Measurement of tZq differential cross-section

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CHAPTER 1

The Standard Model

Since many years, physical phenomena occuring around us has shaped our understanding about nature. The Standard Model (SM) of particle physics is a theory that explains almost everything that nature has to offer. It is based on fundamental particles and their interactions being governed by Quantum Field Theories (QFTs).

The Standard Model is divided into spin-1 fermions and spin-0 bosons. The fermions are further divided into leptons and quarks as shown in FIGURE . Another classification of fermions is into generations. The first generation consstitutes u, d, e^- and ν_e which give rise to matter around us. The second and third generation particles are high energy *siblings* of the first generation particles. These are observed at high energies such as colliders. The SM also considers anti-particles which are clones of particles with opposite quantum numbers.

Add figure

These fermions interact with each other via exchanging bosons which are also called *force-carrier* particles. The massless neutral photon (γ) is the messenger of the electromagnetic (EM) force which is experienced by charged particles. The underlying QFT is called Quantum Electrodynamics (QED). The electrostatic attraction between charged particles is the low-energy manifestation of QED. Among the SM, all fermions except neutrinos are sensitive to the EM force. The underlying symmetry is the U(1) symmetry.

The strong interaction, mediated by massless gluons, is experienced by particles carrying the so-called colour charge. The physics behind the strong interaction is explained in Quantum Chromodynamics (QCD). Only the quarks can interact via the strong interaction. A peculiar thing in QCD is that the gluons themselves also carry colour charge.

The weak force carriers are $W^{\pm}$ and Z, which unlike γ and gluons, are massive and charged in case of $W^{\pm}$. The weak interaction manifests itself in phenomena such as, β-decay and fusion processes inside the sun. All the SM particles, including the neutrinoes, can feel the weak force. Before discussing the elecroweak unification, let's dive into the weak interaction. The interaction mediated by $W^{\pm}$ and Z is called charged-current weak interaction and neutral-current weak interaction, respectively. The famous Wu experiment proved that the charged current weak interaction violates parity. The parity violating nature of the weak interaction suggests that the interaction vertex must be different from that of QED and QCD. The weak interaction is described using a $V - A$ vertex and this fact imples that only left-handed chiral particle states and right-handed chiral antiparticle states can participate in charged-current weak interaction.

The last piece of the SM puzzle is the Higgs boson which is a spin-0 boson. All the particles gain their mass by Higgs mechanism.

1.0.1 Feynman diagrams

Interactions between the SM particles can give rise to various processes. In order to visualise it, a tool called Feynman diagrams is widely used. These diagrams are pictorial representations of the interactions which makes use of straight lines with arrows to show particles and anti-particles. Moreover, curly lines are used to show the boson exchanged between them. The Feynman diagrams are symbolic and have no physical meaning.

Add and explain an example feynman diagram

1.1 The Strong Force

Electrons and nucleus inside an atom are held together by the electromagnetic force. The same force also exists between protons inside the nucleus causing repulsion. However, there exists a force which is strong enough to overcome repulsion and keep the nucleus together. It is called the strong force or the strong nuclear force. The QFT describing the strong force is called Quantum Chromodynamics (QCD) and the underlying symmetry group is SU(3) described by 3×3 matrices. The eight generators of the SU(3) group give rise to eight gluons which are the strong force mediators. The structure of the SU(3) group demands that the wave function of the strongely interacting particle must be a 3-component vector. This gives rise to a new degree of freedom called "colour", with three states called red,blue and green. Consequently, particles having a non-zero colour charge can feel the strong force. Among the SM particles, only quarks have the colour charge which can be either red, blue or green.

A major differentiating factor between QCD and QED is that the gauge boson in QCD carries the charge of interaction. In other words, gluons also carry the colour charge which allows them to interact with other gluons as well. As a result of this self-interaction, no coloured object can be found as a free particle in nature. Due to this so-called colour confinement, quarks cannot exist independently but instead are found in colour-neutral states called *hadrons*. For instance, if two quarks are pulled away from each other, a gluon field is created between them which is proportional to the separation. The gluon fields is so strong that at some point, the energy in this field is sufficient to produce new quarks and antiquarks that form colourless bound states. This process is called hadronisation. Due to colour confinement, only certain configurations for hadrons are permitted. The possible combinations discovered so far can be categorised into mesons ($q\,\overline{q}$), baryons ($q\,q\,q$) and antibaryons ($\overline{q}\,\overline{q}\,\overline{q}$).

1.2 The Electroweak theory

In the 1960s, physicists were trying to formulate a gauge theory for weak interactions similar to QED. A theory can be a gauge theory if it has an underlying mathematical symmetry and it is renormalisable[1]. Glashow, Salam and Weinberg discovered such a gauge theory by unifying electromagnetic force and the weak force.

The electroweak (EW) theory is a unification of QED and the thoery of weak interactions. It is described by the symmetry group $SU(2)_L \otimes U(1)_Y$. The corresponding charges of the electroweak

[1] A quantum field theory is renormalisable if...

theory are the weak isospin I, I_3 and the weak hypercharge Y. The weak hypercharge Y determines the interaction under the $U(1)$ transformations. The weak isospin of particles determines their transformation under $SU(2)$ and therefore, it is used to make multiplets of particles. The left-handed leptons (ℓ_L) will form doublets as shown in EQUATION because they transform into each other under the influence of weak force. This is due to to the $V - A$ vertex form of the weak interaction. On the other hand, the right-handed particles are singlets(ℓ_R). fix the format and label reference

$$
\begin{aligned}
\ell_R &= e^-{}_R, \mu^-{}_R, \tau_R \\
\ell_L &= \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L
\end{aligned}
$$

The Lagrangian of the EW model introduces three bosons $W_\mu^{(1,2,3)}$ corresponding to $SU(2)$ and one B_μ corresponding to $U(1)$. Th experimentally observed $W^\pm$ are combination of $W_\mu^{(1)}$ and $W_\mu^{(2)}$ whereas photon (A) and the Z-boson are linear combinations of $W_\mu^{(3)}$ and B_μ based on the weak mixing angle (θ_W) as given below:

$$
\begin{aligned}
A_\mu &= +B_\mu \cos\theta_W + W_\mu^{(3)} \sin\theta_W \\
Z_\mu &= -B_\mu \sin\theta_W + W_\mu^{(3)} \cos\theta_W
\end{aligned}
$$

The weak interaction for the quark sector can be explained by creating similar $SU(2)$ doublets(Q).

$$
Q = \begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \begin{pmatrix} t \\ b' \end{pmatrix}
$$

The strength of the weak interactions for quarks is determined experimentally by studying nuclear β-decay. It is observed that the vertices corresponding to different quark flavours have different coupling strengths. The reason for this is given by the Cabibo hypothesis which states that, the flavour eigen states that participate in the weak interactions are a mixture of the mass eigen states. The relation between them is given by the Cabibo-Kobayashi-Maskawa (CKM) matrix.

$$
\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}
$$

The values of the CKM matrix elements can be found in [1]. The diagonal of the matrix is close to unity, suggesting that the weak interaction is stronger within the same generation of quarks.

The experiments at the Gargamelle bubble chamber in 1973 hinted the evidence of a neutral massive boson responsible for the observed neutrino interactions [2]. In 1983, the Z-boson was directly discovered at the Super-Proton Synchrotron at CERN. The electroweak theory was verified by this pathbreaking discovery. The properties of the Z-boson were studied at the Large Electron-Positron

(LEP) collider at CERN. The discovery of Z and W bosons are among the crucial tests of the Standard Model.

1.3 The Higgs mechanism

1.4 Physics at the hadron colliders

Pileup

At the LHC 2808 bunches of protons are injected which are 25 ns apart. This results into 1.2×10^{11} protons per bunch giving rise to different particle interactions. The primary hard scatter collisions, that are of interest, are contaminated by soft interactions called pileup. It is defined by the average number of interactions recorded per bunch crossing. Sources of pileup are categorized into in-time and out-of-time pileup. In-time pile up is due to collisions occurring in the same bunch-crossing and out-of-time pile-up is contributed by the collisions from previous or later bunches. Some of the sub-detectors have sensitivity windows longer than the interval between bunch crossings. This eventually affects the recorded number of interactions per bunch. The accurate detection of objects under study becomes difficult due to pile-up events. The higher the luminosity, more the pileup. The object reconstruction algorithms have dedicated procedures to mitigate pileup.

Luminosity and cross-section (σ)

The quantity that measures the ability of a collider to produce particle interactions is called instantaneous luminosity ($\mathcal{L}$). The instantaneous luminosity integrated over the lifetime of collider operation is called integrated luminosity (L).

In order to define the event rate for interesting processes, along with luminosity, we require another quantity called the cross-section. At the subatomic scale, the particle interactions are governed by laws of quantum physics. Therefore, a theory can predict the *probablility* of certain outcomes of collisions. The probablity that a certain process will take place is called its cross-section (σ). Finally, the number of event rate of specific interactions is defined as the product of integrated luminosity and the cross-section (Eq. (1.1)).

$$R = \sigma \cdot \int_{dt} \mathcal{L}(t) \tag{1.1}$$

For a particle collider, beam energies and the luminosity are two important figures of merit. High energy allows the production of new heavy particles and high luminosity allows more flux of particles contributing to high number of collisions.

At the LHC, the incoming protons see each other as a bunch of partons instead of a single proton. The proton is composed of two u- and one d- quark called valence quarks. At high energies, these quarks can exchange gluons and in turn produce more gluons and quarks. In a way, the proton looks like a *sea* of gluons and quarks that altogether are called partons. Here the net flavour of a proton is the same as that of valence quarks. These partons interact at collision points and give rise to different SM processes.

The outcomes of these collisions hold interesting physics and it is studied with the help of particle detectors. The LHC houses four main detectors at the four collision points. The two general purpose detectors are ATLAS (**A** **T**oroidal **L**HC **A**pparatu**S**)[3] and CMS (**C**ompact **M**uon **S**olenoid)[4]. The

LHCb experiment[5] is dedicated to studies based on B-hadron and its decays whereas ALICE(**A** **L**arge **I**on **C**ollider **E**xperiment)[6] analyses the Pb-Pb collisions at the LHC. This analysis uses data from the ATLAS detector which is described in the next section.

Lepton universality..because tZq trilepton, decay into muons and electrons equal probability

branching ratio

CHAPTER 2

The tZq production

High energy proton-proton collisions at the LHC enable multiple processes to take place. The process of interest for this analysis is the electroweak production of the t-quark and the Z-boson. The LO t-channel Feynman diagrams are shown in Fig. 2.1 where a Z-boson can be radiated from any one of the incoming or outgoing quarks (Fig. 2.1(a)) or from the exchanged W-boson (Fig. 2.1(b)). In addition to these resonant contributions, there is also a small non-resonant contribution in the form of $tl^{+}l^{-}q$ (Fig. 2.1(c)) which is also accounted for. In this analysis, this process is referred to as the tZq production.

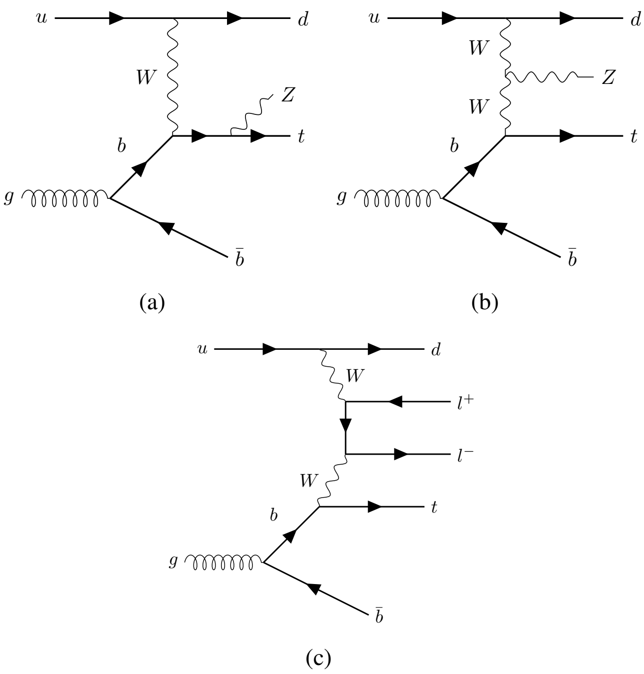


Figure 2.1: Feynman diagrams at LO for the tZq-production. The Z is radiated either from one of the quarks or from the exchanged W boson.

The tZq production is an interesting process to study because it probes the coupling of two fermions

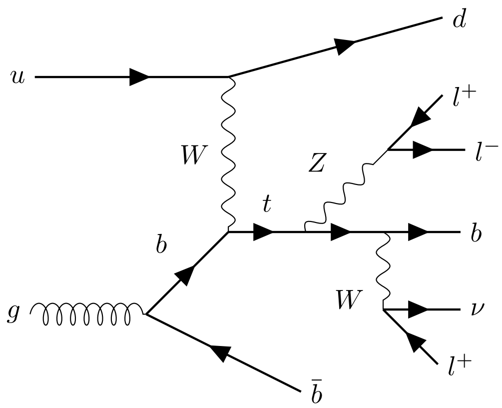


Figure 2.2: The *tZq* trilepton final state

and the coupling of a fermion to a boson in the same interaction. Moreover, it can provide a solid basis to study similar processes such as the tHq process.

In order to study this process, one has to note that the particles involved in this production are quite heavy and therefore, the only way to spot them is from their reconstructed decay products. Conventionally, the possible final states are divided into several *channels* based on certain combinations of leptons and jets. This analysis focuses on the so-called trilepton channel.

2.1 The tZq Trilepton Channel

As the name suggests, the trilepton decay channel of the *tZq* production contains final states with three charged leptons, as shown in Fig. 2.2. The *t*-quark decays almost exclusively into *b W* and the corresponding *W* decays into a charged lepton and a neutrino. The *Z*-boson decays into opposite sign same flavour leptons. The probability for *Z* decaying into leptons is equal across the three lepton families (e^-,μ,τ) due to lepton universality. This analysis accounts for *Z* decays resulting into e^-, μ and leptonically decaying τ[1].

Although the trilepton final state has a small branching ratio, it has a very clean signature due to the three lepton requirement. In addition, three lepton final state is quite difficult to mimic by backgrounds. This is the reason to choose this final state for studying *tZq* process. For this analysis, the trilepton final state is referred to as the signal.

The next task is to reconstruct this final state from the detector data or in other words, find possible occurrences of this final state within the collision events. In order to achieve that, certain requirements are defined in favour of the signal events. The collection of these requirements is called event selection. For this analysis, the primary event selection is discussed below and summarised in Table 2.1.

- **Leptons**
  - Exactly three leptons (e^- or μ), τ is considered if it decays into leptons. These leptons are sorted by their p_{T} which is required to be at least 27,15 and 10 GeV, respectively.

[1] τ is a heavy particle and hence, can be observed only via its decays

  - At least 1 Opposite Sign Same Flavour (OSSF) lepton pair with a minimum difference between its invariant mass (m_{ll}) and m_Z. This is to identify which out of the selected leptons originate from Z.
  - A cut on minimum accepted invariant mass, in order to suppress backgrounds not containing a Z.
  - A cut on the transverse mass of the W-boson is applied to account for the missing transverse energy.
- **Jets**
  - Number of jets are required to be between 2 and 5, with p_{T} more than 25 GeV and $|\eta|$ more than 4.5.
  - Number of b-jets are required to be 1 or 2, reconstructed at 85% working point with $|\eta|$ more than 2.5. Events with 2 jets, both b-tagged are not considered.

Table 2.1: Event selection

Variable	Preselection
N_ℓ $(\ell = e, \mu)$	$= 3$
	$\geq$ 1 OSSF lepton pair
$p_{\mathrm{T}}\,(\ell_1, \ell_2, \ell_3)$	$>$ 27, 15, 10 GeV
$\min(m_{\ell\ell})$	$>$ 20 GeV
$\lvert m_{\ell\ell} - m_Z\rvert$	$<$ 10 GeV
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	$>$ 30 GeV
$N_{\mathrm{jets}}\,(p_{\mathrm{T}} > 25\ \mathrm{GeV})$	2-5
$N_{b-\mathrm{jets}}$@85%	1-2 (no $2j2b$)

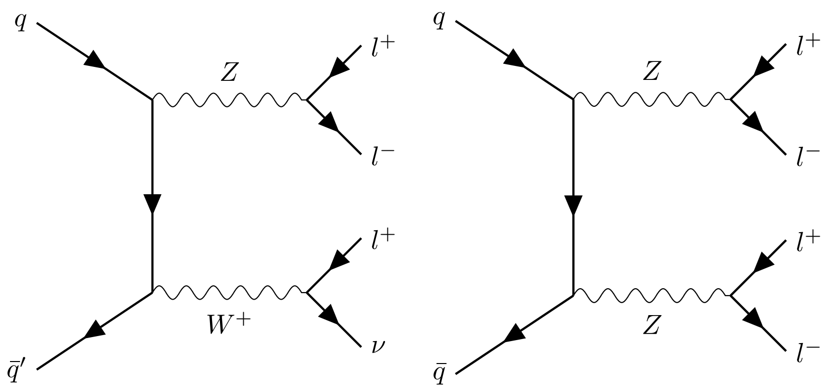
It is important to note here that these requirements are chosen to maximise the probability of selecting signal events but in reality there are background processes that mimic the tZq signature and therefore, contaminate the selected signal events.

2.2 Background processes

The background processes for tZq process can be classified according to the number of prompt (or real) leptons in the final state. A lepton is labelled prompt if it originates from either a τ or a massive boson. On the other hand, non-prompt or fake leptons are objects misidentified as leptons. The source of non-prompt leptons can be meson decays, photon conversions or light jets creating lepton-like signatures. Backgrounds involving only prompt leptons are diboson, $t\bar{t}$+X, $t\bar{t}H$ and tWZ while backgrounds involving non-prompt leptons are $t\bar{t}$, Z +jets and tW.

Backgrounds involving prompt leptons

In the diboson process, two massive bosons are produced which can be ZZ, WW or WZ, as shown in Fig. 2.3. As per Fig. 2.3(a), the leptonic decay of bosons result into three prompt leptons which can pass the signal event selection if additional jets are also found. For the ZZ scenario, as shown in Fig. 2.3(b), one of the leptons needs to fail the requirement for a prompt lepton or is not reconstructed. Due to this strong resemblance of the diboson signature with the signal, it is the dominant background in the tZq production.



(a) (b)

Figure 2.3: Feynman diagrams for the diboson background

The t-quark pair production in association with a heavy boson (Z or W) can be an important source of background. In particular, the $t\bar{t}Z$ process, where the final state already includes a Z boson and a t quark, can produce a very similar signal-like signature. It is shown in Fig. 2.4. The $t\bar{t}H$ contributes less because of its small cross-section.

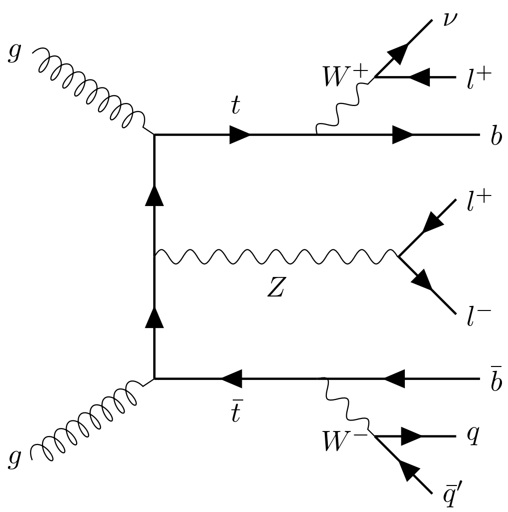


Figure 2.4: Feynman diagrams for the $t\bar{t}Z$ background

Backgrounds involving non-prompt leptons

Backgrounds involving non-prompt or fake lepton are t-quark pair production and the production Z-boson with jets. As shown in Fig. 2.5(b), there are already two leptons from the Z-boson. If the jets are light, they can be misidentified as leptons leading to a non-prompt lepton contribution. In the $t\bar{t}$ production, as shown in Fig. 2.5(b), if one of the b-jet decays into a lepton, then it can satisfy the signal event selection.

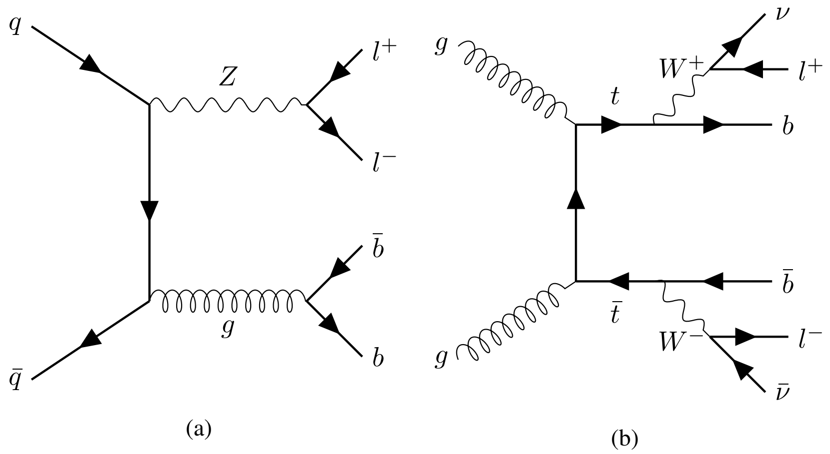


Figure 2.5: Feynman diagrams for non-prompt lepton background

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