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Intermediate Vector Bosons
Production and Identification at the CERN Proton-Antiproton Collider

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The recent discoveries[1]) of the massive $W^\pm$ and Z^o intermediate vector bosons at CERN are a triumph not only for the electroweak theory[2]) which gives a standard prescription of how to unify the electromagnetic and weak interactions, but also for the engineers and physicists who produced and detected $\bar{p}p$ collisions in the SPS collider at CERN.

One of the main achievements of elementary particle physics in recent years has been the development of a new class of unified theories which describe the forces of nature that appeared up to that time to be independent of each other. In the interactions between elementary particles a force is transmitted between two particles by the exchange of another intermediary particle, which is referred to as a vector boson. The boson, named after the Indian physicist S.N. Bose, describes particles which have integral spin; the vector boson has a spin of unity. In the case of the electromagnetic force the vector boson is the photon, which is massless. Experiments carried out using electron or muon beams (leptons) to study the structure of the nucleon are using an electromagnetic probe where the photon is exchanged between the leptons and the quarks which are considered to be the fundamental charged constituents of the nucleon.

The weak force causes certain kinds of radioactivity and also mediates some reactions in the Sun. Experiments carried out using neutrino beams to study the structure of the nucleon are using a weak probe where the charged $W^\pm$ boson is exchanged between the leptons and the quarks. A very important discovery[3]) made at CERN in 1973 showed that in neutrino scattering experiments, a neutral vector boson (Z^o) was also exchanged between the leptons and the quark content of the nucleon.

The quarks are themselves bound together by the strong force and the vector boson which is exchanged between them is called the gluon. This massless particle was discovered[4]) at the PETRA storage ring in DESY in 1978. The fourth force is the gravitational force which holds our Universe together.

The concept of the electroweak interaction is that both the electromagnetic and weak forces stem from a single "electroweak" force. At very high energies, as for example in the early moments after the big bang, the two interactions would be indistinguishable, i.e. the two forces have the same strength, and therefore the photon and the three weak bosons (W^+, W^- and Z^o) form the same family of four particles. The electroweak theory not only requires these four particles but specifies that the $W^\pm$ should be very heavy, ~ 80 GeV, i.e. 80 times the mass of the proton, and the Z^o somewhat heavier, around 90 GeV.

In order to produce a W or Z^o particle, it is possible to use an electron-positron colliding beam machine or a "quark-antiquark" colliding beam machine via the processes as illustrated in Fig. 1. Experiments on deep inelastic lepton scattering at CERN had given information on the quark and antiquark momentum content of the proton which showed that the u and d quarks in the proton carry off on average one fifth of the momentum of the proton, whereas the antiquark ($\bar{u}$, $\bar{d}$) momentum of the proton is at least a factor of two smaller. Therefore in order to produce a Z^o or W of ~ 100 GeV mass, it would be necessary to have an e^+e^- machine of ~ 50 GeV per beam (as will be available in LEP) or to have a proton-antiproton machine of ~ 250 GeV per beam and even more energy for a proton-proton colliding beam machine.

Clearly there is an advantage in accelerating and storing positively and negatively charged particles in the same magnetic structure, as has been applied

Fig. 1 — Possible mechanisms for producing W and Z bosons by proton-antiproton and electron-positron interactions.

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with great success to electron - positron storage rings, it being relatively easy to obtain positrons by converting intense beams of electrons in sufficient numbers to obtain interesting luminosities*. However, for proton-antiproton interactions, the situation is much more difficult, because antiprotons are very scarce and in general diluted in phase space, being produced from proton interactions in a target. In practice, about one antiproton is created for every 10^6 incident protons.

Despite this difficulty, C. Rubbia proposed in 1976 to use the CERN 400 GeV proton synchrotron (the SPS) to accelerate and store bunched beams of protons and antiprotons of energy 270 GeV per beam to give 540 GeV in the centre of mass. This energy is by far the highest that has been produced today.

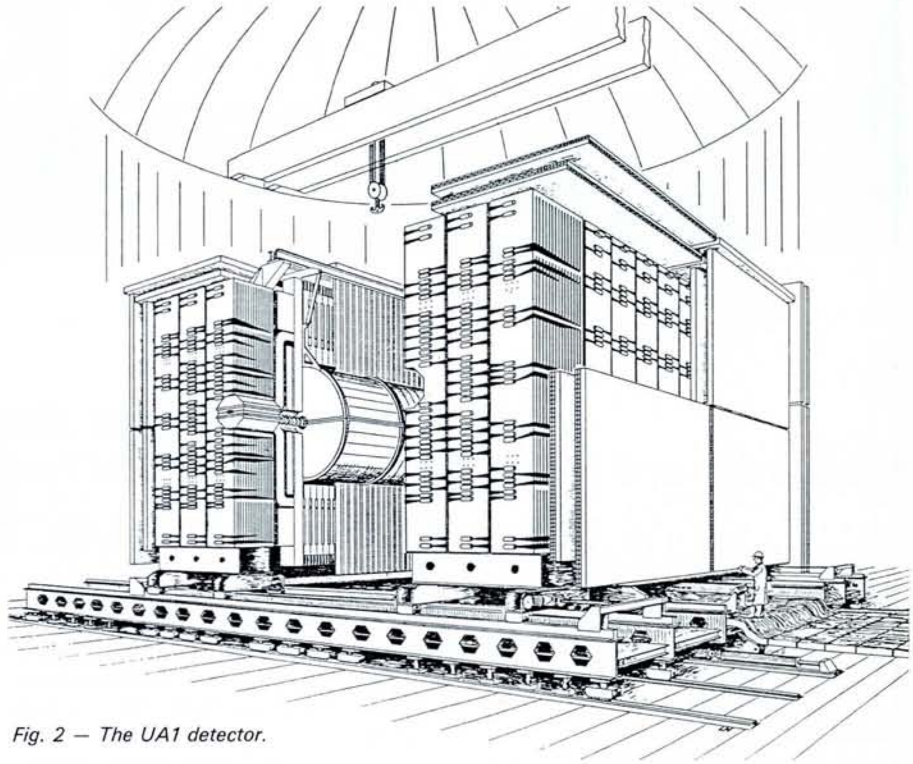


Fig. 2 — The UA1 detector.

Machine Building

The breakthrough which made the idea feasible was the invention of cooling methods which would permit the beam of antiprotons emerging from the target to be compressed in both momentum and transverse dimensions. Many thousands of pulses can then be stacked and stored in a form suitable for injection into a structure of very limited aperture like the SPS.

This implied the construction of an Accumulator Ring (AA) which collects over many hours as many antiprotons as possible from a target illuminated by protons of 26 GeV/*c*, produced by CERN's original proton synchrotron (the CPS), and "cools" them in the three dimensions until an adequate density is reached.

After an experiment with a smaller ring, called ICE, which confirmed the basic principle, the "stochastic" cooling method invented by S. van der Meer in 1968 was retained for incorporation in the AA.

In 1978 the complete project was defined and approved. It consisted essentially, in addition to the AA, of:

i) modifications and additions to the CPS to enable the transfer of bunches of the 3.5 GeV/*c* cooled antiprotons, their acceleration to 26 GeV/*c* and finally their extraction towards the SPS;
ii) a new transfer line to inject the 26 GeV/*c* antiprotons anticlockwise into the SPS, and the upgrading of the existing proton transfer line to 26 GeV/*c*;
iii) various modifications and additions to the SPS, to make it capable of accelerating and storing up to six against six intense bunches of particles and antiparticles;
iv) finally, two underground experimental areas enabling the simultaneous data-taking of two major experiments.

The first beam circulated in the AA in July 1980, exactly two years after project approval. Up to now it has operated many thousands of hours with excellent reliability.

If the transfer of $\bar{p}$'s from the AA to the CPS is a relatively straightforward operation, although it incorporates a 180° bend, the shaping of the $\bar{p}$ bunches in the CPS to make them acceptable to the SPS is a far from trivial operation. Nevertheless, the overall transfer efficiency between the AA stack and the beam coasting at 270 GeV/*c* in the SPS attains an average of 70%.

To turn an existing cyclic accelerator into a collider, which must store and accelerate intense bunches of p's and $\bar{p}$'s over many hours, was not an easy task.

Although the basic magnetic structure could be considered suitable for the new application, the power supplies had to be improved in stability, the residual gas pressure lowered by more than an order of magnitude by adding more than a thousand pumps, the beam diagnostics considerably extended to detect the $\bar{p}$ bunches, and the multipolar magnetic elements increased in number and strength in order to correct and compensate the magnetic resonances created by the new low-β insertions (a system of quadrupole lenses to focus the beams into a small waist at the intersection region) to be added in order to gain an important factor (almost 50) in the luminosity.

Machine Performance

After a shut-down of almost one year for the modification of the machine, and also the excavation and construction of the two large underground areas, the SPS resumed operation as a normal fixed-target accelerator in June 1981.

Soon afterwards, the first tests of collider operation started, and in July the first evidence of $\bar{p}p$ collisions at 540 GeV was obtained. The machine ran continuously in the collider mode with two proton bunches against one antiproton bunch, and a peak luminosity of 5×10^{27} cm^{-2} s^{-1}was achieved in each of the experiments with the low-β insertions in operation. Moreover, by very careful adjustment of the tuning with a precision better than 0.001 it has been possible to avoid resonances. Luminosity lifetimes close to twenty hours have been observed in the experiments.

In 1982, the SPS operated as a collider for physics from October to December, and a peak luminosity of 5×10^{28} cm^{-2} s^{-1} was achieved. This order of magnitude increase was produced mostly by increasing both the number of proton and antiproton bunches to three. The total integrated luminosity during these 600 hours of operation was 28×10^{33} cm^{-2} or 28 inverse nanobarns - a factor of almost 10^3 compared to the 1981 run. In 1983 the peak luminosity has been increased to 1.6×10^{29} cm^{-2} s^{-1} by further squeezing of the low-β system, and a total integrated luminosity of 153 nb^{-1} achieved.

The ultimate luminosoty goal is 10^{30} cm^{-2} s^{-1}.

Experiments

In order to observe the intermediate vector bosons produced in the $\bar{p}p$ interactions two large experiments UA1 [5]) and UA2 [6]) were installed in the Underground Areas, which are large caverns surrounding interaction points. These experiments had different detection features, but had the common aim of detecting the decays:

*The luminosity is defined as the number of particles/cm² s passing through the cross-section of the interaction point.

$W^{\pm} \rightarrow l^{\pm} + \nu_l$ and $Z^o \rightarrow l^+ + l^-$.

In the case of UA1, l was either an electron or a muon, whereas UA2 concentrated solely on electrons. The W decays into leptons with only 8% probability and the Z into lepton pairs with 3% probability; hence it is necessary to have a very large acceptance. In addition, both detectors were designed to study final states containing particle jets of large transverse momentum, since the present theory of strong interactions known as Quantum Chromodynamics, which describes the interaction between quarks and gluons, had predicted that these narrow jets of hadronic particles would be copiously produced at very high collider energies.

The UA1 detector illustrated in Fig. 2 consists of a large transverse dipole magnet of 800 tons which produces a uniform field of 0.7 T over a volume of $7 \times 3.5 \times 3.5$ m^3. The momentum of the charged particles emanating from the interaction point is measured using a central detector consisting of a cylindrical drift chamber 5.8 m long and 2.3 m in diameter. This large chamber is divided into three sections with vertical and horizontal drift regions. It records the time taken for the ionisation produced in the gaseous volume to drift horizontally or vertically. This time, together with a measurement of the position along the wire of the collected charge, gives a bubble-chamber-like record of the tracks in the magnetic field with a spatial resolution of ~ 250 μm (Fig. 3).

Outside this central detector, but still inside the magnetic field volume, is an electromagnetic calorimeter which records the total electromagnetic energy produced by electrons or photons.

The hadronic energy is measured in a calorimeter which is made from sheets of scintillator inserted between the 5 cm iron plates forming the return yoke of the magnet. The calorimeter is segmented into 232 sections, and can be used along with the electromagnetic calorimeter to identify electrons from hadrons with high efficiency. Additional calorimetry in the forward direction down to angles of 0.2° with respect to the direction of the beams enabled the outgoing energy to be recorded.

A muon detector consisting of 50 large drift chambers of $4 \text{ m} \times 6$ m in size surrounds the whole apparatus. Additional iron has been added between the 1982 and 1983 runs to improve the muon detection capability. A large number of calibration devices (e.g. lasers, ^{60}Co source) are provided to ensure the stability of the detector.

The UA2 detector consists of a vertex detector which measures charged particles in a region with no magnetic field. The vertex detector consists of two drift chambers and four multiwire proportional chambers, which enables the position of the vertex to be determined with a precision of ± 1 mm along the beam direction.

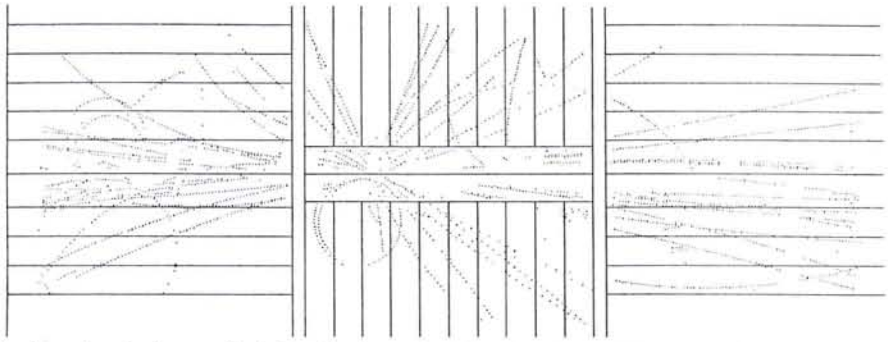


Fig. 3 — A typical event displaying the electronic digitisations in the UA1 central detector.

The vertex detector is surrounded in the central region ($48° < \theta < 140°$) by 200 cells of a highly segmented electromagnetic and hadronic calorimeter.

In the 1981 and 1982 runs, an azimuthal section of $\pm 30°$ around the horizontal plane was left open, and by magnetization of the iron sheets formed a magnetic spectrometer of 1.1 Tesla meter at large angles to detect and record single charged particles emerging from the interaction point together with photons. In the 1983 run, the wedge has been completely sealed by the calorimetric cells. In order to give precise spatial information on the position of the electromagnetic shower, in particular from photons, a cylindrical tungsten converter of 1.5 radiation length followed by a cylindrical proportional chamber is located just outside the vertex chamber. The forward regions ($20° < \theta < 37.5°$ with respect to the proton and antiproton beam direction) are each equipped with twelve toroidal magnet sectors with an average field of 0.38 Tesla meter followed successively by drift chambers, proportional chambers plus photon converter and lead-glass electromagnetic calorimeters. It is possible to measure the sign of the charge of the particles which are analysed in this forward region.

The UA2 detector is also partly used by another experiment the UA4[7]), which is measuring the total cross-section for $\bar{p}p$ collisions to an accuracy of 1% using very small-angle scintillation and wire-chamber hodoscopes upstream and downstream of the UA2 detector. In addition, in the early phase of the SPS collider, two large 6 m streamer chambers were used by the UA5 collaboration[8]) to measure the charged and neutral multiplicities and global properties of $\bar{p}p$ interactions. The detector was interchanged with UA2. The remaining UA3 experiment [9]) uses solid state track detectors to look for magnetic monopoles and is situated inside the UA1 detector as close as possible to the interaction point.

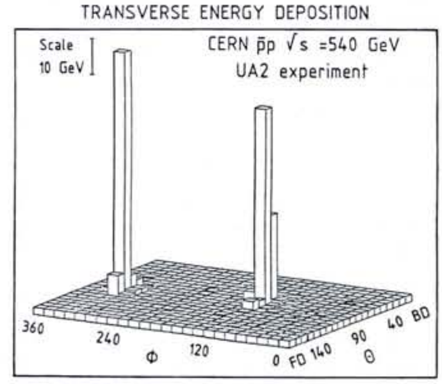
Results

The first evidence that the collider was opening up a new chapter in high energy physics was the emergence of very clear two-jet structures in the detectors. By triggering on total transverse energy as measured in the central calorimeter, UA2 was able to show that at sufficiently large values of E_T the two-jet configuration resulting from a hard scattering process will dominate. A typical two-jet event is illustrated in Fig. 4, which is known as a LEGOPLOT where the transverse energy builds up out of the plane defined by the θ and ϕ co-ordinates. The UA1 experiment has also observed transverse energy jets with an effective mass of the two jets up to ~ 100 GeV. The collider is a unique source of hard gluons, and the majority of these high-mass jets are expected to contain gluon jets. This is very different from e^+e^- interactions, where quark-antiquark pairs dominate the jet production mechanism. To date, the rate of jet production is consistent with the prediction of Quantum Chromodynamics that the jet cross-sections would increase by three orders of magnitude from ISR to SPS collider energies.

In the run of 1983, which has just been completed, a total of 153 nb^{-1} has been achieved and this will have produced more than a thousand jet events of large transverse energy in each detector. It will therefore be possible to study the details of gluon hadronisation and make detailed comparisons with that of quark jets in e^+e^- collisions. However, because of the very large jet cross-section, it will be difficult to search for the top quark by their decay into hadronic jets only, unless some special characteristic feature can be found.

The search for the intermediate charged boson was started during the 1982 run. The theoretical cross-section for the production of charged W bosons decaying into an electron is $\sigma(W^{\pm} \rightarrow e^{\pm}\nu) \cong 5 \times 10^{-34}$ cm^2.

Fig. 4 — A typical 2-jet event in the UA2 detector.



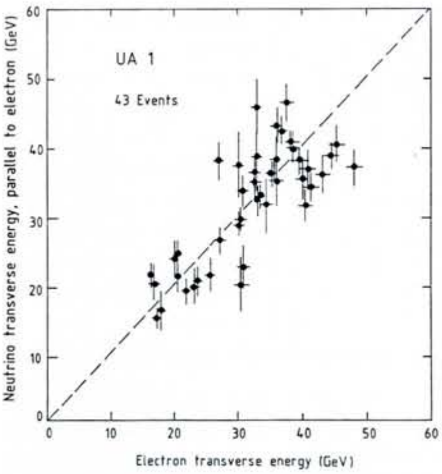


Fig. 5 — The neutrino transverse energy component parallel to the electron momentum versus the electron energy for the data up to and including 1983 for the UA1 detector.

Assuming a factor of 0.5 for the efficiency of the detector to record these events, then in order to produce a "handful" of events (~ 5) it would be necessary for the collider to produce a total luminosity during the run of 25×10^{33} cm^{-2} (25 nb^{-1}). The total luminosity produced during 1982 was 28 nb^{-1}, and therefore these W leptonic events were in principle recorded in the detectors. Since the cross-section for the production and decay of a $Z^o \rightarrow e^+e^-$ is a factor of 10 smaller, it would have required twice the luminosity, i.e. 50 nb^{-1}, to have an even chance of producing one event.

The W Bosons

The UA1 experiment collected $\sim 10^6$ events from 10^9 $\bar{p}p$ collisions, and after applying various selection criteria reduced this number to 2125 events containing a good-quality electron of large transverse energy (15 GeV). At this stage, two independent analyses were carried out:

a) a search for high-energy isolated electrons;

b) a search for high missing transverse energy, i.e. a neutrino signal, since the two energy vectors should be equal in magnitude and opposite in azimuth for a W decay at rest. Following these two separate methods, and removing events where there was clear evidence of hadronic jets, results were obtained, which showed that the same events survived as would be expected from a two-body decay of a W into an electron and neutrino. Assuming that the production mechanism is given only by the process of Fig. 1, and correcting for the transverse momentum of the produced W's, the mass of the W is

$$m_W = 81 \pm 5 \text{ GeV}/c^2.$$

The theoretical value given by the Weinberg-Salam model assuming $\sin^2 \theta_W = 0.23 \pm 0.01$ obtained from existing experiments gives

$$m_W = 82 \pm 2.4 \text{ GeV}/c^2.$$

During the 1983 run, the UA1 experiment has confirmed its previous results and realised much better results on the mass, cross-section and weak interaction properties of the production and decay mechanisms. A total of 52 events have been selected, which pass all the selection tests described previously. Of these events, 24 are electrons, 14 are positrons and the remainder have a track topology which makes the charge determination uncertain. The correlation between the missing neutrino energy and the energy of the electron is very clear, as illustrated in Fig. 5. To achieve the best determination of the electron energy, events have been removed which do not provide unique calorimetric energy measurements and 43 events have been used to give a new value of the mass of

$$m_W = 80.9 \pm 1.5 \text{ GeV}/c^2$$

to which a 3% energy scale uncertainty must be added at this time.

Parity violation, which has been extensively studied in low energy weak interaction experiments, also leads to specific asymmetries which should occur in the production and decay of weak vector bosons. It predicts a large charge asymmetry in W production and decay and a small asymmetry for Z^o production. The electron should emerge predominantly along the proton direction and the positron along the anti-proton direction. This strong forward-backward asymmetry has been studied in the UA1 experiment and found to be in excellent agreement with the V-A theory. In the run of 1983, clean single muon events have been found which correspond to the decay $W^\pm \rightarrow \mu^\pm \nu_\mu$. From electron and muon decays of the W, it should be possible to put limits on the existence of a heavy lepton coming from W decay which can decay into electrons and muons.

The UA2 experiment also produced evidence for W bosons decaying into electrons in their 1982 data. Electrons of large transverse energy were selected by demanding that they fulfilled the electron configuration of the calorimeter. This produced a sample of 363 events with $E_T > 15$ GeV. By demanding an isolated electron track which showers in the tungsten converter and has all the properties of an electromagnetic shower, three events remained. Three events were also found in the forward and backward magnetic toroid sections which satisfied the single isolated electron hypothesis. The final criterion of demanding the presence of a ν, i.e. missing transverse energy similar in magnitude to the electron energy and opposite in azimuth produced four W events in total, giving a mass

$$m_W = 80 \,^{+10}_{-6} \text{GeV}/c^2.$$

The UA2 collaboration have also recorded 35 W events in the 1983 run which has produced a much better mass determination of

$$m_W = 81.0 \pm 2.5 \pm 1.3 \text{ GeV}/c^2$$

where the first error accounts for measurement errors and the second for the uncertainty on the overall energy scale.

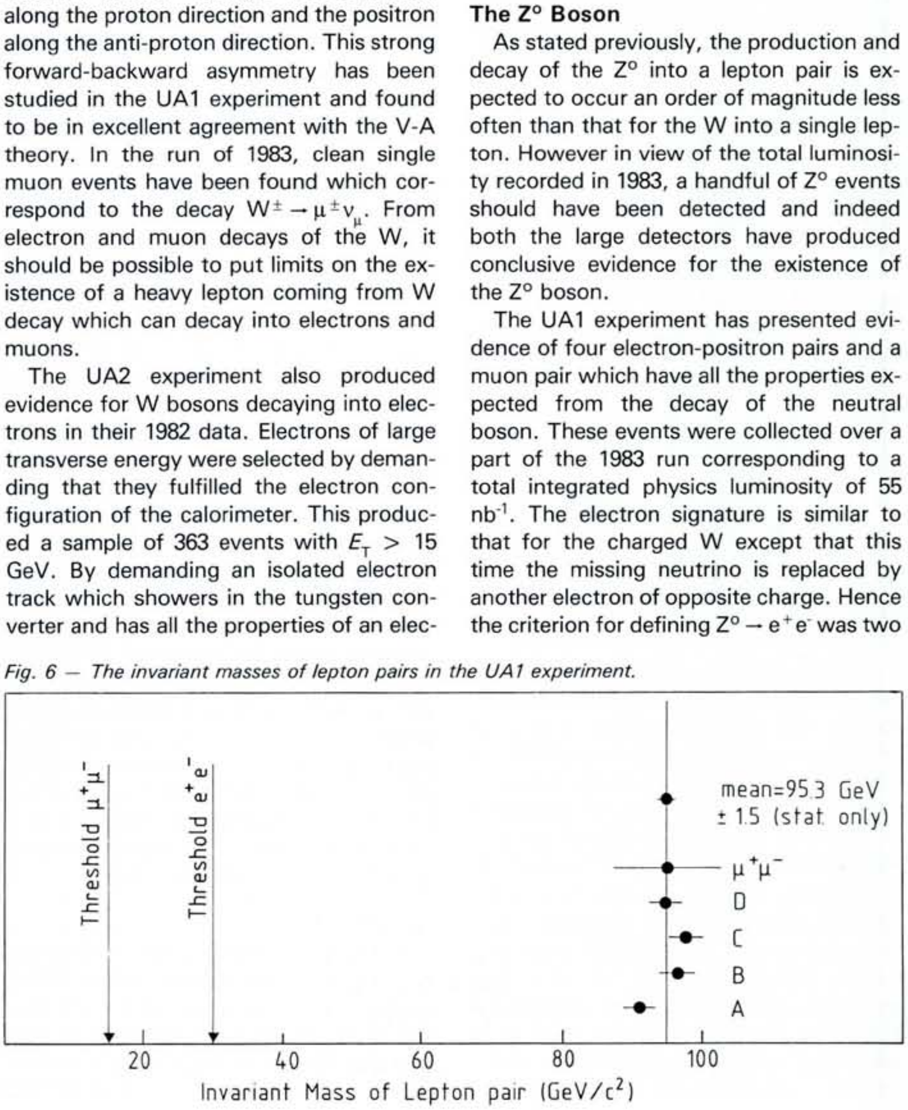
One important conclusion from these two experiments was that the background of hadronic "junk" could be removed from the events by demanding that the electron events have isolated electrons of large transverse energy. The use of electromagnetic and hadronic calorimetry both in triggering and determining a missing energy vector is a very powerful discriminator which has come into its own at these very high collider energies.

The Z° Boson

As stated previously, the production and decay of the Z^o into a lepton pair is expected to occur an order of magnitude less often than that for the W into a single lepton. However in view of the total luminosity recorded in 1983, a handful of Z^o events should have been detected and indeed both the large detectors have produced conclusive evidence for the existence of the Z^o boson.

The UA1 experiment has presented evidence of four electron-positron pairs and a muon pair which have all the properties expected from the decay of the neutral boson. These events were collected over a part of the 1983 run corresponding to a total integrated physics luminosity of 55 nb^{-1}. The electron signature is similar to that for the charged W except that this time the missing neutrino is replaced by another electron of opposite charge. Hence the criterion for defining $Z^o \rightarrow e^+e^-$ was two

Fig. 6 — The invariant masses of lepton pairs in the UA1 experiment.



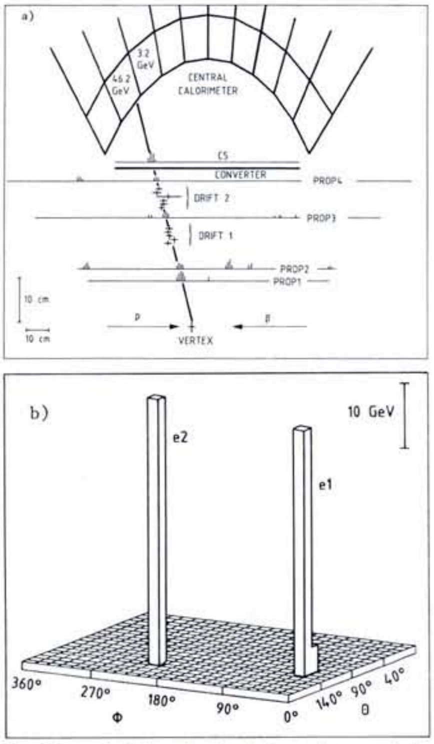


Fig. 7 — a) A longitudinal view of one of the electrons of a Z° event in the central detector of UA2.
b) The LEGOPLOT for the same event.

or more isolated electrons with transverse energy greater than 25 GeV. For the decay $Z^\circ \rightarrow \mu^+\mu^-$, the two muons were required to come from the vertex, penetrate the iron absorber and be recorded in the outer muon drift chambers. The mass plot is shown in Fig. 6 for all events satisfying the above conditions. The most striking feature is that all the events are clustered around one central mass value and there are no background events in the lower mass region. The mass of the Z° is

$$m_Z = 95.2 \pm 2.5 \text{ GeV}/c^2$$

with the same energy scale uncertainty as given for the W. This value of the mass is in excellent agreement with the prediction of the standard model.

The UA2 collaboration has presented evidence for eight electron pair candidates using the data from the total 1982 and 1983 runs which produced a total integrated physics luminosity of 131 nb^{-1}. The sample was first reduced by demanding an electromagnetic transverse energy larger than 30 GeV and the invariant mass of the two energy clusters to be larger than 30 GeV. Further cuts using the hadronic calorimeter energy response to remove jets and additional isolated electron showering criteria resulted in a total of eight events. The features of one of these events in the detector and in the "LEGOPLOT" are shown in Fig. 7. Of these eight events, four are "gold-plated" and are used to give a Z° mass

$$m_Z = 91.9 \pm 1.3 \pm 1.4 \text{ GeV}/c^2$$

where the different terms have been defined previously in the W mass determination.

In both experiments, every effort has been made to simulate backgrounds for the W and Z events but these always turn out to be very small. It is also interesting to note that both groups have an event in their final sample of the type $Z^\circ \rightarrow e^+e^-\gamma$ where a high energy photon has been emitted along the direction of one of the leptons. The probability of this happening is small for each experiment and clearly more events will be required to see if something unexpected is happening.

Both groups have made a determination of $\sin^2\theta_W$ where θ_W is the renormalised weak mixing angle of the standard model and obtain the following results

$$\sin^2\theta_W = 0.226 \pm 0.011 \text{ (UA1)}$$
$$= 0.227 \pm 0.009 \text{ (UA2)}$$

The World low-energy data coming mainly from neutrino experiments give $\sin^2\theta_W = 0.236 \pm 0.030$, so the agreement is excellent. Both groups have used their measurements of m_W and m_Z to obtain a value of ρ which is defined by

$$m_Z^2 = m_W^2/(\rho \cos^2\theta_w)$$

This parameter is unity in the minimal SU(2) XU(1) model. The experimental values are

$$\rho = 0.94 \pm 0.06 \text{ (UA1) and}$$
$$1.004 \pm 0.052 \text{ (UA2)}$$

Within three years of the first beam of antiprotons circulating in the AA ring (July 1980), the W and Z° bosons were discovered in the SPS collider. This is only a beginning. Now one looks for the top quark and "non-standard" physics.

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5. The UA1 Collaboration comprises Aachen—Annecy (LAPP)—Birmingham—CERN—Helsinki—Queen Mary College (London)—Paris (Coll. de France)—Riverside—Rome—Rutherford-Appleton Lab.—Saclay (CEN)—Vienna.

6. The UA2 Collaboration consists of Bern—CERN Niels Bohr Inst.—Paris (Orsay)—Pavia—Saclay (CEN).

7. The UA4 Collaboration consists of Amsterdam (NIKHEF)—CERN—Genova—Naples—Pisa.

8. The UA5 Collaboration consists of Bonn—Brussels—Cambridge—CERN—Stockholm.

9. The UA3 Collaboration consists of Annecy (LAPP)—CERN.