Measurement of tZq differential cross-section

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Nilima Akolkar
aus
Vadodara, India

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1. Gutachter:	Prof. Dr. John Smith
2. Gutachterin:	Prof. Dr. Anne Jones

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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).

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

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:

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

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

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