Master Advanced Lab Course
Universität Göttingen – Fakultät für Physik

Report on the experiment KT.WZE

Measuring Properties of W and Z Bosons with D0 Data

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1 Introduction

In this experiment W and Z bosons are reconstructed from real data originating at the Tevatron collider at Fermilab near Chicago. This is done using the muon decay channels where the Z boson decays to a pair of muons and the W boson decays to a muon and a muon neutrino. Monte Carlo simulation is utilised to develop selection criteria that separate the events from a background consisting mainly of dijet events and cosmic interference.
The masses of the bosons are then determined by the resonances in the invariant mass spectra of the decay products and after accounting for the trigger and reconstruction efficiencies, the branching ratio of the W boson, BR($W \to \mu\nu$), is calculated from the ratio of the two production cross sections.

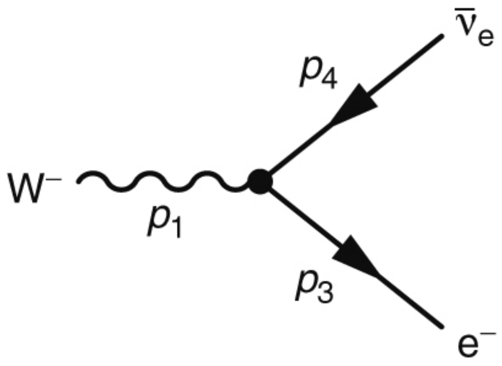

Figure 1: The Feynmann diagram for the decay $W^- \to e^- \bar{\nu}_e$.

2 Theory

2.1 The W boson

As in Quantum Electrodynamics and Quantum Chromodynamics, the weak nuclear force is mediated by a spin-1 particle. Unlike the photon and the gluon, however, the W boson is massive and couples to pairs of fermions differing by one unit of charge. It is also the only interaction found to violate parity, as can be seen in the vector-axial-vector form of the vertex factor:

$$-i\frac{g_W}{\sqrt{2}}\frac{1}{2}\gamma^\mu(1-\gamma^5), \tag{2.1}$$

with g_W the weak coupling constant.
Using the Feynman rules the decay of a W boson to any charged lepton and its associated lepton, for example the electron and electron neutrino depicted in Figure 2.1, the matrix element, $\mathcal{M}$, can be written as

$$\mathcal{M} = \frac{g_W}{\sqrt{2}}\epsilon^\lambda_\mu(p_1)\bar{u}(p_3)\gamma^\mu\frac{1}{2}(1-\gamma^5)v(p4). \tag{2.2}$$

Here ϵ^λ_μ is the polarisation four-vector of the initial W^-, $\bar{u}$ is the adjoint particle spinor and v the anti-particle spinor. Neglecting the mass of the final state fermions and accounting for the three possible polarisation states of the W boson, the spin-averaged matrix element squared is

$$\langle|\mathcal{M}|^2\rangle = \frac{1}{3}g_W^2 m_W^2 \tag{2.3}$$

with m_W the mass of the boson.
This is then inserted into the expression for the decay rate of a a two body decay:

$$\Gamma = \frac{\mathrm{p}^*}{32\pi^2 m_W^2}\int\langle|\mathcal{M}|^2\rangle \mathrm{d}\Omega^* = \frac{\mathrm{p}^*}{8\pi m_W^2}\langle|\mathcal{M}|^2\rangle, \tag{2.4}$$

with p^* the momentum of one of the leptons in the centre-of-mass frame. Assuming $\mathrm{p}^* = m_W/2$, the decay rate for an electron and its neutrino is

$$\Gamma(W^- \to e^-\bar{\nu}_e) = \frac{g_W^2 m_W}{48\pi}. \tag{2.5}$$

According to lepton universality, this is the same for all three leptonic channels once the masses have been neglected. To calculate the total decay width, the hadronic decays must also be considered. These are modified by the elements of the CKM matrix and the three colours, for example $\Gamma(W^- \to d\bar{u}) = 3|V_{ud}|^2\Gamma_{e\nu}$. Six of the nine CKM elements are kinematically accessible and using the unitarity of the CKM matrix results in the following decay width:

$$\Gamma_W = (3+6\kappa_{QCD})\Gamma(W^- \to e^-\bar{\nu}_e) \approx 9.2 \times \frac{g_W^2 m_W}{48\pi} = 2.1\,\mathrm{GeV}. \tag{2.6}$$

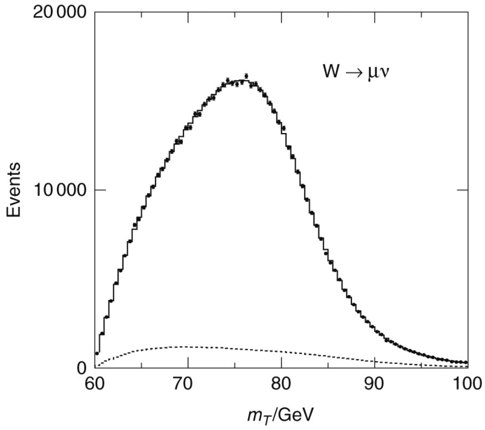

Figure 2: Distribution of the invariant mass, M_T, of the W boson, produced from $p\bar{p}$ collisions at the Tevatron.

The factor $\kappa_{QCD} \approx 1.038$ is a correction factor to account for second order QCD processes, $W \to q\bar{q}'$. This large width correspond to a lifetime of only $\mathcal{O}(10^{-25}\,\mathrm{s})$. The branching ratio to muon and neutrino specifically is then

$$BR(W^- \to \mu^- \bar{\nu}_\mu) = \frac{1}{3 + 6\kappa_{QCD}} = 10.8\%. \tag{2.7}$$

At proton-antiproton colliders such as the Tevatron, W bosons can be produced in the s-channel process $p\bar{p} \to WX$. Here X denotes the hadronic system resulting from the remnants of the protons. The cross section is higher than in lepton colliders, however, reconstruction of the invariant mass is complicated by the composite nature of the colliding hadrons. At both collider types, the neutrino must be reconstructed from the missing momentum. In the hadronic case, the momentum fractions of the annihilating quarks in the z-direction are unknown, and hence only the transverse momentum of the neutrino can be determined. The neutrino transverse momentum, $\mathbf{p}_T^\nu$ and hence the missing transverse energy, MET, can thus be determined from the transverse momentum of the muon, $\mathbf{p}_T^\mu$ and the transverse momentum of the hadronic system, $\mathbf{u}_T$:

$$MET \approx |\mathbf{p}_T^\nu| = |-\mathbf{p}_T^\mu - \mathbf{u}_T|. \tag{2.8}$$

The invariant mass cannot be determined. Instead the transverse mass, M_T, is constructed, defined as:

$$M_T = \sqrt{(MET + \mathbf{p}_T^\mu)^2 - (MET_x + \mathrm{p}_x^\mu)^2 - (MET_y + \mathrm{p}_y^\mu)^2}. \tag{2.9}$$

The distribution of this quantity does not peak at M_W. The approximate mass of the W boson can be estimated by the location of the drop-off, corresponding to the case where the longitudinal component of the invariant mass is close to 0. An example is shown in Figure 2.1.

2.2 The Z Boson

The two W bosons are comprised of the $W^{(1)}$ and $W^{(2)}$ fields of the SU(2)$_L$ local gauge symmetry. They couple only to left-handed particles and right-handed antiparticles. The remaining field, $W^{(3)}$ is not sufficient to describe the neutral Z boson, since it is also found to couple to right-handed particles. In electroweak unification the field corresponding to the Z boson, Z_μ and the photon, A_μ arise from linear combinations of $W^{(3)}$ and a U(1)$_Y$ gauge field, B_μ, coupling to a scalar quantity, Y, called hypercharge:

$$A_\mu = +B_\mu \cos\theta_W + W_\mu^{(3)} \sin\theta_W, \qquad Z_\mu = -B_\mu \sin\theta_W + W_\mu^{(3)} \cos\theta_W, \tag{2.10}$$

with $\theta - W$ the weak mixing angle. The extent to which the Z boson couples to left and right-handed fermions is then determined by the coupling factors

$$c_L = I_W^{(3)} - Q_f \sin^2\theta_W, \qquad c_R = -Q_f \sin^2\theta_W. \tag{2.11}$$

$I_W^{(3)}$ is the third component of weak isospin of the fermion, Q_f its electric charge and the aforementioned hypercharge is given by $Y = 2(Q_f - I_W^{(3)})$.

The Z boson interaction vertex is more commonly expressed in terms of the vector and axial-vector couplings, $c_V = (c_L + c_R) = I_W^{(3)} - 2Q\sin^2\theta_W$ and $c_A = (c_L - c_R) = I_W^{(3)}$ as

$$-i\frac{1}{2}g_Z\gamma^\mu[c_V - c_A\gamma^5], \qquad g_Z = \frac{g_W}{\cos\theta_W}. \tag{2.12}$$

From this the spin-averaged matrix element squared for the decay to any fermion pair is

$$\langle|\mathcal{M}|^2\rangle = \frac{1}{3}(c_V^2 + c_A^2)g_Z^2 m_Z^2 \tag{2.13}$$

and the corresponding partial decay width is

$$\Gamma(T \to f\bar{f}) = \frac{g_Z^2 m_Z}{48\pi}(c_V^2 + c_A^2). \tag{2.14}$$

For $Z \to \mu^+\mu^-$ with $c_V = -0.04$ and $c_A = -\frac{1}{2}$, $\Gamma(Z \to \mu^+\mu^-) = 83.7\,\mathrm{MeV}$. Calculating this decay width for all fermions, excluding the top quark which is too massive, one arrives at a width of

$$\Gamma_Z \approx 2.5\,\mathrm{GeV}. \tag{2.15}$$

The branching ratio to muons is consequently

$$BR(Z \to \mu^+\mu^-) = \frac{\Gamma(Z \to \mu^+\mu^-)}{\Gamma_Z} \approx 3.5\% \tag{2.16}$$

At proton-antiproton colliders the Z boson is predominantly produced in via the s-channel with the annihilation of two quarks. Accounting for the finite lifetime of the Z boson in the propagator, the cross section for $q\bar{q} \to Z \to \mu^+\mu^-$ is proportional to

$$\sigma \propto |\mathcal{M}|^2 \propto \left|\frac{1}{q^2 - m_Z^2 + im_Z\Gamma_Z}\right|^2 = \frac{1}{(q^2 - m_Z^2)^2 + m_Z^2\Gamma_Z^2}. \tag{2.17}$$

Plotting the number of events selected to contain a Z boson over the invariant mass, q, of the two muons one can obtain the mass, M_Z, and the decay width, Γ_Z, by fitting a Breit-Wigner curve.