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Study of polarised $W\gamma$ production at the LHC

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Rebecca Seip
geboren am 15.04.2002 in Schotten

Institut für Kern- und Teilchenphysik
Fakultät Physik
Bereich Mathematik und Naturwissenschaften
Technische Universität Dresden
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1. Gutachter: Dr. Frank Siegert
2. Gutachter: Prof. Dr. Dominik Stöckinger

Abstract

The $W\gamma$ -production is a process that can occur in high-energy particle collisions such as those conducted at the LHC. Compared to other weak-boson interactions it has a relatively high cross-section which enables one to study a variety of effects in this process. In this thesis, the $W\gamma$ -production is studied based on SHERPA simulations with unpolarised setups as well as with polarised setups. One key area of study is the radiation amplitude zero effect that emerges in all three polarisation states of the W-boson. This effect results in a dip in the pseudorapidity-difference distribution between the charged lepton from the W-decay and the final state photon. This dip is a sensitive phase space region for studying new physics, as it could be filled by several theories, and effects of anomalous couplings in the $WW\gamma$ -vertex could also be examined. This work will primarily focus on phase space cuts to deepen the dip and make it visible, even with higher-order diagrams that also fill the dip. Additionally, various properties of W-bosons in terms of polarisation will be discussed. This thesis shows that either cuts on a high photon transverse momentum or a cut on the transverse mass of the whole system improves the depth of the dip in the pseudorapidity distribution significantly. With such cuts, the dip is also visible at next to leading order.

Kurzdarstellung

Die $W\gamma$ -Produktion ist ein Prozess der in hochenergetischen Teilchenkollisionen untersucht werden kann. Dieser Prozess hat dabei im Vergleich zu anderen Prozessen, in die schwache Eichbosonen involviert sind, einen relativ großen Wirkungsquerschnitt und erlaubt es, eine Vielzahl von verschiedenen Effekten zu untersuchen. Der $W\gamma$ -Prozess wird im Folgenden mittels simulierter Daten theoretisch untersucht. Dazu wird der Monte-Carlo-Event-Generator SHERPA verwendet. Eine zentrale Rolle wird der Radiation-Amplitude-Zero-Effekt spielen, der im Standard Model der Teilchenphysik implementiert ist und eine Null im differentiellen Wirkungsquerschnitt in Abhängigkeit des Winkels zwischen dem Endzustands-Photon und einem der Ausgangszustands-Quarks bewirkt. Als Konsequenz dieses Effektes ist es möglich, in anderen Verteilungen, wie der Pseudorapiditätsdifferenz zwischen dem Photon und dem geladenen Lepton aus dem W-Boson-Zerfall, einen Dip zu sehen. Dieser Dip ist sehr sensitiv auf neue Physik und anomale Kopplungen des $WW\gamma$ -Vertex, welche den Dip auffüllen würden. Im Folgenden werden verschiedene Möglichkeiten diskutiert, diesen Dip tiefer zu machen, damit man ihn auch in Experimenten mit großem QCD-Untergrund noch erkennen kann. Des Weiteren werden verschiedene Observablen in einem polarisierten Setup betrachtet. Im Rahmen dieser Thesis wird gezeigt, dass entweder hohe Cuts auf den transversalen Photon-Impuls oder Cuts auf die transversale Masse des gesamten Systems den Dip in der Pseudorapiditätsdifferenz-Verteilung tiefer machen und er somit auch in erster höherer Ordnung QCD noch sichtbar ist.

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Acronyms

CERN	Conseil Européen pour la Recherche Nucléaire
ATLAS	A Torodial LHC ApparatuS
SM	Standard Model
RAZ	Radiation Amplitude Zero
LO	Leading Order
NLO	Next to Leading Order
QCD	Quantum Chromo Dynamics
EW	Electroweak
QED	Quantum Electrodynamics
SHERPA	Simulation of High-Energy Reactions of PArticles
LHC	Large Hadron Collider
BSM	Beyond Standard Model
HEP	High Energy Physics
Rivet	Robust Independent Validation of Experiment and Theory

1 Introduction

Towards the end of the 19th century, physicists thought they had discovered nearly everything and that the end of physics had been reached. But they were at fault. At the beginning of the 20th century, a number of important events occurred. Albert Einstein developed his famous theory of relativity, Niels Bohr, Werner Heisenberg, and a few other physicists developed the theory of quantum mechanics and Marie Curie and her husband discovered radioactivity. So, suddenly a lot of new research topics and unknown effects appeared. Also, new particles were discovered and scientists spotted the indivisibility of the atom. The first particle smaller than an atom was detected in 1897 by Joseph John Thomson. It was the electron. With this new knowledge and these new technologies, physicists began to find more and more particles. The last one was the Higgs-Boson in 2012. Nowadays, particle physics is a major topic in physics and physicists all around the world are trying to find out which particles our world is made of and how they interact with each other. The theory that works best so far in this sector is the so-called Standard Model of particle physics, which is a quantum field theory. However, we know it is incomplete. There are several questions it does not answer and it cannot be the theory that describes the entire universe. Big research facilities such as the CERN in Geneva are researching to test the Standard Model. There, the LHC and its experiments test many different processes implemented in the Standard Model. To compare measured data with theory predictions, Monte-Carlo-Event generators simulate events from particle collisions. For this thesis, the Monte-Carlo-Event generator SHERPA is used.

In this thesis, I will examine a process occurring in the LHC when the two proton beams collide at an experiment like ATLAS, namely the $W\gamma$ -production. In this process two partons coming from the colliding protons in the detectors at LHC produce a W-boson and a photon. This work focusses on the $W\gamma$ -production in a phase space that fits high energy physics experiments such as the ATLAS experiment at CERN (in Geneva). In $W\gamma$ -production process, the differential cross-section is reduced to zero in the distribution of the cosine of the angle between an initial state quark and the final state photon in the center of mass frame of the colliding partons. This so-called radiation amplitude zero is predicted by the Standard Model and leads to a dip in rapidity/pseudorapidity difference distribution between the charged lepton from the W-decay and the photon in the region of $\Delta\eta(\gamma, l^{+/-}) = 0$. The radiation amplitude zero effect in the rapidity-difference distributions plays a central role in this thesis, because it is not possible to measure the exact zero in the angle distribution which was mentioned above. This region of the dip is, as a consequence, sensible to beyond Standard Model (BSM) effects, which would fill the dip. In general, this effect of radiation amplitude zero (RAZ) is suppressed due to

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large QCD corrections that fill in the dip. Consequently, one needs to search for cuts suppressing this background. Additionally, I will also look at different observables in leptonic W-boson-decays in a polarised setup which can be simulated with SHERPA. In the second chapter of this thesis, theoretical basics will be discussed, including the Standard Model of particle physics, the polarisation of massive spin 1 bosons and the $W\gamma$ process with the radiation amplitude zero effect. The third chapter will shortly discuss the Monte-Carlo event generators and the different phase space cuts that were used. The fourth chapter will be about unpolarised $W\gamma$ simulation setups and the fifth chapter will discuss polarised setups.

2 Theoretical basics

In the following chapter, important theoretical basics will be discussed. First, the Standard Model of particle physics will be explained, and subsequently the polarisation of massive gauge bosons as well as the RAZ effect in the $W\gamma$ -production will be discussed.

2.1 The Standard Model of Particle Physics

The Standard Model of particle physics is currently the most functional theory describing the most minuscule components of our world. It is a quantum field theory with a

$$SU(3) \times SU(2)_L \times U(1)_Y \quad (2.1)$$

local gauge invariance. This means it can be expressed in form of a Lagrange-density that is invariant under this symmetry. Quantum Chromodynamics (QCD) which describes the strong interaction has an $SU(3)$ local gauge invariance. In the Standard Model, the electromagnetic and the weak force are unified to one electroweak theory with a local $SU(2)_L \times U(1)_Y$ symmetry.

The particles in the Standard Model are shown in figure 2.1. Within the Standard Model, there are two kinds of particles. The first group consists of the so-called fermions, which are named after the acclaimed physicist Enrico Fermi. Fermions are particles with a spin of $1/2$ that follow Fermi-Dirac statistics. The Standard Model contains twelve different fermions and twelve corresponding anti-fermions, which are further divided into two different groups, namely leptons (green) and quarks (purple), and three different generations or families. There are six different leptons, three of them are electrically charged and three are neutral. The charged ones are the electron, the muon and the tauon. The neutral leptons are the neutrinos, which are very light. Each neutrino is associated with a charged lepton flavour.

The second big group of particles in the Standard Model is that of the so-called bosons (red), which are named after Satyendranath Bose, an Indian physicist. The bosons are carrying the force between the particles as a kind of mediator particle. There is at least one boson per interaction in the Standard Model. In general, four different interactions exist in our universe: gravity, the electromagnetic force, the strong force and the weak force. The photon γ is the boson corresponding to the electromagnetic interaction and is massless. The weak force has three bosons: two charged W-bosons (W^+ and W^-), and one neutral Z-boson. These bosons of the weak interaction have a mass and can interact with each other as well as with the photon. However, because they are quite massive, they also have a rather short life time, which means that one can not detect them in an experiment. We can merely measure their decay products and reconstruct the weak gauge bosons from them.

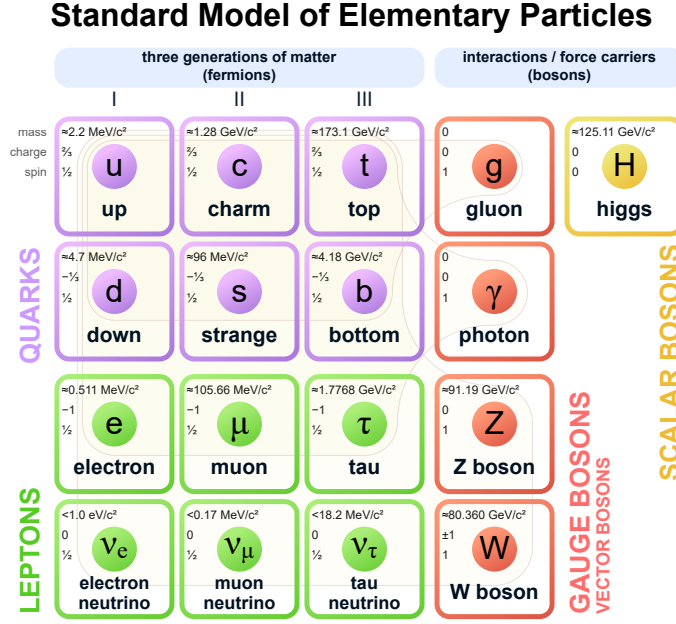


Figure 2.1: The Standard Model of particle physics [18]

The strong interaction has eight massless bosons in sum, the so called gluons. The bosons of the strong interaction can interact with each other due to the fact that each of them carries a strong charge. Gravity is not represented in the Standard Model, which is a big weakness of this theory. Besides the vector bosons that have been mentioned above, there is another scalar boson in the Standard Model, which was discovered in 2012. It is called the Higgs boson (yellow), named after physicist Peter Higgs. This boson belongs to the Brout-Englert-Higgs field and gives the particles their mass due to the Higgs mechanism.

As already discussed the problem with the Standard Model is that we know it is incomplete and we can simply perceive the Standard Model as a low energy limit of a greater theory that has to be discovered or formulated somehow. Beside the fact that gravity is not present in the Standard Model, it contains further weaknesses, such as the dark sector which is not included in the Standard Model, as well as the hierarchy problem, the masses of neutrinos or the asymmetry between matter and antimatter.

2.2 Polarisation of Weak Gauge Bosons

The helicity of a particle is an important quantity in particle physics. It is defined as follows:

$$h = \frac{\vec{S} \cdot \vec{p}}{|\vec{p}|}. \quad (2.2)$$

The helicity describes the component of the spin $\vec{s}$ along the direction of flight, which is described by the momentum $\vec{p}$ of the particle. It is furthermore divided by

$|\vec{p}|$ for normalisation. Fermions have two different helicity states as they have two possible spin-states ($1/2$ and $-1/2$). In general, helicity is not Lorentz-invariant. The exception are massless particles moving with the speed of light, for which Lorentz invariance holds. With the helicity eigenstates, one can define the different polarisation states of a particle. A photon has two different transverse polarisation states. Massive spin-1-bosons such as the W or Z-boson have three helicity states: -1 , 0 and 1 . Thus they have three different polarisation states, because there are $2n + 1$ spin-states for a particle with spin n . The polarisation of massive vector-bosons is interesting as its longitudinal polarisation is a direct consequence of the electroweak symmetry breaking mechanism. The polarisation-vectors of these three spin-states for massive vector bosons are explained in the following:

Equation 2.3 shows the lagrangian of a massive spin 1 field (for a massless spin 1 field, the mass term vanishes) [23].

$$\mathcal{L} = -\frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu} + \frac{1}{2}m^2\mathcal{B}^\mu\mathcal{B}_\mu, \quad (2.3)$$

with the field strength tensor

$$\mathcal{F}^{\mu\nu} = (\partial^\mu\mathcal{B}^\nu - \partial^\nu\mathcal{B}^\mu). \quad (2.4)$$

2.5 is the free field equation

$$(\square + m^2)\mathcal{B}^\mu - \partial^\mu(\partial_\nu\mathcal{B}^\nu) = 0, \quad (2.5)$$

which can be obtained using the Euler-Lagrange equations. Taking the derivative of equation 2.5 leads to the following expression

$$m^2\partial_\mu\mathcal{B}^\mu = 0 \quad (2.6)$$

i.e. the Lorenz condition is satisfied for massive spin 1 bosons. Now, there is no freedom to choose the gauge anymore, since the mass term breaks gauge invariance. With a plane-wave ansatz, we arrive at the following solution for the field $\mathcal{B}$

$$\mathcal{B}^\mu = \epsilon^\mu e^{-iq \cdot x}, \quad (2.7)$$

where q^μ is the four-momentum of the particle. Equation 2.6 implies

$$q_\mu\epsilon^\mu = 0. \quad (2.8)$$

This condition means that there are three independent degrees of freedom in choosing ϵ^μ so that there are three independent polarisation states for a massive spin 1 boson. A boson that travels along the z-axis has two circular (transverse) polarisation states

$$\epsilon_-^\mu = \frac{1}{\sqrt{2}}(0, 1, -i, 0), \quad \epsilon_+^\mu = -\frac{1}{\sqrt{2}}(0, 1, i, 0), \quad (2.9)$$

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and the third polarisation state is orthogonal to these states¹

$$\epsilon_L^\mu = \frac{1}{m}(p_z, 0, 0, E). \quad (2.10)$$

The form of the polarisation vectors depends on the spin basis that has to be chosen. SHERPA uses the polarisation vectors in the helicity basis which are

$$\epsilon_\pm^\mu = \frac{e^{\pm i\phi}}{\sqrt{2}}(0, -\cos\theta \cos\phi \pm i \sin\phi, -\cos\theta \sin\phi \mp i \cos\phi, \sin\theta) \quad (2.11)$$

$$\epsilon_0^\mu = \frac{q^0}{m} \left(\frac{|\vec{q}|}{q^0}, \cos\phi, \sin\theta, \sin\phi \sin\theta, \cos\theta \right) \quad (2.12)$$

for an on-shell vector boson with four-momentum $q^\mu = (q^0, |\vec{q}| \cos\phi \sin\theta, |\vec{q}| \sin\phi \sin\theta, |\vec{q}| \cos\theta)$ [12].

2.3 $W\gamma$ - production

The $W\gamma$ - production process at hadron colliders has a cross-section with the order of (picobarns). This process enables to test the $WW\gamma$ coupling vertex and the radiation amplitude zero effect (RAZ), which will be discussed in the following section, and due to this also several BSM effects like anomalous couplings in the $WW\gamma$ vertex. At the LHC two partons from the protons collide and produce a W-boson and a photon. The W-boson is rather heavy and has a relatively short lifetime so that one cannot detect it directly. In order to study this process, one has to examine its decay products. The W-boson can decay either hadronically or leptonically. Since the identification of the W-boson is easier through the lepton-decay-channel, this thesis will solely examine the W-boson decaying into a charged-lepton neutrino pair. The coupling order of this process is $\mathcal{O}(\alpha_{EW}^2)$. The process and the final state look as follows for either a negatively charged or a positively charged W-boson:

$$pp \longrightarrow W^+ \gamma \longrightarrow l^+ + \nu_l + \gamma \quad (2.13)$$

$$pp \longrightarrow W^- \gamma \longrightarrow l^- + \bar{\nu}_l + \gamma \quad (2.14)$$

At leading order (LO) there are three diagrams contributing to the matrix element. Figure 2.2, shows three diagrams of the $W\gamma$ process at LO for the initial state of an up quark and an anti-down quark.

¹It is normalised so that the longitudinal polarisation state only has a z-component in the rest frame of the gauge boson.

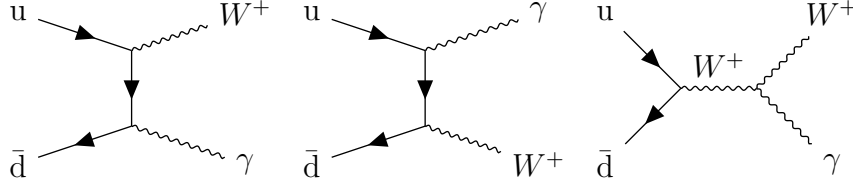
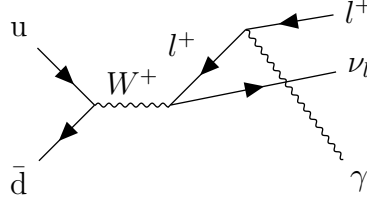


Figure 2.2: LO Feynman-diagrams

In practice, there is another diagram with the same initial and final states which is shown in figure 2.3. This diagram does not produce a intermediate W-boson that decays resonant into a $l^+\nu_l$ -pair. However, it belongs to the process $pp \rightarrow l^+\nu_l\gamma$. This means that it has to be taken into account when looking at the results. The process containing the RAZ is $pp \rightarrow W^{+/-}\gamma$, which cannot be detected by a detector because the W-boson is instable. The influence of this diagram is discussed in the next chapter because it does not contribute to the radiation amplitude zero effect.

Figure 2.3: Feynman-diagram which cannot be separated from the $W\gamma$ -production diagrams (does not contribute to RAZ)

In the following analysis, we solely examine a positive W-boson that decays into an anti-muon and a muon-neutrino. For a W-boson which decays into a $e^+\nu_e$ -pair one would expect the same results, the same holds for negatively charged W-bosons that decays into a lepton and an anti-lepton-neutrino.

2.3.1 QCD Corrections

In this short section, the corrections at next to leading QCD order are discussed. In general, there are two different kinds of corrections. One of these are virtual corrections, which do not affect the final state, and the other kind are real corrections where an additional particle occurs in the final state of the process. Virtual corrections are loops in the diagram as shown in figure 2.4. The simulations discussed in this thesis do not contain virtual corrections. Examples for real corrections are shown in figure 2.5 with an additional gluon in the final state that would lead to

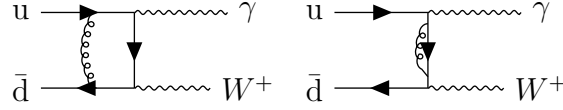


Figure 2.4: Examples for virtual QCD corrections

a jet in an experiment such as ATLAS. QCD corrections with one additional jet in the final state or additional loops have a considerable impact on the observation of the RAZ effect, as discussed in the following chapter. The additional diagrams that have to be taken into account when allowing additional jets in the final state do not contribute to the RAZ effect and fill the corresponding dip.

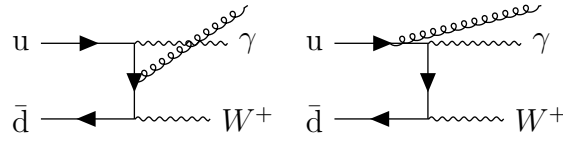


Figure 2.5: Examples for real QCD corrections

2.3.2 Radiation Amplitude Zero Effect

This thesis focus on studying the so called Radiation Amplitude Zero (RAZ) effect that occurs in $W\gamma$ -production for a specific decay angle between an incoming quark and the produced photon². This section deduces the RAZ effect. This RAZ effect is hard to observe because higher-order corrections destroy the exact zero. The RAZ effect results from calculations within the Standard Model.

The matrix element calculation can be performed as shown in the following equations [14][17].

Since three different diagrams contribute to this process at LO, a matrix element has to be calculated for each diagram individually. In the following, the momenta of the two incoming quarks are referred to as p_1 and p_2 . k describes the momentum of the final state photon, q the momentum of the final state W-boson, and p the momentum of the propagator. Q_1 and Q_2 are the charges of the two initial state quarks. The Mandelstam variables are defined as usual $s = (p_1 + p_2)^2 = 2p_1 \cdot p_2$, $t = (k - p_1)^2 = -2k \cdot p_1$ and $u = (k - p_2)^2 = -2k \cdot p_2$. The quarks considered to be massless. Furthermore is $m_w^2 = s + t + u$. In the following the term $\mathcal{M}_1$ belongs to the left diagram in figure 2.2, $\mathcal{M}_2$ belongs to the diagram in the middle and $\mathcal{M}_3$ the right one. Thus, the matrix element can be written according to the Feynman rules as follows:

$$\begin{aligned}\mathcal{M}_1 &= \bar{v}(p_2)(-iQ_2e\gamma^\nu)\frac{\not{p}}{p^2}(-i\frac{g_w}{\sqrt{2}}\gamma^\mu\frac{1}{2}(1-\gamma^5))u(p_1)\epsilon^\nu(k)\epsilon^\mu(q) \\ &= ie\frac{g_w}{2\sqrt{2}}\epsilon^\nu(k)\epsilon^\mu(q)\bar{v}(p_2)Q_2\gamma^\nu\frac{\not{p}}{p^2}\gamma^\mu(1-\gamma^5)u(p_1)\end{aligned}$$

²The RAZ effect can also be observed in other processes that involve massive gauge bosons.

$$\begin{aligned}
 &= ie \frac{g_w}{2\sqrt{2}} \epsilon^\nu(k) \epsilon^\mu(q) \bar{v}(p_2) Q_2 \frac{\gamma^\nu \gamma^\lambda p_{2\lambda} \gamma^\mu - \gamma^\nu \gamma^\lambda k_\lambda \gamma^\mu}{-2k \cdot p_2} (1 - \gamma^5) u(p_1) \\
 &= ie \frac{g_w}{2\sqrt{2}} \epsilon^\nu(k) \epsilon^\mu(q) \bar{v}(p_2) \frac{Q_2}{u} (p_{2\lambda} (2g^{\nu\lambda} - \gamma^\lambda \gamma^\nu) \gamma^\mu - \gamma_\nu \not{k} \gamma^\mu) (1 - \gamma^5) u(p_1) \\
 &= ie \frac{g_w}{2\sqrt{2}} \epsilon^\nu(k) \epsilon^\mu(q) \bar{v}(p_2) \frac{Q_2}{u} (2p_2^\nu \gamma^\mu - \gamma^\nu \not{k} \gamma^\mu) (1 - \gamma^5) u(p_1) \\
 \mathcal{M}_2 &= \bar{v}_2(p_2) (-i \frac{g_W}{\sqrt{2}} \gamma^\mu \frac{1}{2} (1 - \gamma^5)) \frac{\not{p}}{p^2} (-Q_1 e \gamma^\nu) u(p_1) \epsilon^\nu(k) \epsilon^\mu(q) \\
 &= ie \frac{g_W}{2\sqrt{2}} \epsilon^\nu(k) \epsilon^\mu(q) \bar{v}_2(p_2) Q_1 \frac{\gamma^\mu \gamma^\lambda p_\lambda}{p^2} \gamma^\nu (1 - \gamma^5) u(p_1) \\
 &= ie \frac{g_w}{2\sqrt{2}} \epsilon^\nu(k) \epsilon^\mu(q) \bar{v}_2(p_2) Q_1 \frac{\gamma^\mu \gamma^\lambda p_{1,\lambda} \gamma^\nu - \gamma^\mu \gamma^\lambda k_\lambda \gamma^\nu}{t} (1 - \gamma^5) u(p_1) \\
 &= ie \frac{g_w}{2\sqrt{2}} \epsilon^\nu(k) \epsilon^\mu(q) \bar{v}_2(p_2) Q_1 \frac{2p_{1,\nu} \gamma^\mu - \gamma_\mu \not{k} \gamma_\nu}{t} (1 - \gamma^5) u(p_1) \\
 \mathcal{M}_3 &= \bar{v}(p_2) (-i \frac{g_w}{\sqrt{2}} \gamma^\mu \frac{1}{2} (1 - \gamma^5)) \left((Q_1 - Q_2) \frac{-ig_{\mu\nu}}{p^2 - m_w^2} \right) ie(g_{\mu\nu}(p - q)_\sigma + \\
 &\quad g_{\nu\sigma}(q - k)_\mu + g_{\sigma\mu}(k - p)_\nu) u(p_1) \epsilon^\nu(k) \epsilon^\mu(q) \\
 &= ie \frac{g_w}{2\sqrt{2}} \epsilon^\nu(k) \epsilon^\mu(q) \bar{v}(p_2) (Q_1 - Q_2) \gamma^\mu \frac{g_{\mu\nu}}{s - m_w^2} (g_{\mu\nu}(p - q)_\sigma + \\
 &\quad g_{\nu\sigma}(q - k)_\mu + g_{\sigma\mu}(k - p)_\nu) (1 - \gamma^5) u(p_1) \\
 &= ie \frac{g_w}{2\sqrt{2}} \epsilon^\nu(k) \epsilon^\mu(q) \bar{v}(p_2) \\
 &\quad \frac{Q_1 - Q_2}{s - M_w^2} (\gamma^\mu g_{\mu\nu} g_{\mu\nu} k_\sigma + \gamma^\mu g_{\mu\nu} g_{\nu\sigma} (p_1 + p_2 - 2k)_\mu + \gamma^\mu g_{\mu\nu} g_{\sigma\mu} (k - (p_1 + p_2))_\nu) (1 - \gamma^5) u(p_1) \\
 &\quad = \dots\dots \\
 &= ie \frac{g_w}{2\sqrt{2}} \epsilon^\nu(k) \epsilon^\mu(q) \bar{v}(p_2) \left(-2 \frac{Q_1 - Q_2}{s - m_w^2} \right) (\gamma_\mu (p_1 + p_2)_\nu + g_{\mu\nu} \not{k} - k_\mu \gamma_\nu) (1 - \gamma^5) u(p_1)
 \end{aligned}$$

Together they can be written as

$$\begin{aligned}
 \mathcal{M} &= ie \frac{g_w}{2\sqrt{2}} \epsilon^\mu(q) \epsilon^\nu(k) \bar{v}(p_2) \left(-\frac{Q_1 (2p_{1\nu} \gamma_\mu - \gamma_\mu \not{k} \gamma_\nu)}{t} + \frac{Q_2 (2p_{2\nu} \gamma_\mu - \gamma_\nu \not{k} \gamma_\mu)}{u} \right. \\
 &\quad \left. - \frac{2Q (\gamma_\mu (p_1 + p_2)_\nu + g_{\mu\nu} \not{k} - k_\mu \gamma_\nu)}{s - m_w^2} \right) (1 - \gamma^5) u(p_1)
 \end{aligned} \tag{2.15}$$

In order to determine the differential cross-section, one needs to take the square of this expression and sum over all initial state spins and final state polarisations

$$|\mathcal{M}|^2 = 2e^2 g_w^2 \frac{(Q_1 u + Q_2 t)^2}{ut(u + t)^2} (n - 2) (sm_w^2 - ut + \frac{1}{4} (n - 2)(u + t)^2) \tag{2.16}$$

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	u or $\bar{u}$	d or $\bar{d}$
W^+	$\cos(\theta^*) = -\frac{1}{3}$	$\cos(\theta^*) = \frac{1}{3}$
W^-	$\cos(\theta^*) = \frac{1}{3}$	$\cos(\theta^*) = -\frac{1}{3}$

Table 2.1: Theory prediction for the RAZ angles between the photon and an initial state quark

with n being the dimension [17]. In this expression, the condition for the radiation amplitude zero is already visible:

$$Q_1 u + Q_2 t = 0 \quad (2.17)$$

In a pp-collider, one expects the differential cross-section in dependence of the pseudorapidity-difference between the photon and the charged lepton from the W-decay to have a dip at $\Delta\eta(\gamma, l) = 0$. In this region, a dip can be observed. This region is sensitive to beyond-standard-model effects because there are several theories that would "fill" the dip.

The RAZ effect in $pp \rightarrow W\gamma$ was discovered by Brown, Sahdev, Mikaelian, and Samuel [5][14] in the late seventies of the last century and theoretically described by Brodsky and Brown [4].

There is a classical analogon to this effect which is presented in Ref. [4] (Brodsky and Brown), namely the vanishing of the dipole radiation in collisions of particles that have the same g factors and the same charge-to-mass ratio. The RAZ condition in the $W\gamma$ -process can be thought of as a quantum mechanical version of this classical condition.

With equation 2.17, one arrives at [15]:

$$\begin{aligned} \cos \theta^* &= -(1 + 2Q_i) & \text{for } W^- \\ \cos \theta^* &= +(1 - 2Q_i) & \text{for } W^+ \end{aligned} \quad (2.18)$$

with θ^* being the angle between an initial state quark and the final state photon. From this equation, it can be calculated that the amplitude in pp-collisions vanishes at the cosine values in table 2.1.

In order to visualise this, we conducted a simulation of the $W\gamma$ -process on parton-level with an up-quark and an antidown-quark in the initial state. The distributions are shown in figure 2.6. To get this distribution we first defined a four-momentum for both initial state quarks and then transformed the final state photon and one of the initial state quarks into the rest frame of the combined quark four-momentum. For these plots a cut on the transverse mass of the whole $W\gamma$ -system was applied, the reason for this will be explained in the next chapters.

2.3 $W\gamma$ - production

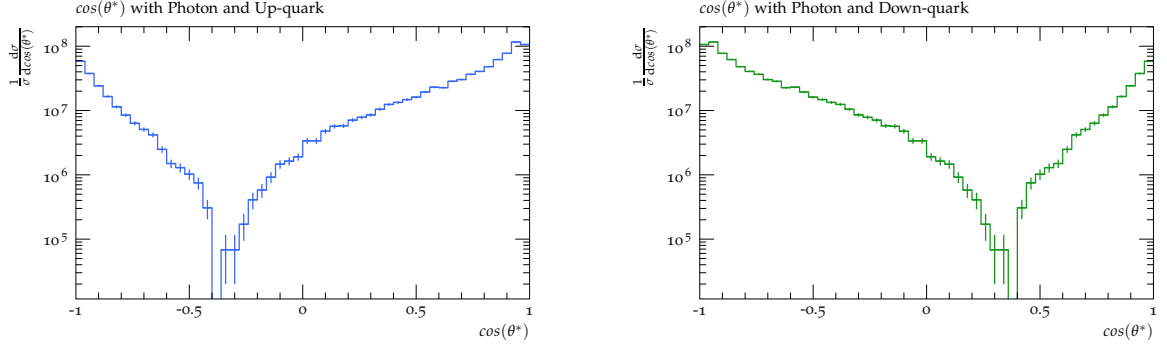


Figure 2.6: Angle between final state photon and initial state quark in the parton-parton frame for the process $u+\bar{d} \rightarrow W^++\gamma$, the up-quark was expected to travel in +z-direction and the anti-down-quark in -z-direction

The following part of this thesis discuss how to apply cuts and how to select a suitable phase space to observe the dip in rapidity distributions at LO and, more importantly, at next to leading order (NLO).

3 Setup

This brief chapter explains Monte-Carlo event generators and the important observables for the analysis as well as the standard phase space that has been used in the following.

3.1 Event Generation and Analysis Framework

In order to validate measured data with the theory predictions, Monte-Carlo event generators are used to simulate various particle collisions and processes in high-energy experiments. They allow to simulate different processes and to compare different observables with the data one has measured in a real experiment. This study uses SHERPA as this event generator can also simulate polarised setups [6][11]. With Monte-Carlo event generators, it is also possible to look at certain processes without electronic background effects or other disturbing factors within a detector. Examining these processes may help to understand the physics behind them and to test which cuts have to be set to observe interesting signals before using measured data. To do this, the events one would expect in a detector are separated due to their energy scale starting with the highest energies [20].

To simulate processes with SHERPA, so-called run-cards are used. These are codes in .yaml format which contain all the necessary information such as beam energy, the definition of the hard process, cuts on different particle characteristics¹. Figure 3.1 illustrates the steps of the event generation for a Monte-Carlo event generator. At first, the hard process needs to be simulated. In the picture, this is represented by the red circle caused by the collision of two partons coming from the colliding hadrons (dark green). The purple flat circle shows an underlying event. The red particles show the short-distance interactions that cause a signal in a detector. The blue curly lines represent radiative QCD corrections from gluons that are radiated from quarks. The light green flat circles show the hadronization that is simulated after the QCD radiation. The other green lines and particles beyond the light green hadronisation show further particle decays coming from unstable hadrons in the process. These dark green lines and particles are long-distance interactions. The yellow lines show the additional QED corrections.

¹see appendix C for two example runcards

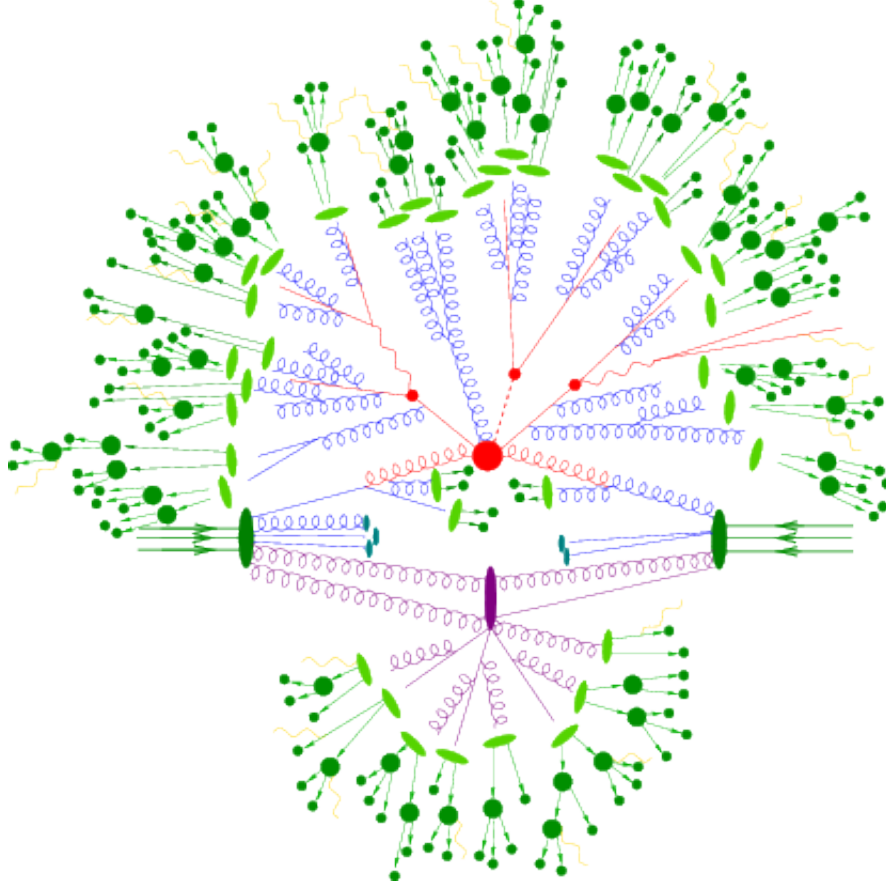


Figure 3.1: Illustration of event generation in SHERPA [22]

To analyse the simulated events for this thesis a suitable Rivet analysis was written, that applied different cuts on the particle properties and calculated different observables of interest.

Rivet (Robust Independent Validation of Experiment and Theory) is a C++ framework for analysis algorithms that can be used to analyse simulated data from Monte-Carlo event generators such as SHERPA. In the field of high energy physics, it is widely used to compare theoretical predictions with real data from experiments [13].

3.2 Important Observables

In most collider experiments, the z-axis is put in the beam direction and a polar coordinate system is used. The two partons that are colliding on the z-axis and the particles which are produced are detected by the detectors that are placed around the interaction-point (point where the two proton-beam are brought to collision). With the detectors the momentum and energy of the particles can be detected and additionally also the missing transverse momentum and energy. The missing transverse momentum which comes from the neutrinos² can be reconstructed due to momentum conservation, since the sum of the transverse momenta of an event

²Neutrinos cannot be detected in detectors from collider experiments since they are weakly interacting with any matter.

have to sum up to zero, because the colliding partons have a negotiable transverse momentum. For the transverse energy it is the same. These quantities will also be discussed in the following sections.

Rapidity and Pseudorapidity

The Rapidity is a quantity that is often used in HEP to describe a collision in an experiment. It is defined as follows [23]:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right). \quad (3.1)$$

E is the energy of the particle and p_z is the momentum in the direction of the beam (here z-axis). The pseudorapidity is defined in equation 3.2 and has the advantage that it is invariant under boosts in the beam direction. At colliders like the LHC, we look at the collisions in the center of mass frame of the two colliding protons and not in the frame of the two partons in the quarks that actually interact. One can also use the pseudorapidity which is defined as

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right). \quad (3.2)$$

θ is the polar angle of the particle of interest (angle between a particle and the beam axis/z-axis). For massless particles the rapidity and the pseudorapidity are equal.

Transverse Mass

The transverse mass of the lepton and the neutrino is calculated using this formula [8]:

$$M_{T,\mu^+\nu} = \sqrt{2p_{T,\mu^+} \cdot p_{T,miss}(1 - \cos(\Delta\phi_{\mu^+,miss}))}. \quad (3.3)$$

The *miss*-values belong to the neutrino which is reconstructed from the missing transverse momentum in a detector. The transverse mass of the whole system (photon, lepton, and neutrino) is calculated with this formula [8]:

$$M_{T,\mu^+\nu\gamma} = \sqrt{\left(\sqrt{M_{\mu^+\gamma}^2 + |p_{T,\mu^+} + p_{T,\gamma}|^2} + p_{T,miss} \right)^2 - |p_{T,\mu^+} + p_{T,\gamma} + p_{T,miss}|^2}. \quad (3.4)$$

3.3 Standard Phase Space

In order to find the cut where the radiation amplitude zero is the best visible, different pT-cuts are applied on the final state photon and the final state charged lepton. The standard cuts are chosen as in this paper [1] from the ATLAS collaboration. The basic cuts that are used are summarised in table 3.1.

3 Setup

Particle	Cuts
ν (p_{Tmiss})	$p_T > 25$ GeV
μ	$ \eta < 2.5$, $p_T > 25$ GeV
γ	$ \eta < 2.5$, $p_T > 15$ GeV
μ, γ	$\Delta R = 0.7$
jet	$p_T > 30$ GeV

Table 3.1: Standard cuts implemented in the Rivet analysis

$\Delta R(\gamma, l)$ shows the separation of the photon and the lepton in the pseudorapidity azimuthal angle frame. ΔR represents a Euclidean distance in this plane and can be calculated as follows [8]:

$$\Delta R_{ij} = \sqrt{(y_i - y_j)^2 + \phi_{ij}^2}. \quad (3.5)$$

ϕ_{ij} is the azimuthal angle difference between two particles i and j. Additionally, some cuts are already included at generator-level in the SHERPA run-card:

In order to find the phase space region where the RAZ is best visible, we test differ-

Quantity	Cuts
$p_{T,\gamma}$	$p_{T,\gamma} > 20$ GeV
$p_{T,\mu}$	$p_{T,\mu} > 10$ GeV
y_γ	$-2.7 < y_\gamma < 2.7$
y_μ	$-5 < y_\mu < 5$
γ IsolationCut (isolation cone parameters)	dR = 0.2, exponent = 2, epsilon = 0.10
ΔR y , angular separation	$0.1 < \Delta R < 1000.0$

Table 3.2: Generator-level Run-Card-Cuts

ent values of an additional muon or photon transverse momentum selection criterion. For the muon, we tested 50 GeV, 100 GeV, 150 GeV and 200 GeV and for the photon 20 GeV, 40 GeV, 60 GeV, 80 GeV, 100 GeV and 120 GeV. When ever we applied a cut on the transverse momentum of the photon, the transverse momentum of the muon stays at the value of the standard cut and vice versa. As a next step, a cut on the transverse mass of the whole $W\gamma$ -system was implemented as well, for the other observables we used the standard cuts.

General remarks to the SHERPA simulation:

In all setups two proton-beams with energies of 6800 GeV are used. The center of mass energy is 13,6 TeV. The setup, called NLO in the following for simplicity, consists of $pp \rightarrow l^+ \nu_l \gamma$ merged with $pp \rightarrow l^+ \nu_l \gamma j$. Hence, it is not completely NLO QCD accurate, since virtual corrections are not included. Exemplary run-cards are shown in the appendix C.

3.3 Standard Phase Space

- coupling order at LO : $\mathcal{O}(\alpha_{EW}^3)$; at NL : $\mathcal{O}(\alpha_s \alpha_{EW}^3)$
- PDF set : PDF4LHC21_40_pdfas
- Merging scale CKKW : 20 GeV for NLO setups
- Matrix element generator : Comix
- Electroweak scheme: G_μ scheme ($G_\mu = 1.166397 \cdot 10^{-5} \text{GeV}^{-2}$)
- W-boson mass and width: $M_W = 80.399 \text{ GeV}$, $\Gamma_W = 2.0843 \text{ 1/GeV}$ (= 0 for polarised setups)
- factorisation scale (CORE_SCALE): $\sqrt{p_{T,\gamma}^2 + |p_l + p_\nu|^2}$
- if not stated otherwise, fully realistic events are generated, i.e. parton shower, hadronisation, QED corrections and underlying event simulation are included
- the laboratory frame is assumed as reference system for polarisation definition in polarised runs, if not differently declared

4 Unpolarised $W\gamma$ -production

In this chapter, the unpolarised $W\gamma$ -production is discussed. For the following analysis and discussion, we only look at W^+ -bosons that decay into an antimuon and a muon-neutrino. The same applies to W^- -bosons. A corresponding exemplary run-card can be found in the appendix C.2.

4.1 Leading Order $W\gamma$ -production

This section discusses at first the pseudorapidity difference distribution which has a dip, caused by the RAZ effect. After this, different cuts are discussed to make this dip deeper.

4.1.1 Rapidity and Pseudorapidity Distributions

In theory, the differential cross-section should vanish completely at a specific point in the $\cos(\Delta\theta)$ distribution where $\Delta\theta$ is the angle between an initial state quark and the photon in the rest frame of the two colliding partons (see also section 2.3.2 where $\Delta\theta = \theta^*$). This distribution cannot be reproduced with real measured data from experiments the initial state partons cannot be reconstructed. This zero in the angle distributions leads to a dip in the pseudorapidity-difference distributions between W and photon or muon and photon. Since we want to discuss the RAZ effect in a way that can also be applied to real measured data, we will look at the muon photon distributions. To conclude, the RAZ dip is present in the LO $W\gamma$ -process for the distribution of rapidity-difference $\Delta y(\gamma, \mu)$ and pseudorapidity-difference $\Delta\eta(\gamma, \mu)$ between photon and lepton, which are nearly equal in case of experiments at the LHC because the particles are moving ultrarelativistically. Both quantities are defined as in equations 3.1 and 3.2. For the simulation run at leading order and center-of-mass energy of 13.6 TeV in proton-proton collisions, the dip is visible as shown in figure 4.1.

These observables are used because we cannot detect a W -boson directly. After all, it is very shortlived due to its high mass. The rapidity and pseudorapidity are almost similar for massless particles like photons or muons in this process as we neglect the mass.

However, for particles with a rather high mass such as the W -boson, the condition $\eta \sim y$ does not hold anymore, which is shown in figure 4.2. Thus, we would expect a dip coming from the RAZ effect in the $\Delta\eta(W, \gamma)$ distribution but not necessarily in the $\Delta y(W, \gamma)$ distribution. This is also demonstrated in Ref. [3]. In general, the $\Delta\eta(\gamma, \mu)$ distribution delivers rather precise approximation for the $\Delta\eta(W, \gamma)$ distribution because the muon is mostly emitted in the direction of the W -boson. We also validated this with the angle between the W -boson and the muon in the laboratory

4 Unpolarised $W\gamma$ -production

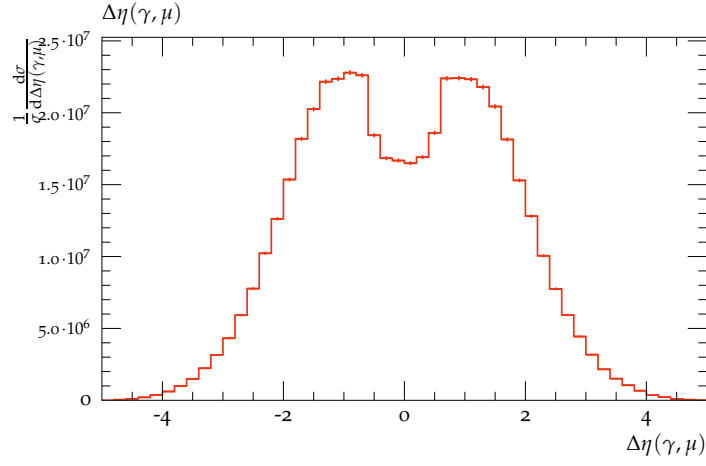


Figure 4.1: Pseudorapidity difference $\Delta\eta(\gamma, \mu)$ between photon and muon.

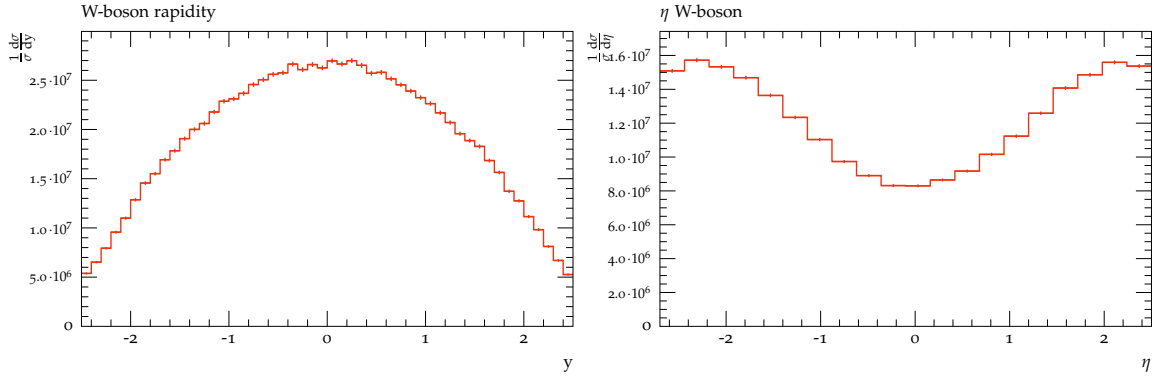


Figure 4.2: W-boson rapidity and pseudorapidity

frame. The corresponding plot can be seen in figure 4.3.

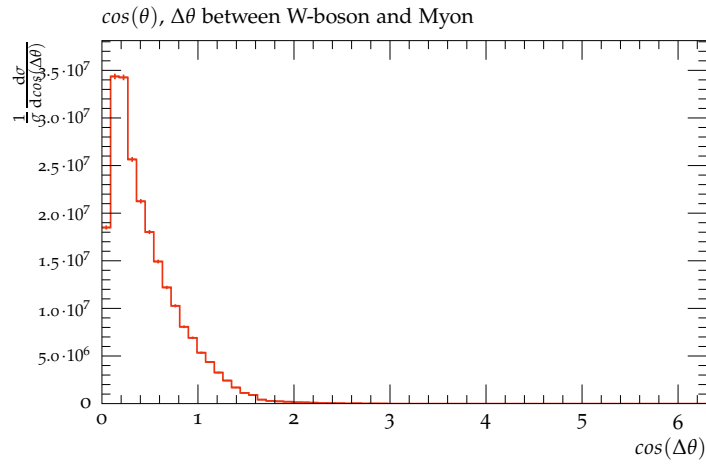


Figure 4.3: Angle between W-boson and anti-muon in the laboratory frame

Different effects such as QCD correction can fill the dip, these are discussed in the next section. At this point, we will only look at LO $W\gamma$ -production. Another contribution that fills in the dip is the diagram 2.3, which also contributes to the matrix element of $pp \rightarrow l^+ \nu_l \gamma$.

In Ref. [9], de Florian and Signer mention the fact that there is a dip, which is caused by the radiation amplitude zero effect in the $\Delta\eta(W, \gamma)$ distribution. However, we could not observe a dip in the $\Delta\eta(W, \gamma)$ distribution in any of our setups, not even in the setup on parton-level.

Now the aim is to make the dip in the $\Delta\eta(\gamma, \mu)$ distribution as deep as possible at the leading order, so that we may also see a dip at the next-to-leading order QCD (discussed in section 4.2). In figure 4.1, the $\Delta\eta(\gamma, \mu)$ distribution with applied standard cuts (see table 3.1) is shown.

4.1.2 Photon and Muon p_T -cuts

After applying the standard cuts, we also tested different cuts on the photon transverse momentum and the muon transverse momentum. This shows that the dip and the depth of the dip are quite sensitive to cuts in this distribution. For the rapidity distributions, it is better to cut on the photon p_T , because the photon is a direct final state particle from $W\gamma$ -production. The muon emerges from the reconstructed W-boson. In an experiment, we cannot measure the missing transverse momentum, which is the neutrino. This behavior can be seen in the plots in figure 4.4. The higher the photon or muon p_T cut, the deeper the dip. However, at some point, one loses too much statistics to have smooth curves. This is not too big of a problem for theoretical simulations but for experiments. This limits the cut. We can see that the dip from the $p_T > 120$ GeV curve is deeper than the dip from the $p_T > 60$ GeV curve.

4.1.3 Transverse Mass Cut

Another option is to cut on the transverse mass of the whole system $M_T(\mu, \nu, \gamma)$ [3][7]. This would also offer the opportunity to avoid contributions from the diagram in figure 2.3. $M_T(\mu, \nu, \gamma)$ is shown in figure 4.5a. The distribution reaches a small peak at approximately the W-boson mass at 80 GeV (PDG W-mass: $(80, 377 \pm 0, 012)$ GeV [10]). This peak shows the contribution of diagram (2.3) in this phase space region because the s-propagator in this diagram is resonant to the mass of the W-boson and, as a consequence, this diagram is more likely to contribute in this region due to an on-shell produced W-boson. In figure 4.5b, a $p_{T,\gamma} > 20$ GeV-cut is applied and, as we see, the peak at the W-mass vanishes.

4 Unpolarised $W\gamma$ -production

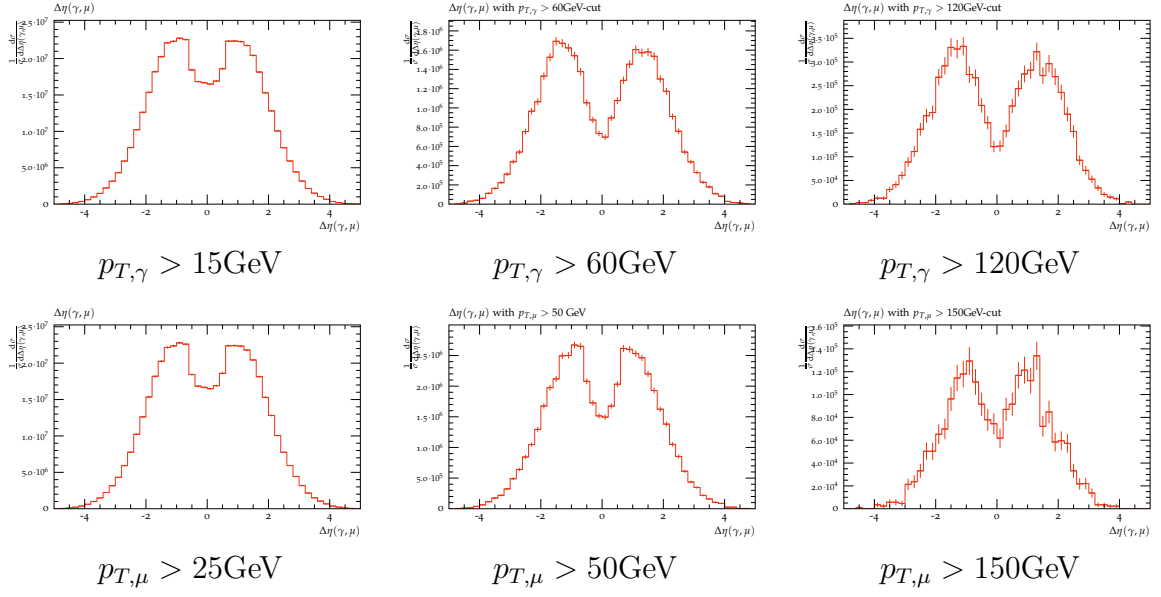


Figure 4.4: $\Delta\eta(\gamma, \mu)$ with different cuts on the transverse momenta of the photon and the muon

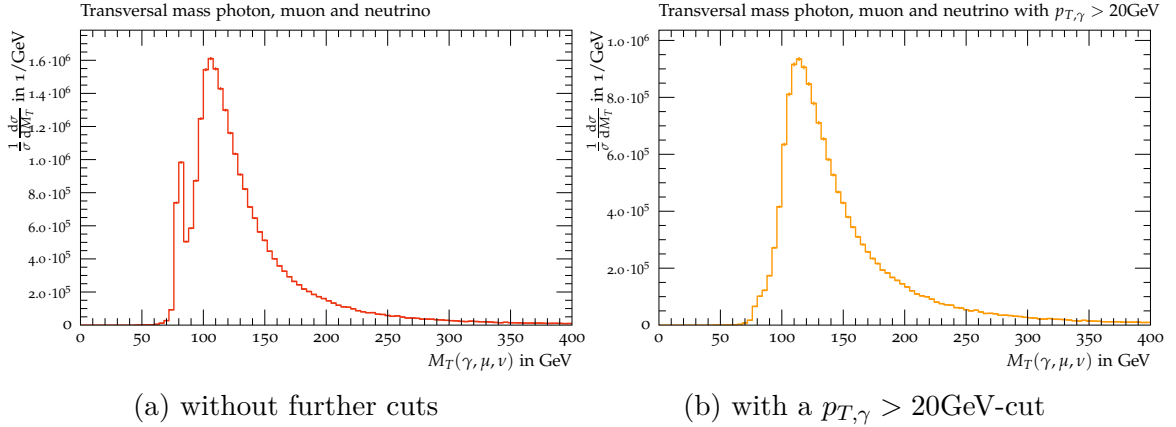
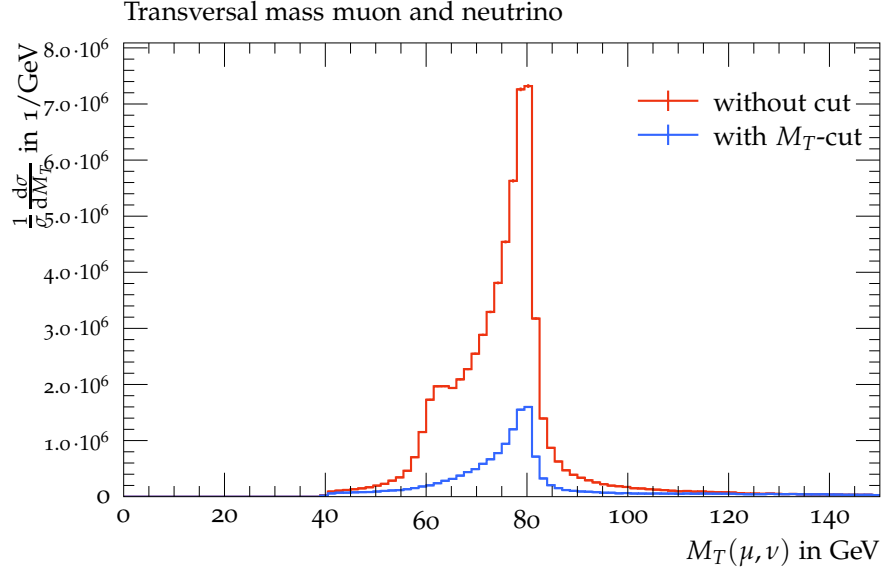


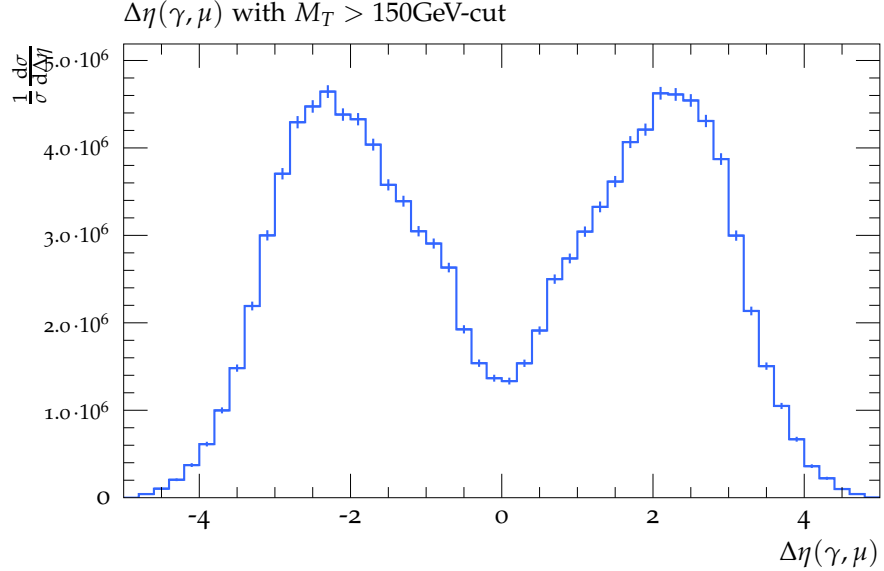
Figure 4.5: Transverse mass of the whole system $M_T(\mu, \nu, \gamma)$

In figure 4.6, one can see the transverse mass of the charged lepton and the neutrino $M_T(\mu, \nu)$. As expected, there is a huge peak at approximately the W-boson mass. Without any further cuts, we see that the peak is smeared out towards smaller masses. This also shows the influence of the process displayed in diagram 2.3 because in this case the mass of the lepton and the neutrino would not amount to the W-boson mass. Another effect that slightly smears out the peak in the $M_T(\mu, \nu)$ distribution arises from the fact that a W-boson has three polarisation states. Transverse polarised W-bosons are emitted with a momentum that is orthogonal to the direction of the beam, which means that they cause this peak at the W-mass. However, for the third polarisation state, namely the longitudinal one, the W-boson is emitted in the forward or backward beam direction, which means that one would not expect to have a high pT for this polarisation state.

Figure 4.6: Transverse mass of muon and neutrino $M_T(\mu, \nu)$

To reduce the influence of diagram 2.3, we cut on the transverse mass of the system. We attempted a cut at $M_T(\gamma, \mu, \nu) > 150$ GeV as also mentioned in a CMS paper [7]. The pseudorapidity distribution can be seen in figure 4.7. Here, the dip is quite deep and wide.

In order to compare it with the dip that can be seen in the distribution with the

Figure 4.7: $\Delta\eta(\gamma, \mu)$ with $M_T(\mu, \nu, \gamma) > 150$ GeV-cut

standard cuts applied, the two distributions are plotted into one diagram figure 4.8.

4 Unpolarised $W\gamma$ -production

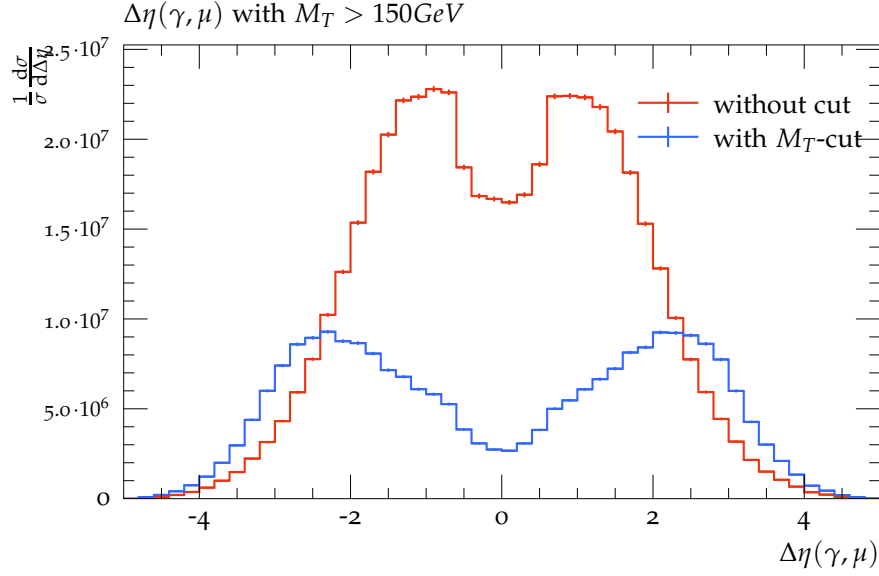


Figure 4.8: Pseudorapidity difference between the charged lepton and the photon

In general, we observe that an $M_T(\mu, \nu, \gamma)$ -cut produces a considerably wider and also deeper dip than other cuts we applied. However, there is also a big loss of statistics, but since the $W\gamma$ -production is not one of the rarest processes, this should not be too big a disturbance, especially not when measuring data with high luminosity experiments such as these conducted at the LHC.

To conclude this section, one can say that the dip is very sensitive to cuts. The transverse mass is the most successful in enhancing it. In the next section, this cut is also applied to the NLO setup.

4.2 NLO $W\gamma$ -production

The QCD corrections have a very big impact in observing the radiation amplitude zero, so we also looked at $W\gamma+1\text{jet}$ production. In figure 4.9, one can see that the dips in the pseudorapidity-difference distribution with the standard setup that were visible at LO are now mostly filled. The dip is still visible without higher photon p_T cuts, but it would be very hard to look for new physics in this dip.

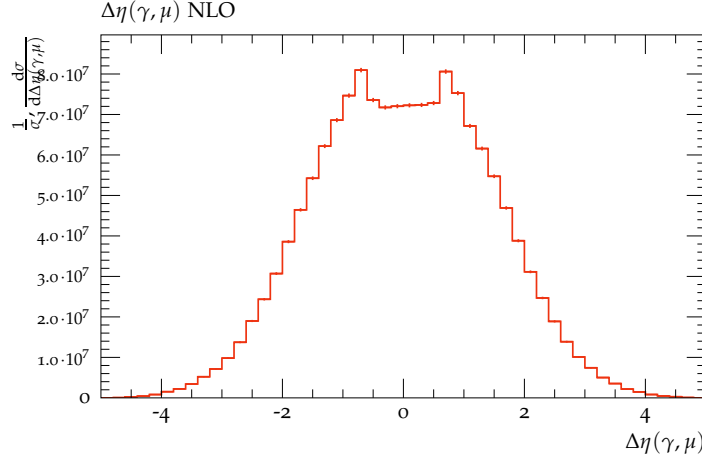


Figure 4.9: $\Delta\eta(\gamma, \mu)$ at NLO

As shown in section 4.1.3, it is good to apply a high cut on the transverse mass of the system $M_T(\gamma, \mu, \nu)$ to make the contributions of the diagram 2.3 small. With this cut, the distribution shows a little dip, as can be seen in figure 4.10.

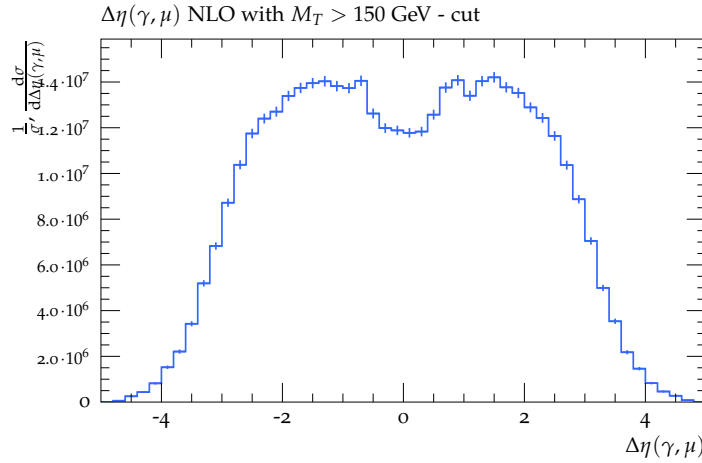


Figure 4.10: $\Delta\eta(\gamma, \mu)$ at NLO with $M_T(\gamma, \mu, \nu) > 150$ GeV-cut

With an applied $M_T(\gamma, \mu, \nu)$ -cut, the dip is wider and better visible than in the distribution without the $M_T(\gamma, \mu, \nu)$ -cut, but in comparison with the LO distribution one can clearly see, that QCD-corrections strongly fill the dip.

5 Polarised $W\gamma$ -production

As the next step, we also look at the same setups but polarised to see whether there are differences between different polarisation states. In this case, we do not have to care about the contribution of the diagram 2.3 which does not contribute to the RAZ, because it is not possible to define the W-boson-polarisation in such diagrams. However, this also means that one can compare the polarised with the unpolarised setup to find out how big the contribution of this diagram is. This is done in the next sections.

5.1 RAZ in polarised $W\gamma$ -production

At first, we looked at the RAZ in the $\cos(\Delta\theta)$ distribution with $\Delta\theta$ being the angle between the final state photon and one of the initial state quarks in the parton-parton rest frame. The corresponding distributions for the different polarisation states are plotted in figure 5.1.

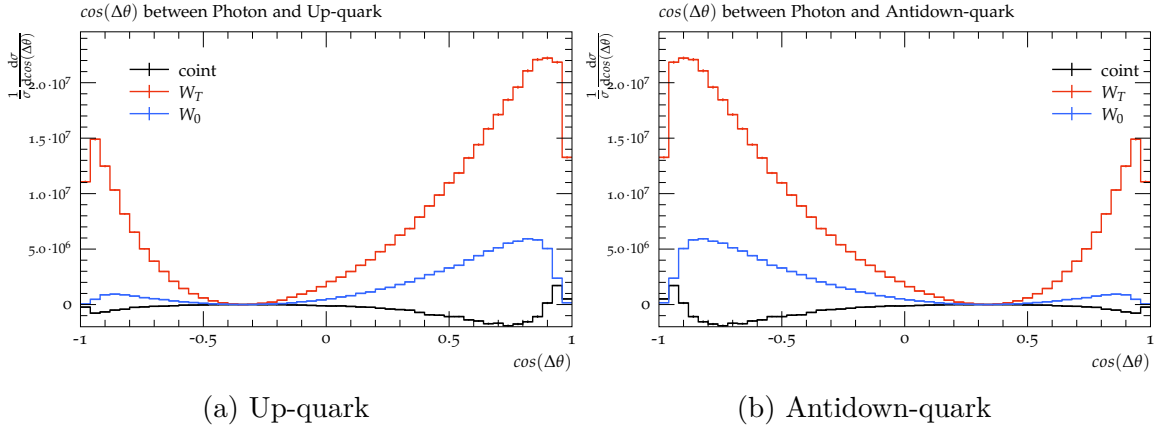


Figure 5.1: Radiation amplitude zero in polarised $W\gamma$ -production

Due to the fact that we already observed the zero in this distribution for the unpolarised setup, it is not surprising that we get a total zero in the polarised setup as well. The individual polarised distributions do not have an exact zero due to interference between different polarisation states (for details on that see section B in the appendix). The “coint” distribution shows the interference term between the total transverse and the longitudinal polarisation and the “int” distribution (which is not shown here) shows the interference between the all polarisation states. The transverse distribution includes the righthanded and lefthanded polarisation states and also the interference terms between this states [11]. There are differences

in magnitude in the distributions for the different polarisation states which are discussed in the following sections. In the rest of this chapter we do not look on the interference term and plot all different polarisation states in one plot.

5.2 LO Rapidity-Difference

In figure 5.2, the differential cross-section of the pseudorapidity difference between photon and muon is plotted. This plot shows that all polarisation states contribute to the RAZ. The cross-section of the longitudinal polarised W-boson is much lower than the one of the transverse polarisation. This can be explained due to the fact that longitudinal polarised W-bosons have to be produced spin aligned with the quarks from the collision. This can be seen in the definition of the longitudinal polarisation vector (see section 2.2) and this is less likely to happen than the W-boson being emitted orthogonal to the beamline, because the asymmetry between the momenta of the two colliding partons is usually not very big and there has to be a difference which is big enough to produce a W-boson which than flies in the direction of the parton that had more momentum. Figure 5.3 shows the LO $\Delta\eta$

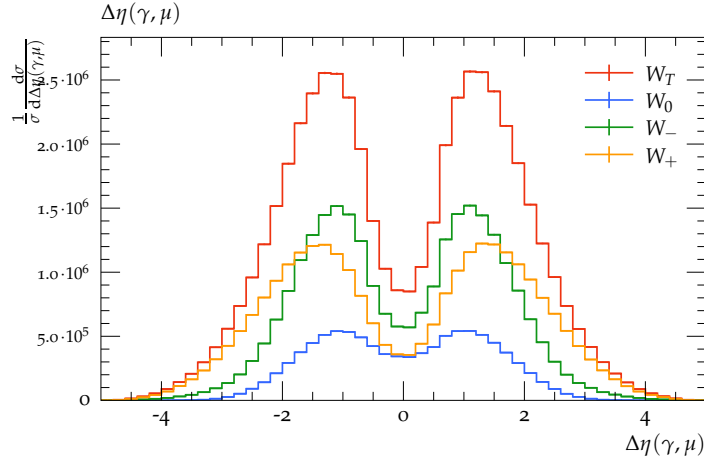
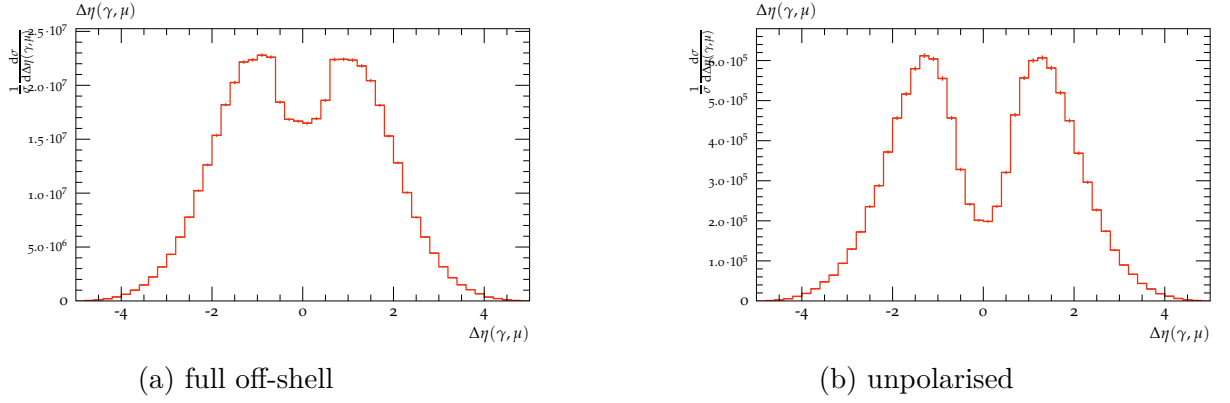
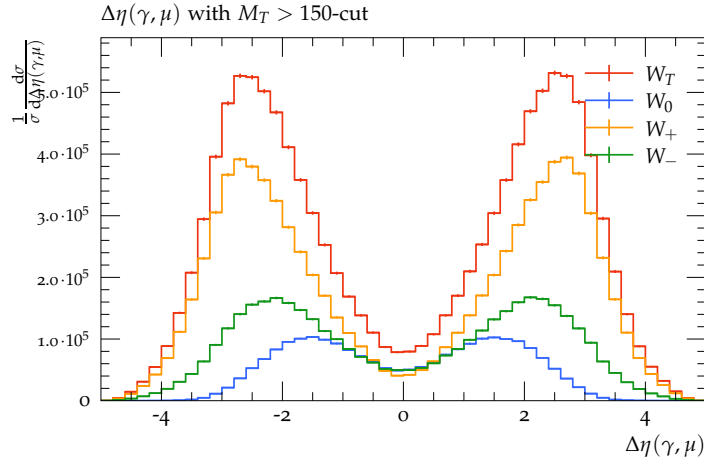


Figure 5.2: $\Delta\eta(\gamma, \mu)$ at LO

distributions. In figure 5.3a one can see the distribution for setup which is used in chapter 4, the full off-shell setup which includes the whole process $pp \rightarrow l^+ \nu_l \gamma$ at $\mathcal{O}(\alpha_{EW}^3)$. Figure 5.3b shows the unpolarised distribution which was build from a polarised setup as a sum over left- and righthanded as well as the longitudinal polarisation states plus interference terms. Looking at both distributions we can conclude that the impact of the diagram 2.3 is not negligible.

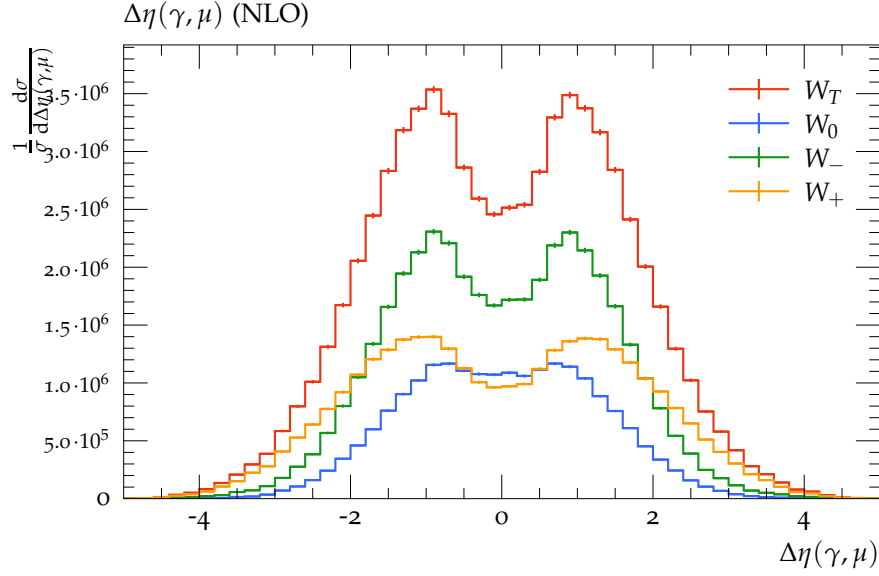
We can also look at the different transverse polarisation states in figure 5.2. Without further cuts, one can see that the left and right-handed polarisation states are nearly equal in magnitude with the right-handed state being a little smaller. In figure 5.4 one can see the distribution with an additional $M_T(\mu, \nu, \gamma) > 150$ GeV-cut applied.


 Figure 5.3: $\Delta\eta(\gamma, \mu)$ at LO

 Figure 5.4: $\Delta\eta(\gamma, \mu)$ with $M_T(\mu, \nu, \gamma) > 150$ GeV-cut

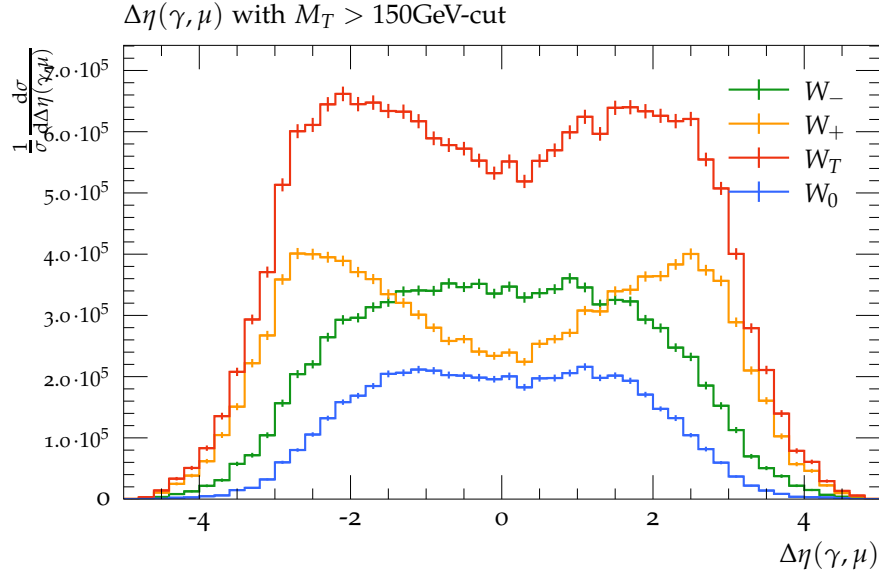
Comparing figures 5.2 and 5.4 one can see, the transverse mass cut suppresses the lefthanded W-polarisation state and the magnitude of the lefthanded distribution becomes less.

5.3 NLO Rapidity-Difference

In figure 5.5 we see the pseudorapidity difference between the muon and the photon at NLO. Since the longitudinal polarisation cross-section is much lower in comparison with the transverse polarisation, the dip is not really visible in this polarisation state anymore. In the transverse distribution, however one can clearly see a small dip. Here, one also has to keep in mind, that we have no contribution of the additional diagram which fills the dip. It is also visible that the lefthanded W-boson-polarisation state makes a bigger fraction compared to the righthanded polarisation state in the distribution.


Figure 5.5: $\Delta\eta(\gamma, \mu)$ at NLO

In figure 5.6, one can see the $\Delta\eta$ distribution with an applied $M_T(\mu, \nu, \gamma) > 150$ GeV-cut. Noticeable is that the cut again has a primary effect on the righthanded polarisation state. For this state the dip becomes wider and deeper while the dip for the lefthanded state becomes washed out.


Figure 5.6: $\Delta\eta(\gamma, \mu)$ with $M_T(\mu, \nu, \gamma) > 150$ GeV-cut at NLO

5.4 Transverse Energy and Momenta at LO and NLO

Looking at the transverse energy and momentum distributions from the muon and the neutrino, one can also see differences in the different transverse polarisation

5.4 Transverse Energy and Momenta at LO and NLO

states. In figures 5.7 and 5.8 the transverse momentum distributions for the muon and the neutrino are plotted at LO and at NLO.

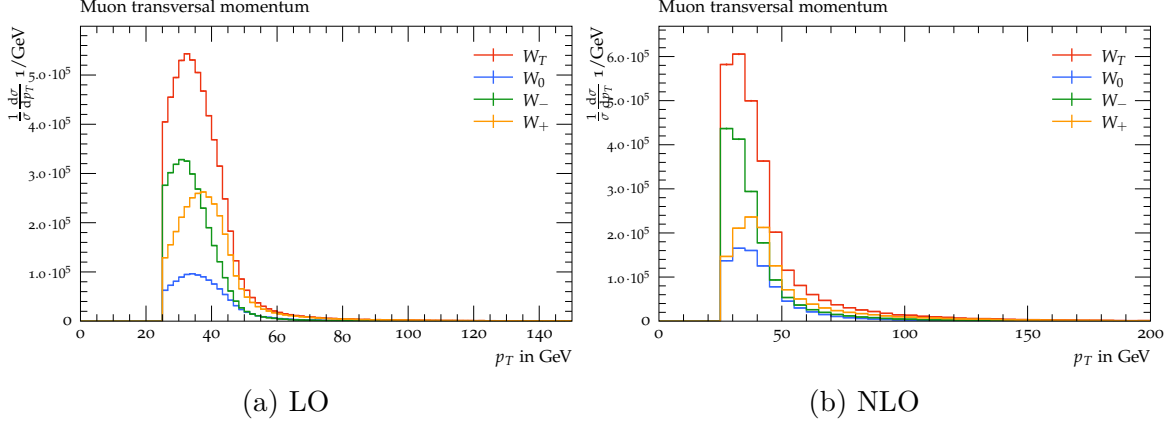


Figure 5.7: Transverse momentum of the muon

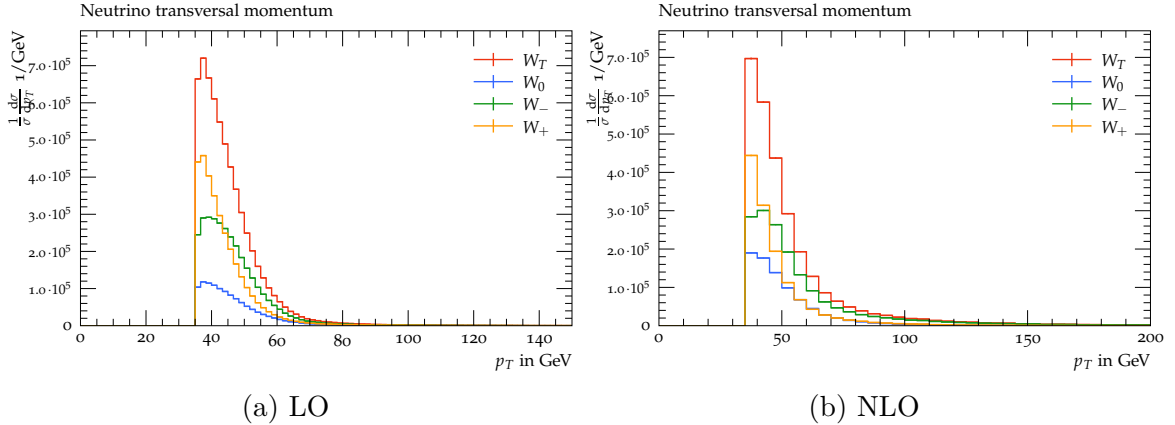


Figure 5.8: Transverse momentum of the neutrino (missing transverse momentum)

The distribution for the lefthanded W-boson polarisation becomes more dominant at NLO. In general, one would expect that there are slightly more lefthanded W-boson produced in this process at proton-proton-colliders like the LHC because the quark momenta are on average bigger than the momenta of anti-quarks. This can be illustrated in a simplified setup for W-production from two colliding quarks on the beam axis. A lefthanded W-boson is produced if the momentum of the quark is bigger than the momentum of the anti-quark. This can be also seen in the quark-momentum distributions in figures 5.9. These distributions were made with simulated data on parton-level with a colliding up and anti-down-quark. The up-quark travels in +z-direction and the anti-down-quark in -z-direction, these cuts were applied in the analysis.

5 Polarised $W\gamma$ -production

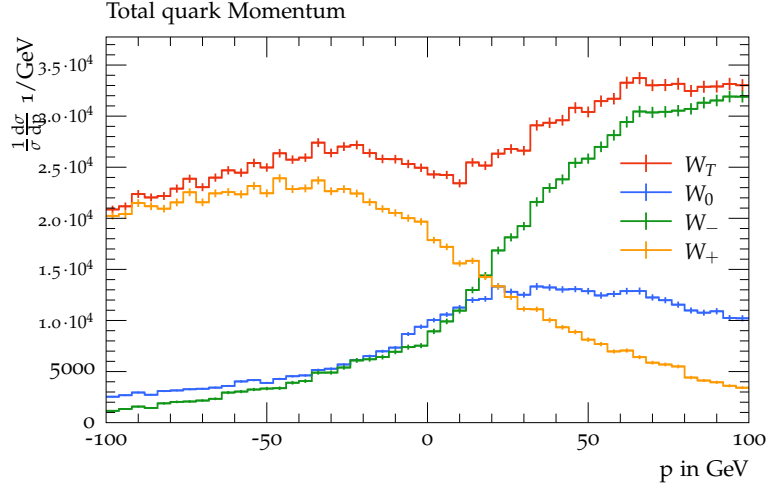


Figure 5.9: Summed quark-momentum (up-quark momentum + down-quark momentum)

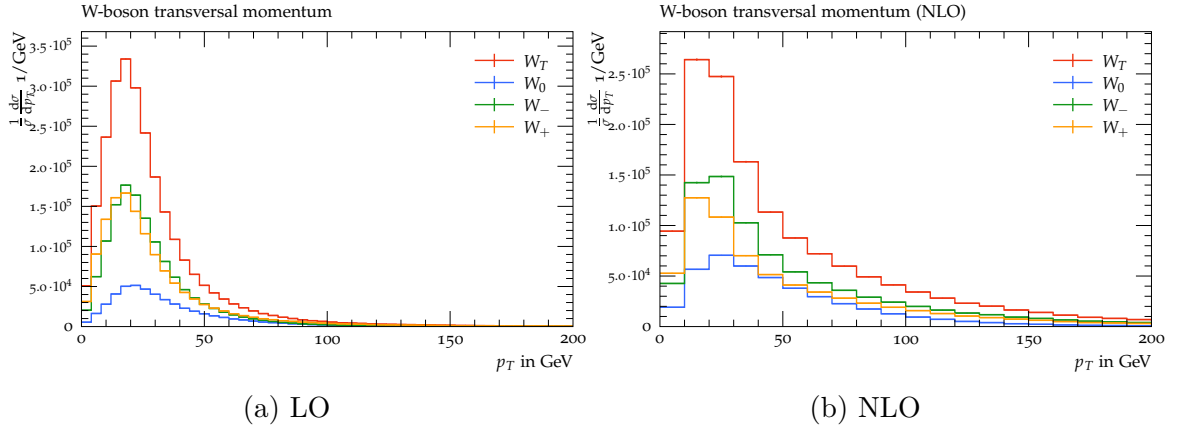


Figure 5.10: Transverse momentum of the W-boson

In figure 5.10 the transverse momentum distributions of the W-bosons can be viewed. Since the W-boson is reconstructed out of the muon and the neutrino it is no surprise that this distribution looks fairly similar. Here, also the difference between the lefthanded polarisation state between LO and NLO is visible. In figure 5.11 the transverse energy of the W-boson is plotted, here a small kink is visible at approximately 80 GeV. Interestingly, in figure 5.11 the longitudinal polarisation has nearly the same magnitude as the other two polarisation states.

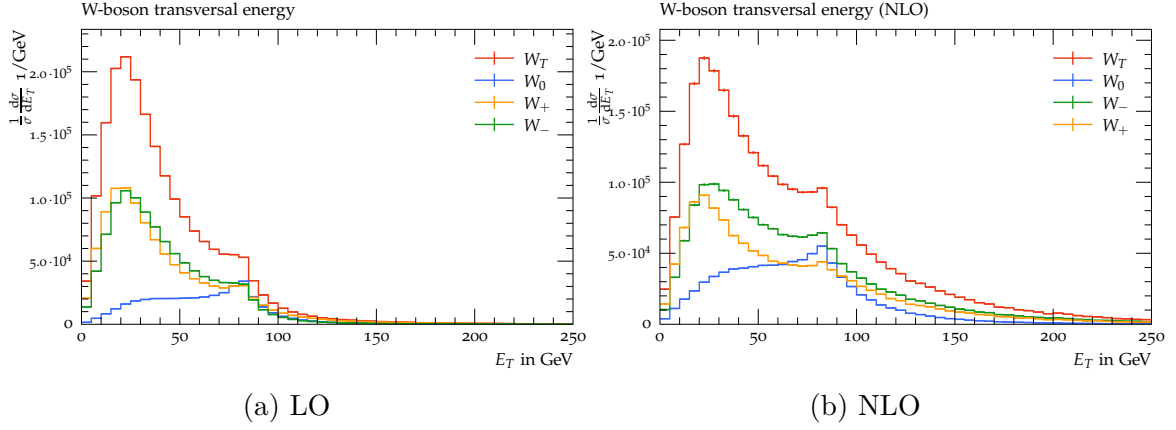


Figure 5.11: W-boson transverse energy

5.5 Rapidity

As one can see, there are also differences for individual polarisation states in the rapidity distributions of the individual particles. As in figure 5.12 we see that the longitudinal distribution looks very different for the photon and the W-boson rapidity. While the rapidity goes down near zero in the photon distribution for the longitudinal polarisation state, the W-boson rapidity has a peak at 0. This sharp peak is only present in the laboratory frame. In the other reference system that was defined in the SHERPA-run-card ($W\gamma$ rest frame) the distributions look very different. The corresponding plot can be found in appendix A.1a.

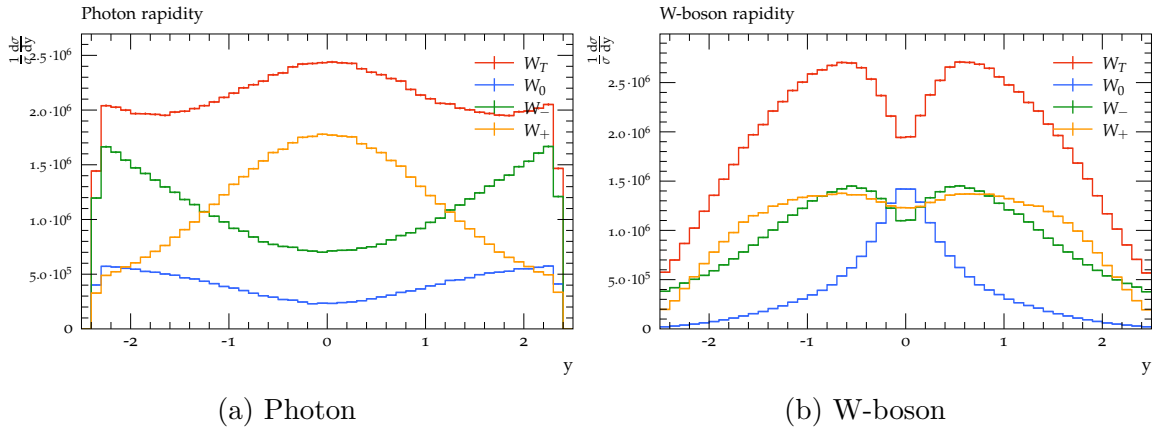


Figure 5.12: Rapidity distributions of photon and W-boson

The rapidity distribution of the muon is shown in figure 5.13. For the muon the transverse distribution does not have a dip like the transverse distribution in the W-boson rapidity plot in 5.12b and also the lefthanded distribution does not show a dip in the muon rapidity.

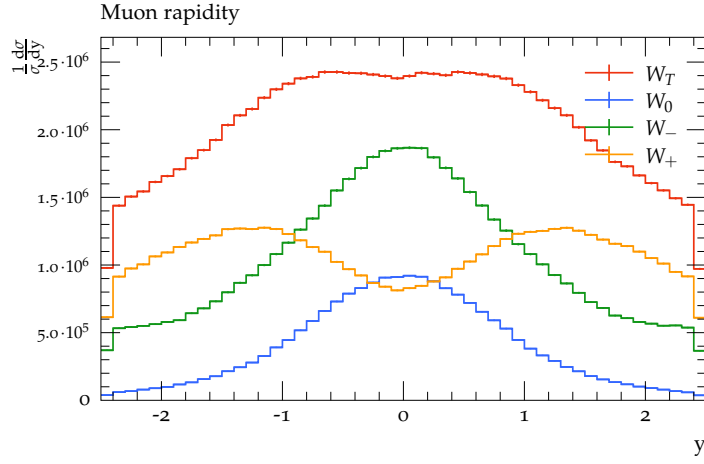


Figure 5.13: Muon rapidity

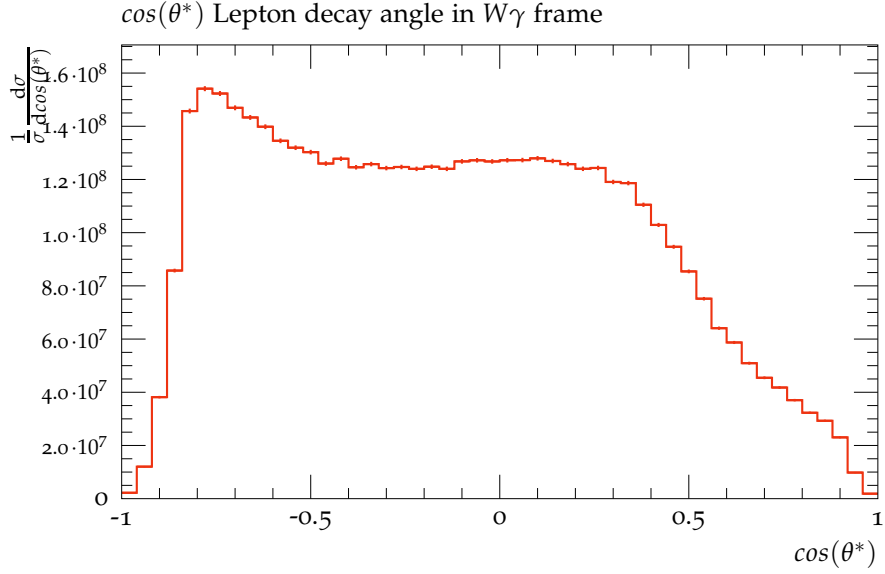
5.6 Lepton-Decay-Angle

Another polarisation-sensitive observable is the decay angle θ^* , which is the angle between lepton momentum in the rest frame of the W-boson and the direction of the W-boson in the $W\gamma$ rest frame [16]. To get this decay angle, several steps are necessary. At first, a four-momentum for the W-boson combined with the photon has to be constructed, and then the W-boson and the muon from the W-decay have to be transformed in the rest frame of the $W\gamma$ -system. Then the muon needs to be boosted into the W-boson rest frame and then the cosine of the angle between the W-boson in the $W\gamma$ rest frame and the muon in the W-boson rest frame is plotted into a diagram, which can be seen in figure 5.14 for an unpolarised setup.

In comparison with the distribution in the polarised setup in figure 5.15, one sees that there is a peak in the left side of the unpolarised distribution that might come from the diagram that does not contribute to the polarised distributions. This specific angle is very sensitive to the W-polarisation. In figures 5.15a and 5.15b the LO and NLO $\cos(\theta^*)$ distributions are plotted. If the W-boson is produced righthanded, the anti-muon (righthanded) is emitted in a forward direction and the muon-neutrino (lefthanded) is emitted in a backward direction due to momentum conservation. For a W-boson that is produced lefthanded it is the other way around and the anti-muon is emitted in the backward direction.

The theory prediction for the behaviour of the differential cross-section in dependency on the $\cos(\theta^*)$ for the different polarisation states is

$$\begin{aligned}
 P_+ &= \frac{3}{8}(1 - \cos \theta^*)^2 \\
 P_- &= \frac{3}{8}(1 + \cos \theta^*)^2 \\
 P_0 &= \frac{3}{4} \sin^2 \theta^*
 \end{aligned} \tag{5.1}$$

Figure 5.14: Unpolarised distribution of $\cos(\theta^*)$, θ^* lepton decay angle

where P are the probability amplitudes [16][19] that also have to be scaled by some prefactors. For small θ^* (muon is emitted in forward direction) one expects more lefthanded W-bosons and for $\theta^* \approx \pi$ one expects more righthanded polarised W-bosons.

The theory curves are plotted in figure 5.16 and as one can see in comparison with the simulated distributions, the simulation for the LO and NLO process is in good agreement with this. The theory plot shows also that slightly more lefthanded W-bosons are produced at NLO. The cuts that were applied in the analysis also lead to a deviation between the simulated distributions and the theory plots. The cuts on the transverse momenta like they are mentioned in table 3.1 cutting off the edges at ± 1 in the simulated plots. The prefactors (polarisation fractions) that are needed for plotting the scaled probability amplitudes are calculated with the total cross sections for the individual polarisation states. The calculated factors are listed in table 5.1.

	LO	NLO
f_0	0.1556	0.2196
f_+	0.4277	0.3454
f_-	0.4166	0.4349

Table 5.1: Polarisation fractions at LO and NLO

5 Polarised $W\gamma$ -production

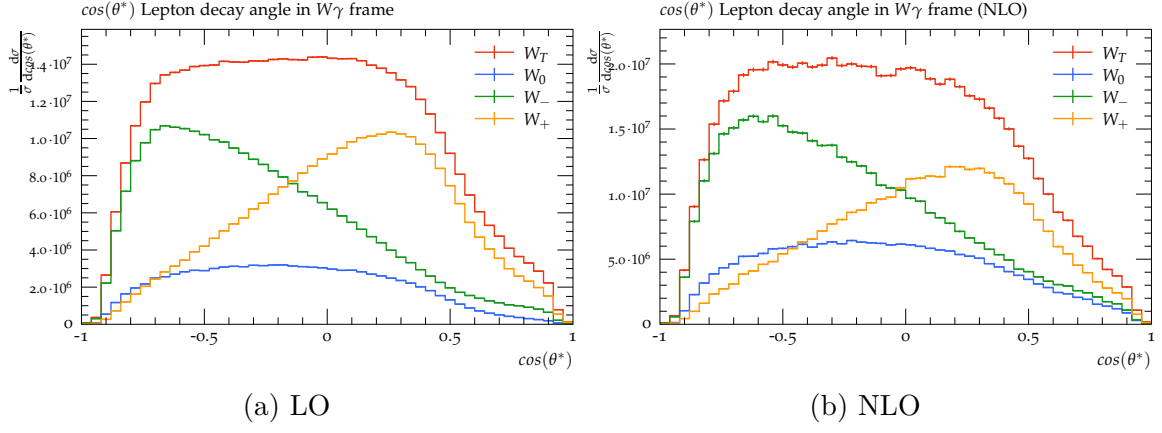


Figure 5.15: $\cos(\theta^*)$ with θ^* lepton decay angle

The main difference between the two plots is that in the NLO distributions, the lefthanded distribution becomes more dominant, as observed in other distributions in this chapter. The fraction of the longitudinal polarised W-bosons also becomes bigger at NLO.

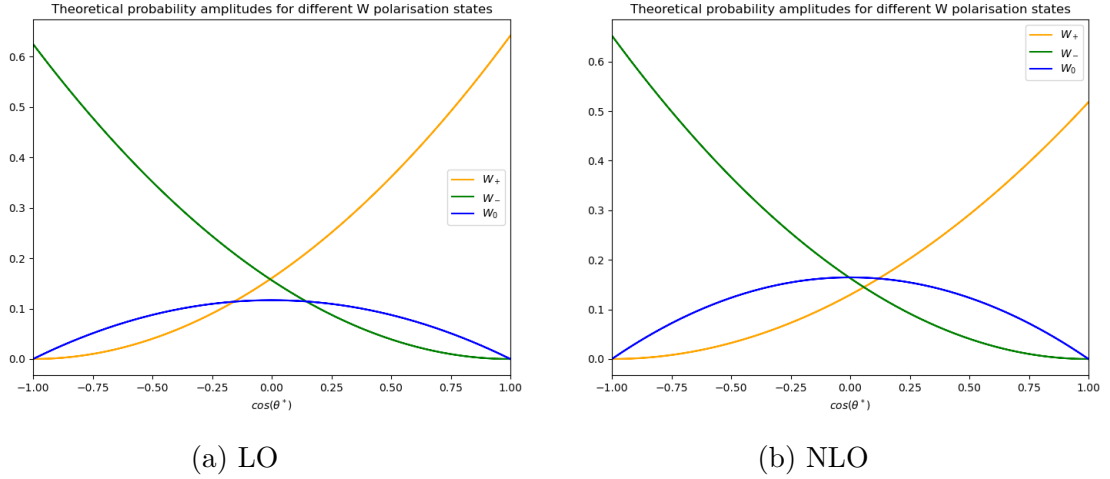


Figure 5.16: Probability amplitudes for different polarisation states at LO and NLO

6 Summary and Outlook

In this thesis, it was possible to reconstruct the radiation amplitude zero in the angle distribution between the final state photon and an initial state quark from simulated data with SHERPA for an unpolarised and polarised setup. This exact zero is predicted by the Standard Model but not measurable by an experiment. The different polarisation distributions for the individual W-boson polarisation states are also not measurable in experiments since we can not measure polarisation.

However, the RAZ effect influences other distributions like the pseudorapidity difference between the photon and the charged lepton from the W-boson decay. In this distribution, we expect a dip at $\Delta\eta(\gamma, \mu) = 0$, which we could reproduce with our phase spaces oriented by real experiments such as the LHC experiments. It was also possible to reproduce several distributions that were previously presented by other groups in the last years.

In order to find an event-selection where the RAZ dip is visible, different phase spaces were tested. After applying different cuts on the photon and muon p_T , we concluded that a cut on the photon p_T is the better choice. Already relatively small cuts like $p_{T,\gamma} > 40$ GeV deepened the dip significantly. However, we received the best results with a cut on the transverse mass of the whole system, which made the dip very deep and wide at LO. We used an $M_T(\mu, \nu, \gamma) > 150$ GeV-cut. This cut was also successful at NLO. The dip is by far not as deep as at LO, but without this cut, the RAZ dip is totally suppressed.

Our results show that the transverse polarisation states are the dominant ones in the investigated phase space. It was also possible to see that there are more lefthanded than righthanded W-bosons in the $W\gamma$ -production when we allow 1 jet in the final state.

Since the RAZ effect offers the opportunity to study anomalous couplings, exotic resonances, or similar new physics effects, one could also study these effects within data simulated by SHERPA and make theory predictions out of this. These simulations can be done either unpolarised or polarised.

To obtain higher-order realistic results, more corrections should be taken into account, for example more jets in the final state, and also QED and electroweak corrections.

Another step would also be to look at the $M_T(\mu, \nu, \gamma)$ -cut in the polarised setup which mainly influenced the righthanded W-polarisation distribution in more detail to understand this behaviour.

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A Additional plots

A.1 Polarised Rapidity in the $W\gamma$ rest frame

For polarised setups, one has to choose a reference system within the SHERPA-run-card as the helicity of massive particles such as the W-boson is not Lorentz invariant. The reference system has been chosen as the $W\gamma$ rest-frame (see also section C.2) [21]. The following plots show the rapidity distributions of different particles in the $W\gamma$ rest-frame.

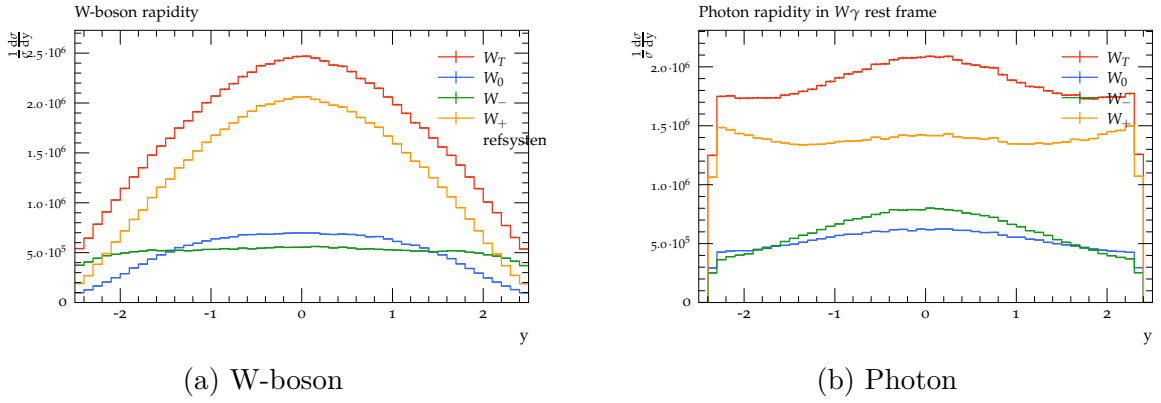
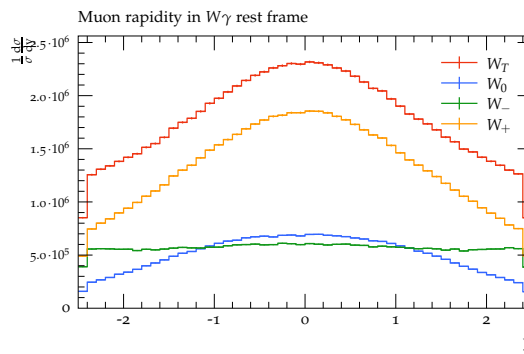


Figure A.1: Rapidity distributions in the $W\gamma$ rest frame



A.2 Initial State Quark Momentum

The following plots show the momenta of the initial state quarks. The corresponding simulation was on parton level. It is visible that the quarks, on average, have more momentum than the antiquarks.

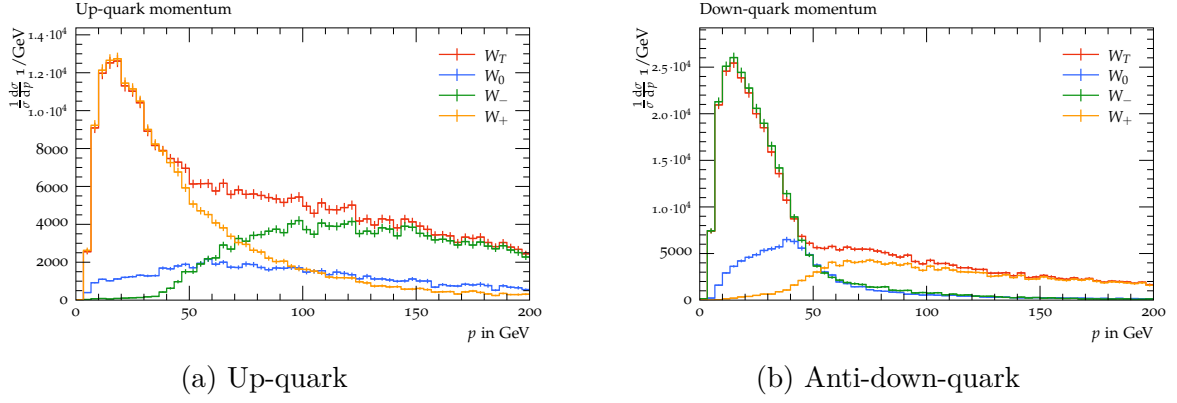


Figure A.3: Initial state quark momenta

B Polarisation of intermediate Vector-bosons

Vector bosons such as the W-boson have a rather short lifetime. Thus, they cannot be detected directly but have to be reconstructed through their decay-products. As a consequence, one cannot look at different polarisation states as it is shown in section 2.2 where the polarisation of external vector bosons is shown [11]. The W-boson has to be treated as propagator. The propagator term for a massive vector boson is

$$D_{\mu\nu} = \frac{-i(g_{\mu\nu} - \frac{q_\mu q_\nu}{m^2})}{q^2 - m_v^2 + i\Gamma_v m_v} \quad (\text{B.1})$$

with q being the vector boson momentum, m_v the mass of the vector boson and Γ_v being the width. In order to get the polarisation vector in this term one can use a completeness relation [23]

$$\sum_{\lambda} \epsilon_{\lambda}^{*\mu} \epsilon_{\lambda}^{\nu} = -g^{\mu\nu} + \frac{q^{\mu} q^{\nu}}{m^2} \quad (\text{B.2})$$

λ stands for the different polarisation states. If one considers a matrix element with a vector-boson propagator that decays into a lepton pair (ψ_f and $\psi_{f'}$ are the lepton spinors) as

$$M = M_{\mu}^p \left(\frac{-i(g_{\mu\nu} - \frac{q_{\mu} q_{\nu}}{m^2})}{q^2 - m_v^2 + i\Gamma_v m_v} \right) (-ig\bar{\psi}_f \gamma_{\nu} \left(\frac{1}{\sqrt{2}} \frac{1 - \gamma^5}{2} \right) \psi_{f'}) \quad (\text{B.3})$$

we can substitute B.2 into B.3. Now, M can be factorised into $M_{\lambda}^P M_{\lambda}^D$ with $M_{\lambda}^P = M_{\mu}^p \epsilon_{\lambda}^{\mu}$ being the matrix-element-term that stands for the vector boson production and M_{λ}^D representing the decay (third factor in B.3).

$$\begin{aligned} M &= \frac{i}{q^2 - m_v^2 + i\Gamma_v m_v} \sum_{\lambda} M_{\mu}^p \epsilon_{\lambda}^{*\mu} \epsilon_{\lambda}^{\nu} (-ig\bar{\psi}_f \gamma_{\nu} \left(\frac{1}{\sqrt{2}} \frac{1 - \gamma^5}{2} \right) \psi_{f'}) \\ &= \frac{i}{q^2 - m_v^2 + i\Gamma_v m_v} \sum_{\lambda} M_{\lambda}^P M_{\lambda}^D = \sum_{\lambda} M_{\lambda}^F \end{aligned} \quad (\text{B.4})$$

Finally the squared matrix element has to be calculated (sum over all polarisations λ):

$$|M|^2 = \sum_{\lambda} |M_{\lambda}^F|^2 + \sum_{\lambda \neq \lambda'} M_{\lambda}^F M_{\lambda'}^{*F} \quad (\text{B.5})$$

B Polarisation of intermediate Vector-bosons

The second term which emerges is an interference term between different polarisation states. Usually, this term does not sum up to zero. The first term shows an incoherent sum of polarised contributions [11].

For the polarised distributions that were shown in chapter 5, this means that the different polarised components are displayed individually. To get the unpolarised distribution out of this, the interference terms always have to be taken into account [2]. In SHERPA, the polarisation-weight 0, -, + and “int” sum up to the unpolarised distribution, or 0, T and “coint” sum up to the unpolarised distribution.

C Run-Cards

In this section, SHERPA-run-cards are shown as an example for an unpolarised and a polarised setup. Throughout the work, different run-cards were used. However, they basically had the same structure as the following ones. For this thesis unpolarised and polarised runs at LO, NLO (with one additional jet in the final state) and for a fixed-order setup at parton-level were performed. Further information about run-cards can be found in [21].

C.1 Unpolarised Setup

The following run-card shows an unpolarised setup for $W\gamma$ -production at LO. To also consider one additional jet in the final state (real NLO QCD corrections), the PROCESSES - Section has to be modified such that

```
# pp -> W[lv] + gamma + 1 jet
PROCESSES:
- 93 93 -> -13 14 22 93{1}:
  Order: {QCD: 0, EW: 3}
  CKKW: 20
```

```
1 # Sherpa configuration for W[lv]+gamma production LO, unpolarised
2
3 # set up beams for LHC run 3
4 BEAMS: 2212
5 BEAM_ENERGIES: 6800
6
7 # matrix-element calculation, ME_generator setting
8 ME_GENERATORS:
9 - Comix
10
11 EW_SCHEME: Gmu
12 GF: 1.166397e-5
13
14 PARTICLE_DATA:
15 # define the mass and width of W and mass of the b quark
16 24:
17   Width: 2.0843
18   Mass: 80.399
19 5:
20   Mass: 4.95
21
22 # factorization and renormalization scale @ fixed LO
23 MEPS:
24   CORE_SCALE: VAR{PPerp2(p[4])+Abs2(p[2]+p[3])}
```

```
25
26 # pp -> W[lv] + gamma
27 PROCESSES:
28 # definition of the process with initial and final states,
29 # p + p -> anti-mu + mu-neutrino + gamma
30 - 93 93 -> -13 14 22:
31     # coupling orders:
32     # at L0 there are three electroweak couplings and no QCD couplings
33     Order: {QCD: 0, EW: 3}
34
35 # cuts (on matrix-element-level), act on particles in PROCESSES
36 SELECTORS:
37 - [PT, 22, 7.0, E_CMS]
38 - [Y, 22, -5.0, 5.0]
39 - [IsolationCut, 22, 0.1, 2, 0.10]
40 - [DR, 22, 90, 0.1, 1000.0]
41 - [PT, -13, 10, E_CMS]
42 - [Y, -13, -5.0, 5.0]
43
44 EVENTS: 500000
45
46 # Rivet-Analysis with different cut-options
47 ANALYSIS: Rivet
48 RIVET:
49 --analyses:
50 - MC_Wy
51 - MC_Wy:pT_yCut=Cut20
52 - MC_Wy:pT_yCut=Cut40
53 - MC_Wy:pT_yCut=Cut60
54 - MC_Wy:pT_yCut=Cut80
55 - MC_Wy:pT_yCut=Cut100
56 - MC_Wy:pT_yCut=Cut120
57 - MC_Wy:pT_muCut=Cut50
58 - MC_Wy:pT_muCut=Cut100
59 - MC_Wy:pT_muCut=Cut150
60 - MC_Wy:pT_muCut=Cut200
61 - MC_Wy:mT_systemCut=Cut
62 --skip-weights: 1
```

C.2 Polarised Setup

```
1 # Sherpa configuration for W[lv]+gamma production L0, polarised
2
3 # set up beams for LHC run 3
4 BEAMS: 2212
5 BEAM_ENERGIES: 6800
6
7 # matrix-element calculation, ME_generator setting
8 ME_GENERATORS:
9 - Comix
10
11 COMIX_DEFAULT_GAUGE: 0
12
13 EW_SCHEME: Gmu
```

```

14 GF: 1.166397e-5
15
16 PARTICLE_DATA:
17 # define the mass and width of W, Width has to be set to 0
18 24:
19     Width: 0
20     Mass: 80.399
21 5:
22     Mass: 4.95
23
24 WIDTH_SCHEME: Fixed
25
26 # factorization and renormalization scale @ fixed L0
27 MEPS:
28     CORE_SCALE: VAR{PPerp2(p[3])+Abs2(p[2])}
29
30 # pp -> W[lv] + gamma
31 PROCESSES:
32 #definition of the process with initial and final states + Jets, but
33     Jets not allowed at L0 since Order QCD is set to 0
34 - 93 93 -> 24 22:
35     # at L0 there are two electroweak couplings and no QCD couplings
36     Order: {QCD: 0, EW: 2}
37
38 HARD_DECAYS:
39     Enabled: true
40     Channels:
41         24,14,-13: {Status: 2}
42     Pol_Cross_Section:
43         Enabled: true
44         Reference_System: [Lab, 2 3]
45
46 # set up cuts, that are applied to the PROCESS section
47 SELECTORS:
48 - [PT, 22, 7.0, E_CMS]
49 - [Y, 22, -5.0, 5.0]
50 - [IsolationCut, 22, 0.1, 2, 0.10]
51 - [DR, 22, 90, 0.1, 1000.0]
52
53 EVENTS: 500000
54
55 # Rivet-Analysis with different cut-options
56 ANALYSIS: Rivet
57 RIVET:
58 --analyses:
59 - MC_Wy
60 - MC_Wy:pT_yCut=Cut20
61 - MC_Wy:pT_yCut=Cut40
62 - MC_Wy:pT_yCut=Cut60
63 - MC_Wy:pT_yCut=Cut80
64 - MC_Wy:pT_yCut=Cut100
65 - MC_Wy:pT_yCut=Cut120
66 - MC_Wy:pT_muCut=Cut50
67 - MC_Wy:pT_muCut=Cut100
68 - MC_Wy:pT_muCut=Cut150
69 - MC_Wy:pT_muCut=Cut200

```

C Run-Cards

69 - MC_Wy:mT_systemCut=Cut

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D Selbstständigkeitserklärung

Hiermit erkläre ich, dass ich, Rebecca Seip, diese Bachelorarbeit im Rahmen der Betreuung am Institut für Kern- und Teilchenphysik ohne unzulässige Hilfe Dritter verfasst und alle Quellen als solche gekennzeichnet habe.

Diese Arbeit wurde noch nicht in gleicher oder ähnlicher Form im Rahmen einer anderen Prüfungsleistung vorgelegt.

Rebecca Seip
Dresden, Mai 2024