Measure of the Z boson mass

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In this experiment, the mass and decay width of the Z boson has been determined by the detecting of its decay products. The case studied of its possible decays is the pair muon-antimuon. After detecting these muons and filtering them to meet some quality criteria, the values obtained for the mass and the decay width of the Z boson are $m_Z = (90.86 \pm 0.23)$ GeV/c^2 and $\Gamma = (2.679 \pm 0.181)$ GeV/c^2.

I. Introduction and Theoretical Framework

The Z boson is one of the elementary particles that mediate the weak interaction. The Z boson has no charge, it is electrically neutral, it has a spin of 1, and it is its own antiparticle. It is also responsible for the interaction between neutrinos. In fact, it mediates the transfer of energy, momentum and spin when they scatter elastically.

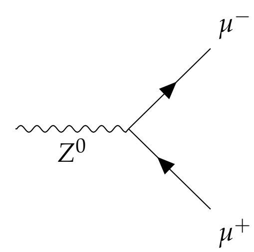
The Z boson is a very massive particle. For this reason, its lifetime is very short. As the Z boson is electrically neutral, the sum of the charges of the decay products must be 0. Because of this, when the Z boson decays, it always decays in a particle and its antiparticle.

There are just 3 possibilities of decay for the Z boson. The first one, is that it decays into a charged lepton and antilepton pair, which can either be an electron and a positron, a tau and an antitau or a muon and an antimuon. These kind of decays happen about 10% of the times.

The second decay possibility is a neutrino-antineutrino pair, which happens in 20% of the times. Finally, the remaining 70% of the decays are a quark and an antiquark.

However, the detectors are not able to detect these two last types of decays. In the case of the neutrinos, they do not interact with almost anything, as they are electrically neutral. The only way to "see" them is if some energy or transverse momentum is found missing after the collision. As for the pair quark-antiquark, they appear as particle showers in the detector, also known as jets.

In this experiment, the decay that will be detected is the muon-antimuon pair, which is shown in the following Feynman diagram.



The decay rate Γ of a particle is the probability per unit time that this particle decays. With this decay rate, the evolution of the number of particles with time can be found with

$$dN = -\Gamma N dt \Rightarrow N(t) = N_0 e^{-\Gamma t}$$

where N_0 is the number of particles at $t = 0$. The lifetime of this particle is just $\tau = 1/\Gamma$.

However, if the particle has several decay modes, just as it happens with the Z boson, the total lifetime is determined with the sum of all the decay rates $\tau = 1/\Gamma_{tot}$, where $\Gamma_{tot} = \sum_i \Gamma_i$.

Due to the uncertainty principle $\Delta m \Delta t \approx \hbar$, the unstable particles do not have a fixed mass. By using a Breit-Wigner function, which is

$$N(m) = N_{max} \frac{(\Gamma/2)^2}{(m - M_0)^2 + (\Gamma/2)^2}$$

the mass and the decay rate of the particle can be obtained.

The invariant mass is a characteristic of the total energy and momentum of an object or a system of objects. It is called invariant because it is independent of the frame of reference in which it is measured. For a particle that decays in two daughter particles, the invariant mass is

$$M^2 = m_1^2 + m_2^2 + 2(E_1 E_2 - p_1 p_2 \cos\theta)$$

being p_i the momentum of the daughter particles, m_i their mass and E_i their energy.

II. State of the art

The discovery of the Z boson played a very important role in the confirmation of the electroweak theory. The model developed in the 70's was consistent with the observed charged current interactions, but the predicted neutral current interactions had never been observed.

But in 1973, the first neutral current interaction was observed. With this observation, the discovery of the $W^{\pm}$ and Z^0 bosons was very urgent, in order to directly test the electroweak theory.

Finally, in 1983, the Z boson was experimentally discovered, almost at the same time as the $W^{\pm}$ bosons. The detectors in which these bosons were detected were built and operated by collaborations of physicists and engineers, which were the largest in the history of physics at the time.

This discovery was a great triumph for experimental physics, but even more for the theoretical part. The masses and widths of these particles, as well as their cross-sections, were in almost perfect agreement with the predictions of the electroweak theory.

III. Experimental Methods

As explained before, the only way to detect the Z boson is by studying the decay products of its decay. For this reason, what is going to be measured are the final decay products.

For all the events that are produced, a selection is needed in order to use just the physic process that want to be studied. In this experiment, the decay products studied are pairs muon-antimuon, so only pairs of muons compatible with a Z boson are going to be selected.

The particle detectors in which they were detected are composed by various layers. The first layer, the closest to the collisions, is the tracking chamber. They are the responsible for the momentum measurements. They also measure the interaction and secondary vertex from decay particles.

The electromagnetic calorimeters can be found in the second layer. They measure the energy from light electromagnetic particles based on electromagnetic showers such as the bremsstrahlung or pair production. After this layer, there is the hadron calorimeter, which measures the energy of hadrons (particles made of quarks and gluons). In addition to this, it provides indirect measurement of the presence of non-interacting, uncharged particles such as neutrinos.

Finally, the furthest layer from the collisions is the muon chambers. As the muons are very energetic particles and can penetrate several meters of iron without interacting, this chamber is the last one in the detectors, so they are the only particles likely to detect a signal.

By tracking the position of the hits of the particle among the muon detector, as well as with tracker measures, the particle's path can be precisely traced. As particles with less momentum bend more in a magnetic field, this gives a measurement of the momentum of the particle.

As explained before, it is a key aspect to select the events that are going to be used to determine the Z boson's mass. In the first place, the final decay products must be pairs muon-antimuon.

However, not every pair will be valid for the experiment. Some filters are applied, in order to remove muons that may come from other places or possible particles detected that are not muons. Also, some of the filters are just a quality criteria for the muons.

One of the most important filters is the one applied to the pseudorapidity. The pseudorapidity (η) is a quantity that is Lorentz invariant in the transverse plane, and it describes the angle of a particle relative to its beam axis. In this case, it is selected to be less than 2.4 to prevent the border effect. Another filter applied is that the transverse momentum must be higher than 5 GeV/c, as muons with those momentums are well detected by the detector.

But not only the filters are applied to determined quantities. For instance, the filter called global checks for hits that are linked in the tracker and the muon chamber. This filter just double checks that the particle is a muon. Another key filter is the one called relative isolation, which requires the muon to be relatively isolated.

After every requirement, a cut to the number of muons is applied. Finally, with those quality muons' momentum and energy completely determined, by plotting the number of muons against the invariant mass of the system, some candidates for the invariant mass of the Z boson can be obtained.

IV. Results

`efficiency.png`

Figure 1: Number of muons left after each filter.

In this figure, the number of muons left after each filter is applied is shown. From the information in it, the total efficiency of the quality criteria can be calculated, knowing that the initial detected muons were 781606 and the ones that passed all the filters were 77745. From this data, the total efficiency for the filters is 9.9%.

In the following figure, the invariant mass of the muons is shown for all the muons detected and the ones selected after passing the filters from Figure 1.

`invariantmass.png`

Figure 2: Number of muons against their invariant mass for all the muons detected and the ones that fulfilled the requirements.

This figure is already providing some information about the invariant mass of the Z boson, as it can already be seen that there is a peak at around 90 GeV. This peak can be seen with all the muons, but it is very clear with the selected muons. This makes it a really good candidate to be the Z boson.

Finally, a fit is made to the peak seen in Figure 2. For this fit, it would make sense to fit the curve to a Breit-Wigner distribution. However, if the detector resolution is relatively poor, then a gaussian fit is a good enough fit, as the gaussian detector resolution will overwhelm its Breit-Wigner shape.

On the other hand, if the detector resolution is good enough, then the curve can be fit to a Breit-Wigner convoluted with a gaussian, which would describe both the shape of the peak and the detector effects.

In this case, the fit was made to a gaussian distribution, and it is shown in the following figure.

fit.png

Figure 3: Fit of the curve to a gaussian distribution.

For this fit, the obtained mass for the Z boson is $m_Z = (90.86 \pm 0.23)$ GeV/c^2, and for its decay width is $\Gamma = (2.679 \pm 0.181)$ GeV/c^2.

V. Conclusion

The accepted value of the mass of the Z boson is (91.1876 ± 0.0021) GeV/c^2. The obtained value in this experiment differs in just a 0.36% from this accepted value. However, the accepted value of the mass is not inside the error interval of the obtained value.

As for the decay width, its accepted value for the Z boson is (2.4952 ± 0.0023) GeV/c^2. The value which was obtained by fitting the peak of invariant mass differs from the accepted value in a 7%. As it happens with the mass of the Z boson, the accepted value is not inside the error interval of the obtained value.

These small differences, as well as that the obtained values do not contain the accepted values in the error interval, could be due to the fitting of the curve. For instance, the fitting might not be the most adequate for the curve, as it may have some background noise and another function may need to be included to take care of this.

Another explanation for these differences may be the quality of the muons. In spite of having passed through some filters, the filters may not have been rough enough for the selection of the muons.

Bibliography

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