σ_j is the differential cross section in the j th p_T^Z bin and $P_8 = 1 + \cos^2 \theta$.

Using $f_j(\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth})$, an estimate of $p(r|t)$ can be constructed:

$$p^{MC}(r|t) = \frac{w_{event}(r, t)}{f_j(\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth})}, \quad (\text{A.4})$$

where an event based weight, $w_{event}(r, t)$, is the product of scale factors in order to compensate for the deficiencies of the detector. The definition can be found in Equation 3.6, which includes: generator event weight, isolation, identification, trigger, and reconstruction efficiency.

The final template is then summed over all events in the discrete ranges of $(\Delta p_T^{Z, Truth})_j$, $(\Delta p_T^{\ell\ell, Reco})_j$, $(\Delta \cos \theta_{CS}^{Reco})_j$, and $(\Delta \varphi_{CS}^{Reco})_j$ denoted by Δ_j . The templates are expressed as:

$$T_{ij} = \sum_{event \in \Delta_j} P_i(\cos \theta_{CS}^{Reco}, \varphi_{CS}^{Reco}) \frac{w_{event}(r, t)}{f_j(\cos \theta_{CS}^{Truth}, \varphi_{CS}^{Truth})}. \quad (\text{A.5})$$

APPENDIX B

MC USED

The MC samples used in this analysis are listed in this appendix. Table B.1 has the MC samples of $Z \rightarrow ee, \mu\mu$, which is the desired signal. Table B.2 has the MC samples that correspond to the background, which is used in the kinematic distributions in Section 4.5.

Process	$\sqrt{s}$	Generator	$\sigma \times \epsilon_{\text{filter}}$ [pb]	N_{events}
$Z \rightarrow ee$	5 TeV	Powheg+Pythia8	660×1.025	6.3×10^6
$Z \rightarrow \mu\mu$	5 TeV	Powheg+Pythia8	660×1.025	1.4×10^6
$Z \rightarrow ee$	13 TeV	Powheg+Pythia8	1910×1.03	5.0×10^6
$Z \rightarrow \mu\mu$	13 TeV	Powheg+Pythia8	1910×1.025	5.0×10^6
$Z \rightarrow ee$ ($0 < p_T^Z < 70$)	13 TeV	Sherpa 2.2.1	1933×0.821	8.0×10^6
$Z \rightarrow ee$ ($70 < p_T^Z < 140$)	13 TeV	Sherpa 2.2.1	108.0×0.694	1.5×10^6
$Z \rightarrow ee$ ($140 < p_T^Z < 280$)	13 TeV	Sherpa 2.2.1	39.64×0.616	2.0×10^5
$Z \rightarrow ee$ ($280 < p_T^Z < 500$)	13 TeV	Sherpa 2.2.1	8.46×0.569	2.0×10^4
$Z \rightarrow ee$ ($500 < p_T^Z < 1000$)	13 TeV	Sherpa 2.2.1	1.76×1	5.0×10^3
$Z \rightarrow \mu\mu$ ($0 < p_T^Z < 70$)	13 TeV	Sherpa 2.2.1	1932×0.822	8.0×10^6
$Z \rightarrow \mu\mu$ ($70 < p_T^Z < 140$)	13 TeV	Sherpa 2.2.1	106.3×0.690	1.5×10^6
$Z \rightarrow \mu\mu$ ($140 < p_T^Z < 280$)	13 TeV	Sherpa 2.2.1	38.89×0.593	2.0×10^5
$Z \rightarrow \mu\mu$ ($280 < p_T^Z < 500$)	13 TeV	Sherpa 2.2.1	8.31×0.561	2.0×10^4
$Z \rightarrow \mu\mu$ ($500 < p_T^Z < 1000$)	13 TeV	Sherpa 2.2.1	1.74×1	5.0×10^3

Table B.1: Table of $Z \rightarrow \ell\ell$ signal events where $\ell = e, \mu$. The tables summarize the process, the centre-of-mass energy, the MC generator used, the production cross-section used multiplied by the filter efficiency, and the number of events in the MC sample. For the Powheg+Pythia8 samples, the filter efficiency is greater than 1 because the cross-section is for the range $66 \leq m_{\ell\ell} \leq 116$, while the MC is generated over a wider range. It is first organized by generator then for Powheg+Pythia8 it is subdivided by $\sqrt{s}$. The Sherpa 2.2.1 samples are split into ranges of p_T^Z with boundaries [0, 70, 140, 280, 500, 1000] GeV.

Process	$\sqrt{s}$	Generator	$\sigma \times \epsilon_{\text{filter}}$ [pb]	N_{events}
$Z \rightarrow \tau\tau$	13 TeV	Powheg+Pythia8	1910×1.025	1.0×10^6
$ZZ (q\bar{q}\ell\ell)$	13 TeV	Sherpa 2.2.1	15.56×0.141	1.0×10^4
$ZZ (4\ell)$	13 TeV	Sherpa 2.2.2	1.252×1	1.0×10^4
$WW (q\bar{q}\ell\nu)$	13 TeV	Sherpa 2.2.1	2.472×1	2.0×10^4
$WW (\ell\nu q\bar{q})$	13 TeV	Sherpa 2.2.1	2.472×1	2.0×10^4
$WW (2\ell 2\nu)$	13 TeV	Sherpa 2.2.2	12.5×1	1.0×10^4
$WZ (q\bar{q}2\ell)$	13 TeV	Sherpa 2.2.1	3.433×1	1.0×10^4
$WZ (\ell\nu q\bar{q})$	13 TeV	Sherpa 2.2.1	11.42×1	1.0×10^4
$WZ (3\ell\nu)$	13 TeV	Sherpa 2.2.2	4.583×1	1.0×10^4
$WZ (\ell 3\nu)$	13 TeV	Sherpa 2.2.2	3.235×1	1.0×10^4
$t\bar{t}$	13 TeV	Powheg+Pythia8	729.8×0.544	5.0×10^5

Table B.2: Table of top background process of the $Z \rightarrow \ell\ell$ signal events. This includes the top three backgrounds: $Z \rightarrow \tau\tau$, VV - where $V = \{W, Z\}$, and $t\bar{t}$. The table summarizes the process, the centre-of-mass energy, MC generator used, the production cross-section used multiplied by the filter efficiency, and the number of events in the MC sample.

APPENDIX C

ADDITIONAL PLOTS

Not all plots can be included in Chapter 4, as they do not have the same level of importance. So additional plots that are relevant to what was presented are here. This includes additional plots of combined channels for A_i coefficients - for Powheg+Pythia8 and Sherpa 2.2.1 - and additional kinematic distributions for electrons and Z bosons.

C.1 Additional Combined Channels

Section 4.4.1 only included the combination of predictions in electron and muon channels for A_4 using a weighted average at $\sqrt{s} = 13$ TeV for Powheg+Pythia8. The rest of the coefficients A_{0-3} can be seen in Figure C.1. The combination of predictions was not presented for Sherpa in Section 4.4.4 but they can be found in Figure C.2. Using a weighted average allows for the statistical sensitivity to be increased in each p_T^Z bin.

Figure C.1: Combination of predictions for coefficients A_{0-3} in electron and muon channels for Powheg+Pythia8 at $\sqrt{s} = 13$ TeV using the weighted average Equation 4.3.

Figure C.2: Combination of predictions for coefficients A_{0-4} in electron and muon channels for Sherpa 2.2.1 at $\sqrt{s} = 13$ TeV using the weighted average Equation 4.3.

C.2 Additional Kinematic Distributions

Section 4.5 included the kinematic distributions for the leading electron and majority of the distributions for the Z boson. Here the subleading electron p_T , η , and ϕ distributions are presented in Figure C.3 as well as the η and ϕ distributions of the dielectron system can be seen in Figure C.4. The subleading electron is the electron with the smaller p_T value of the dielectron pair. For the subleading electron in Figure C.3, the p_T distribution is the only kinematic variable that changes shape, compared to the leading electron. This is expected because the subleading electron should have majority of the p_T distribution shifted to a lower p_T value, compared to the leading electron. Data and MC are in good agreement for the low p_T but disagree above 50 GeV because the MC is not a sufficiently high enough order to correctly model the data. As seen in the leading electron η distribution, there is a similar modulation, which can be attributed to the electron trigger modulation [51]. Lastly, the ϕ distribution is in good agreement between data and MC, as all of the points are within a 5% agreement.

For the η^{ee} distribution in Figure C.4, data and MC are in good agreement for $|\eta^{ee}| < 4$ but start to disagree at higher η^{ee} . This could be attributed the MC not being a higher enough order to sufficiently model the data, however, this has not been studied. Another consideration is that there are few events at this high of an η^{ee} value. For ϕ^{ee} , data and MC are in good agreement, as all are within 4%.

Figure C.3: Subleading electron p_T (top), η (middle), and ϕ (bottom) distributions for $Z \rightarrow ee$ within $66 \leq m_{ll} \leq 116$ GeV mass window and pass selection criteria. The subleading electron refers to the electron with the lower transverse momentum in the dielectron pair. Data denoted by the points and statistical uncertainty. The MC signal and background distributions are normalized to the data luminosity denoted by the filled histograms. The uncertainty band in the ratio plot is the MC statistical and systematic uncertainty added in quadrature.

Figure C.4: Dielectron pseudorapidity (top) and azimuthal angle ϕ (bottom) distributions for $Z \rightarrow ee$ within $66 \leq m_{ll} \leq 116$ GeV mass window and pass selection criteria. Data denoted by the points and statistical uncertainty. The MC signal and background distributions are normalized to the data luminosity denoted by the filled histograms. The uncertainty band in the ratio plot is the MC statistical and systematic uncertainty added in quadrature.

APPENDIX D

GLOSSARY

List of abbreviations and definition used in order of appearance throughout the main text:

- **SM - Standard Model:** The current particle physics theory that describes elementary particles and their interactions through electromagnetism, the weak force, and the strong force.
- **CERN - European Organization for Nuclear Research:** A particle physics research organization that operates a particle accelerator complex on the French-Swiss border, outside of Geneva. It is also used to refer to the research complex.
- **LHC - Large Hadron Collider:** A 27 km circumference particle accelerator that accelerates two beams of protons in opposite directions to be collided in order to observe their interactions.
- **MC - Monte Carlo:** A type of simulation that randomly samples a distribution to give numerical results.
- **QCD - Quantum Chromodynamics:** The theory of the strong interaction between quarks and gluons by the exchange of colour. Unique because of the properties of confinement and asymptotic freedom.
- **QED - Quantum Electrodynamics:** The theory of the electromagnetic interaction between charged particles through the exchange of a photon.
- **PDF - Parton Distribution Function:** A probability function, $f_i(x_i)$, determined experimentally, of the probability to find a parton with a momentum fraction, x_i .
- **LO - Leading Order:** The zeroth order expansion of perturbative QCD.

- **NLO - Next to Leading Order:** The first order expansion of perturbative QCD.
- **NNLO - Next to Next to Leading Order:** The second order expansion of perturbative QCD.
- **CS Frame - Collins-Soper Frame:** A rest frame of the Z boson, as defined in Section 1.4.
- **PS - Proton Synchrotron:** A synchrotron of circumference 628 meters at CERN that is part of the chain to accelerate protons to be sent to the LHC, which accelerates the protons from 1.4 GeV to 25 GeV.
- **SPS - Super Proton Synchrotron:** A synchrotron of circumference 6.9 km at CERN that is part of the chain to accelerate protons to be sent to the LHC, which accelerates the protons from 25 GeV to 450 GeV. Also functions to bunch the accelerated protons before injecting them to the LHC.
- **ATLAS - A Toroidal LHC Apparatus:** One of the major experiments on the LHC ring that has proton-proton interactions in the centre of the detector. It uses trackers, calorimeters, and a muon spectrometer to measure as much information possible from each interaction to reconstruct the interactions.
- **ID - Inner Detector:** A subdetector of the ATLAS experiment to measure trajectories of charged particles in the detector.
- **IBL - Insertable B-Layer:** An added barrel layer to the pixel detector in the ID, which sits closest to the beam line. It was added during the first upgrade period (2013-15) between Run 1 and 2 at CERN.
- **SCT - Semiconductor Tracker:** A subdetector of the ID comprised of silicon strip semiconductors used to measure charge particle tracks.

- **TRT - Transition Radiation Tracker:** The outer most subdetector in the ID, comprised of 4 mm diameter straws filled with a gaseous mixture to measure ionization energy of charged particles that pass through. The straws are surrounded by polypropylene fibres in the barrel and polypropylene foil in the endcap. Serves for electron identification.
- **ECAL - Electromagnetic Calorimeter:** Innermost of two calorimeter systems in the ATLAS detector to detect particles that shower electromagnetically. Comprised of EMB, EMEC, and the first layer of the FCAL.
- **HCAL - Hadronic Calorimeter:** Outermost of two calorimeter systems in the ATLAS detector for detecting hadronic particles. Comprised of Tile calorimeter, HEC, and the outer two layers of the FCAL.
- **EMB - Electromagnetic Barrel:** Calorimeter comprised of lead absorbers and LAr, the active material, to measure the electromagnetically showering particles in the region $|\eta| < 1.475$.
- **EMEC - Electromagnetic Endcap:** Calorimeter comprised of lead absorbers and LAr, the active material, to measure the electromagnetically showering particles in the region $1.375 < |\eta| < 3.2$.
- **FCal - Forward Calorimeter:** Part of the ECAL and HCAL systems in the endcaps that cover the range $3.2 < |\eta| < 4.9$. Comprised of copper and LAr for the first layer for the ECAL and tungsten and LAr for the second and third layers for the HCAL.
- **LAr - Liquid Argon:** Active material used for a majority of the calorimeter systems to measure the deposited energy.
- **HEC - Hadronic Endcap:** One of three HCAL subdetectors that covers the range $1.5 < |\eta| < 3.2$ positioned behind the EMEC. It uses copper absorbers and LAr as the active material.

- **MS - Muon Spectrometer:** Outermost subdetector of the ATLAS experiment to measure muon charge and momentum with deflection in a magnetic field.
- **MDT - Monitored Drift Tube:** One of four subdetectors in the MS, located in the barrel, and the two outermost wheels in the endcap. Comprised of tubes with a gas mixture to give precision measurements of position and transverse momentum.
- **CSC - Cathode Strip Chamber:** One of four subdetectors in the MS, located in the small inner endcaps. Comprised of strips with a mesh anode to give precision measurements of position and transverse momentum.
- **RPC - Resistive Plate Chamber:** One of four subdetectors in the MS, located in the barrel. Comprised of two plastic resistive plates filled with gas and is used as part of the muon trigger system.
- **TGC - Thin Gap Chamber:** One of four subdetectors in the MS, located in the middle endcap. Comprised of strips with a mesh anode and is used as part of the muon trigger system.
- **CC - Central Central:** A set of leptons with both leptons in the region $|\eta| < 2.4$.
- **CF - Central Forward:** A set of leptons with one lepton in the region $|\eta| < 2.4$ and one lepton in the region $|\eta| > 2.4$.

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