Big Data: ATLAS
Finding the invariant mass of Z^o by summation of its decay products.

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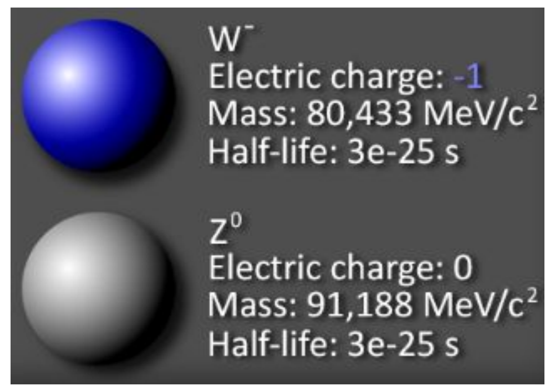
Summary

Quoted by CERN themselves, "The discovery of the W and Z-bosons was an extraordinary triumph" because it helped them to confirm another critical aspect of the standard model of particle physics.



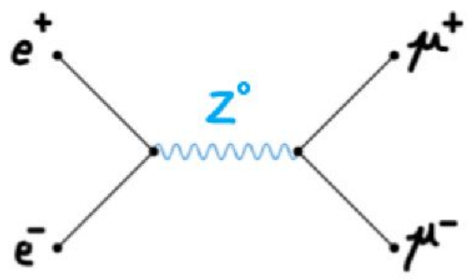
Using the particle accelerator at CERN, scientists were able to locate W-bosons which are bipolar in nature.

However the discovery of Z-bosons were significant because not only did they have the same half life as the W-bosons, but they did not have a charge at all.

Thus, W-bosons ($W^{\pm}$) and Z-bosons (Z°) are referred to as cousins.

Similarly discovered by physicists at CERN in 1983 was the Z-boson

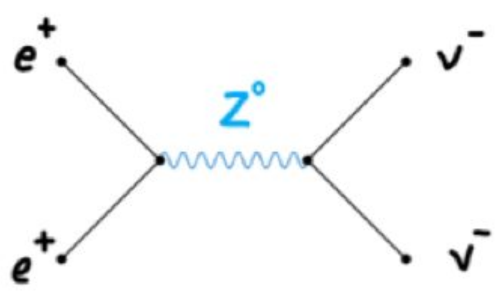
The Z° has a neutral charge and has a weak force. Z°'s weak nuclear force is almost the same as it's electromagnetic force. However it only appears weak because of its large mass which limits the range to $\approx 10^{-18}$[m]



The image on the left shows the creation of a Z° prior to the annihilation of 2 oppositely charged particles.

Since Z°'s are neutral in nature, the product of their decay must also be neutral

Which is why the muon and antimuon are formed as a result of the annihilation.

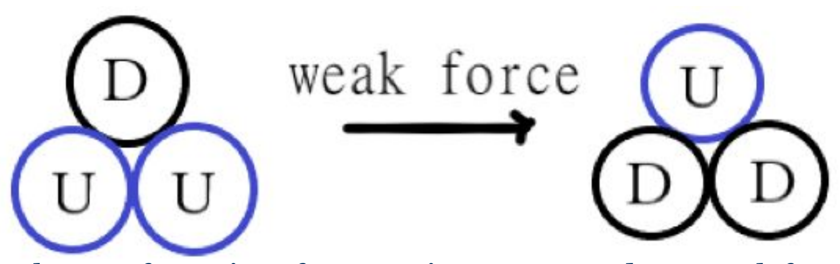


Here is another example of the neutral charge of the Z°. If we consider the sum of charges before the annihilation to be (-2). Then the total charge of the decayed particles must be (2). This way the sum of charges before and after the annihilation is = 0

In other words:
"Total charge before annihilation = Total charge after annihilation"

The Feynman diagram shown in Figure 1 shows the annihilation between a positron and an electron resulting in a formation of Z° which then later decays into a muon-neutrino and muon-antineutrino pair.

Figure 2 :



The transformation of a proton into a neutron due to weak-force

Z° radioactive decay

Z° has a neutral charge, so the sum of charges after it fully decays must also be equal to zero. This is why when the Z° decays, it always splits into a particle-antiparticle pair. Some examples are mentioned in the background information section.

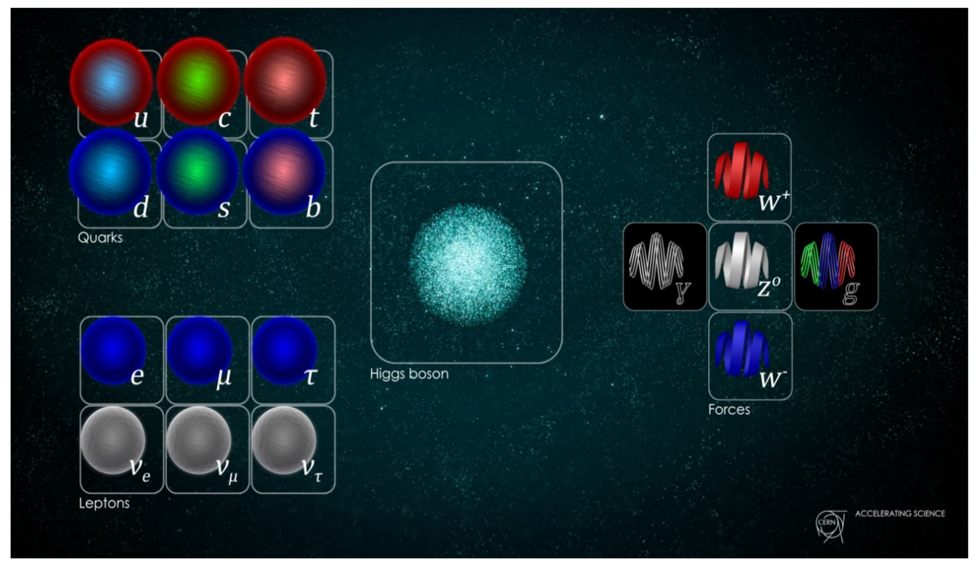


Figure 3: The standard model of particle physics

Research aims

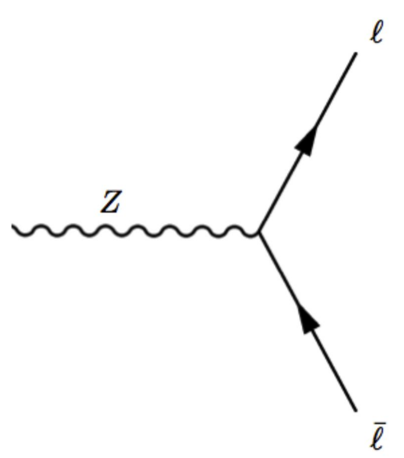
The aim of this project is to find the invariant mass of the Z^o boson, by observing its two primary decay routes, and using data collected by the ATLAS detector to reconstruct the Z^o boson and calculate its invariant mass.

Background information

The neutral Z-boson along with the electrically charged W^+ and W^- bosons are all mediators of the weak force - one of the four fundamental forces that governs all matter in the universe. Unlike the concrete roles of the W bosons - responsible for radioactivity, transforming protons into neutrons and vice versa, the Z-boson has a somewhat elusive role.

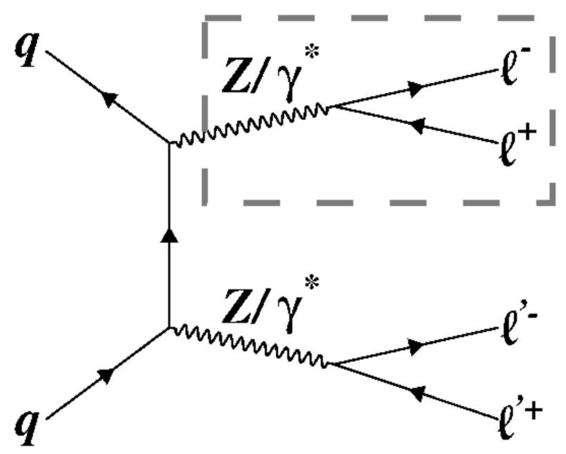
The Z-boson allows for neutrinos to interact; since neutrinos don't have an electric charge, they cannot self-interact via a photon, through which electromagnetic interactions proceed.

The Z^o boson has two primary decay routes (depicted by the Feynman Diagrams below) , but each share a common trait - lepton pairs. The Z^o boson can decay into either two leptons or four leptons, with a lepton being an elementary particle of half-integer spin that does not undergo strong interactions.



Two Leptons

Z^o boson decaying into two leptons, one with a positive charge, and one a negative charge, denoted by ℓ and ℓ^- respectively.



Four Leptons

Quarks colliding to become 2 Z^o bosons which then decay into four leptons (2 positively charged and 2 negatively charged).

Background information (continued)

Calculating the invariant mass of the Z^o boson can be done by observing the energy and momentum of its decay products, since both must be conserved, which can be written as the following: $\vec{p}^{\,tot}_{before} = \vec{p}^{\,tot}_{after}$, and $E^{tot}_{before} = E^{tot}_{after}$.

This can be written in the form of a *Lorentz Vector* of 4 components which neatly packages together energy and momentum with μ being an arbitrary index.

$$P^{\mu} = (E/c, \vec{p}) = (E/c, p_x, p_y, p_z)$$

$$P^{\nu}_{e^+} + P^{\nu}_{e^-} = (E_{e^+} + E_{e^-}, \vec{p}_{e^+} + \vec{p}_{e^-}) = P^{\nu}_{tot}$$

The formula for calculating the invariant mass can be derived from Physics' most famous equation, E=mc². However, this is only true for objects that are stationary. If an object is not stationary, such as our decay products, we must use the following equation, with *m* being the invariant mass:

$$E^2 = m^2c^4 + p^2c^2. \qquad m = \frac{1}{c^2}\sqrt{E^2 - p^2c^2}$$

Which can then be simply rearranged for *m* - which is shown above on the right.

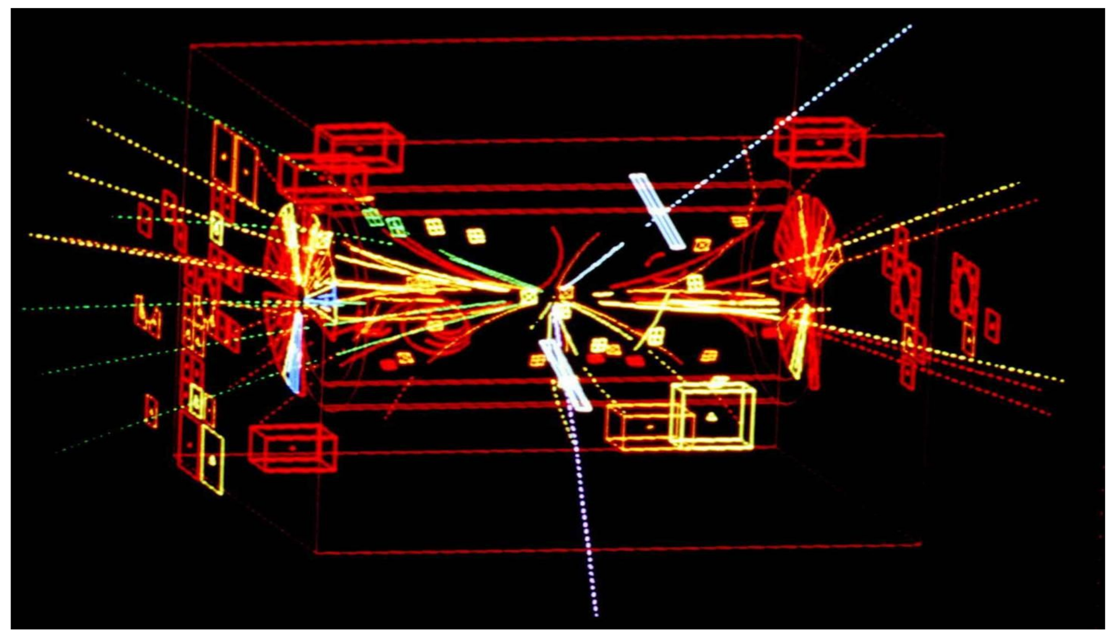


Figure 4: Annihilation collision experiment at CERN that birthed the Z-boson

Experimental Method

Due to the short-lived nature of the Z-boson (appearing for just 3×10^{-25} seconds before decaying), directly observing the invariant mass is infeasible, therefore, we must calculate the invariant mass by inferring its properties from its 2 main decay routes: 2 leptons (single pair), or 4 leptons (two pairs).

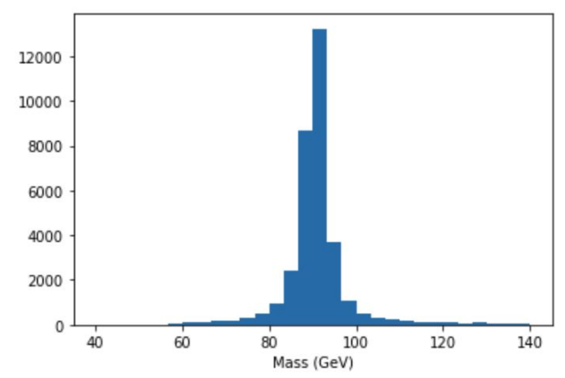
Using data collected from the ATLAS detector, we can reconstruct the Z^o boson, however, the ATLAS collects data from many other particles and decays. Therefore, in order to analyze the data we want, we must make the appropriate 'cuts'.

For both the single pair and two pair, we loop through the events performing cuts, ensuring we only process lepton pairs that have opposite charges and are of the same 'flavour'. Once our cuts have been made, we can reconstruct the Z^o and plot the information on a histogram.

Results

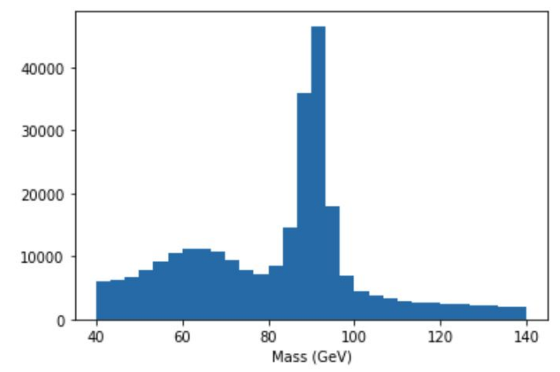
In this analysis, two histograms were plotted to examine the invariant mass of decay products from a particle, presumed to be the Z boson. One histogram represented events where the particle decayed into two leptons, and the other represented events where the particle decayed into four leptons. Both histograms displayed a prominent peak at 90 GeV. This consistent peak in both histograms indicates that the invariant mass of the decaying particle is 90 GeV. The agreement between the two different decay modes further reinforces the accuracy of this measurement, confirming that the invariant mass of the Z boson is indeed 90 GeV.

This measurement matches the result obtained by experiments conducted by CERN in the late 1980s and 1990s that confirmed the invariant mass of the Z^o boson to be approximately 91.19 GeV.



Two Leptons

Histogram showing mass distribution of two lepton decays.



Four Leptons

Histogram showing mass distribution of four lepton decays.

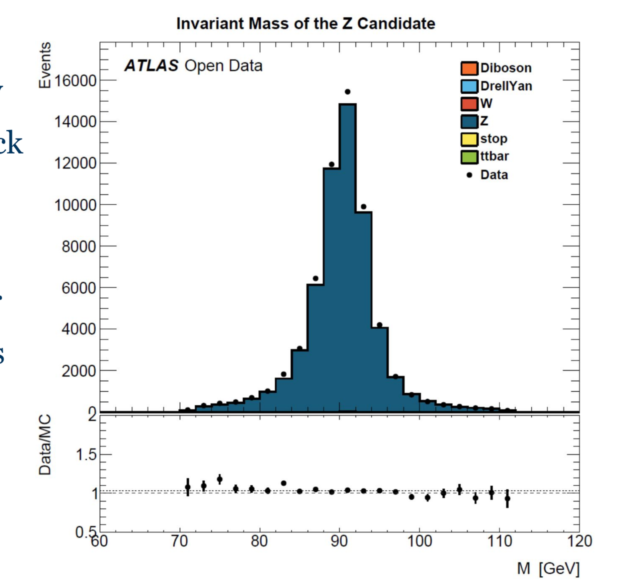
Conclusion & real world comparison

In real experimental physics, determining the properties of particles like the Z boson involves more than just theoretical decays and diagrams. Instead, experiments are conducted using particle detectors, and the data obtained from these experiments is analyzed using complex code.

However, in the experiment we conducted, the data analyzed was not real but simulated. This simulation was based on the Standard Model, specifically for Z boson decays into leptons ($Z^o \to \ell^+\ell^-$ and $Z^oZ^o \to \ell^+\ell^-\ell^+\ell^-$) as would be observed in the ATLAS detector at the LHC.

In actual experiments, scientists write analysis code and run it on both simulated data (based on theoretical models) and real data collected by detectors. By comparing the results from the simulation and the real data, scientists can determine how accurately their theoretical models reflect reality.

An example of this comparison shows that the simulated data (represented by bars) and real data (represented by black dots) match closely, indicating that the model is accurate. While the histogram might contain contributions from other processes, the large number of Z decays dominates, making the comparison reliable and informative.



References