

The experiments

1.6×10^{29} . By the time the run closed on 3 July the integrated luminosity had reached 1.5×10^{35} . The threshold of machine performance had been crossed for observation of the Z particles.

Future plans

At the PS the present ten bunches from the booster will be 'box car' stacked in the transfer line so as to give five bunches in the PS. This process can then be repeated to feed in another five bunches and the process of combination in the PS ring will result in putting more protons (some 2×10^{13}) on the antiproton production target at the AA.

In the AA new ferrite pick-ups will improve precooling at higher antiproton fluxes and a series of improvements to the cooling electronics are under way. A new injection damper should improve injection of the antiprotons into the PS. In the SPS, the number of colliding bunches will be increased from the present three per beam, the low beta insertion could be made stronger and it might be possible to increase the peak energy of the collider to 310 GeV to increase the W and Z production rates.

Longer term, the possibility of adding a separate ring, an Antiproton Collector, ACOL, has been studied with the aim of accumulating antiprotons at ten times the present rate. This is similar to the scheme at Fermilab where a proton-antiproton collider of up to 1000 GeV energy per beam has become feasible with the operation of their superconducting synchrotron (see page 380).

Although the collider, scheduled to run for physics again in autumn 1984, has yet to reach its somewhat ambitious design performance, this has hardly detracted from the richness of the physics results. Perhaps

never has a new energy range given so many important new results so quickly. A fitting tribute to the inventiveness, skill and ingenuity of the machine physicists who made it all happen.

UA1 and UA2 represent the accumulation of many years of knowledge and experience in the design, construction and operation of particle physics experiments.

The CERN Intersecting Storage Rings (ISR), a masterpiece of a machine, was built ahead of its time in the sense that only towards the end of its lifetime has it been equipped with detectors that do justice to the available physics.

The designers of the UA1 and UA2 detectors had no reason to be caught in the same trap. For the SPS proton-antiproton collider, the aim was to have maximum detector capability right from the start, with adequate tracking and calorimetry (energy deposition measurements); maximum solid angle coverage and powerful data handling systems.

Despite their immense size, the two experiments which discovered the W and Z particles are not readily visible to a visitor to the CERN site. The proton-antiproton collisions which the experiments study take place underground in the ring of the SPS machine, and the detectors are housed in deep caverns.

The 7-kilometre underground SPS ring was designed and built for 'fixed-target' experiments. For this research, high energy proton beams are made to fly off tangentially from the ring. These beams provide the particles which feed the experiments, installed in large, relatively easily accessible experimental halls. Viewed from the elevated gangways, these CERN experimental halls resemble aircraft hangars, but with beamlines and detectors replacing aircraft. The UA1 and UA2 underground halls look very different, but are of the portent of things to come at LEP and other giant new machines to supply colliding particle beams.

Detectors studying colliding beams have to surround the region

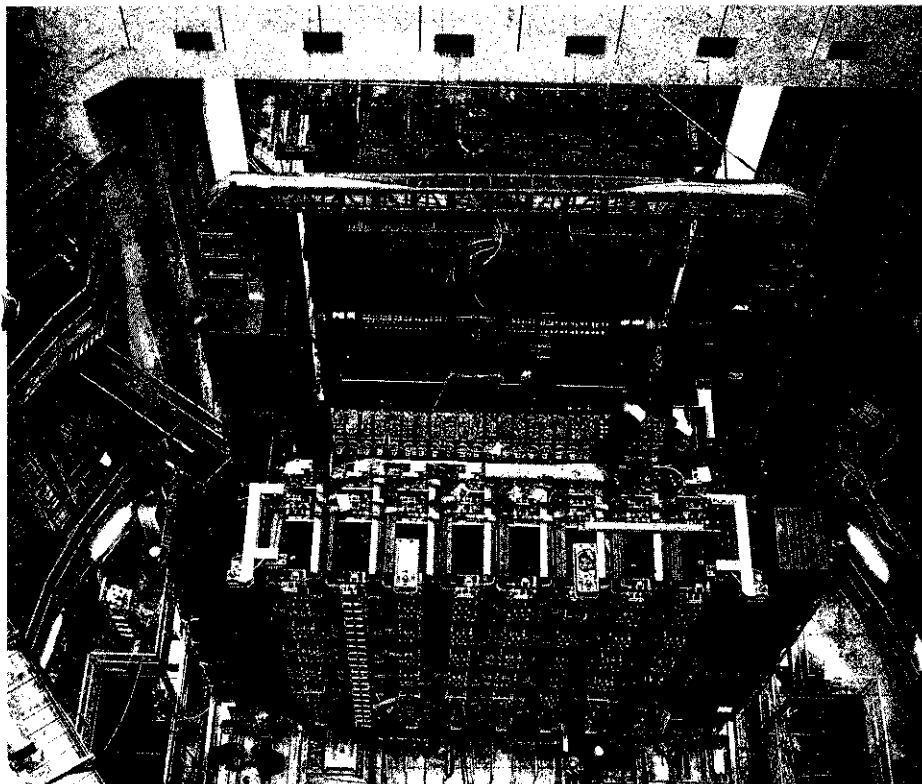
On 1 July, Herwig Schopper toasts CERN's achievements at a crowded party to celebrate the end of the epic 1983 antiproton run in the SPS.

(Photo CERN 39.7.83)



A view of the UA1 detector during installation. The two halves of the main magnet/hadron calorimeter are drawn apart, showing inside the elements of the electromagnetic calorimeter surrounding the cylindrical space to be occupied by the inner tracking chamber. When assembled, most of the UA1 detector is covered by its large outer slabs of muon detectors.

(Photo CERN 229.2.81)



where the beams are brought together. Simply to get the envisaged detectors into the SPS ring would have demanded a mammoth effort of construction and engineering. As if the task of installing a 2000-ton detector with fraction of a millimetre precision in a confined underground space was not enough, there were other restrictions. At the SPS, collider physics would not replace fixed target operation. While the collider experiments were assembled, the machine would continue to operate, and even once the detectors were commissioned, the machine would run alternate periods of fixed target and collider physics according to a prearranged schedule.

Thus the underground caverns had to be made large enough to provide room for the completed detectors to be positioned in the ring, plus enough 'garage' space so that they could be assembled without having to shut

down the machine. The detectors could be rolled back when a period of data-taking was completed and the SPS reverted to fixed-target operation. In these underground garages and shielded by movable walls, the experimenters could assemble apparatus or tinker with their detector, only several feet away from the intense high energy proton beams in the SPS.

The countryside around CERN is far from flat. Although the two experiments are only about one kilometre distant in the SPS ring, the beampipe for UA1's collisions is about 20 metres below the surface, while that for UA2 is some 50 metres underground. The civil engineering for the UA1 premises which began in 1979 used the 'cut and cover' method, while the aptly named 'cathedral' for UA2 was excavated from within.

While the earthmoving and exca-

vating teams began work, a vast physics effort was being mobilized across Europe. Responsibility for the various components of the UA1 and UA2 detectors was delegated to the different research centres in the collaborations, including of course CERN.

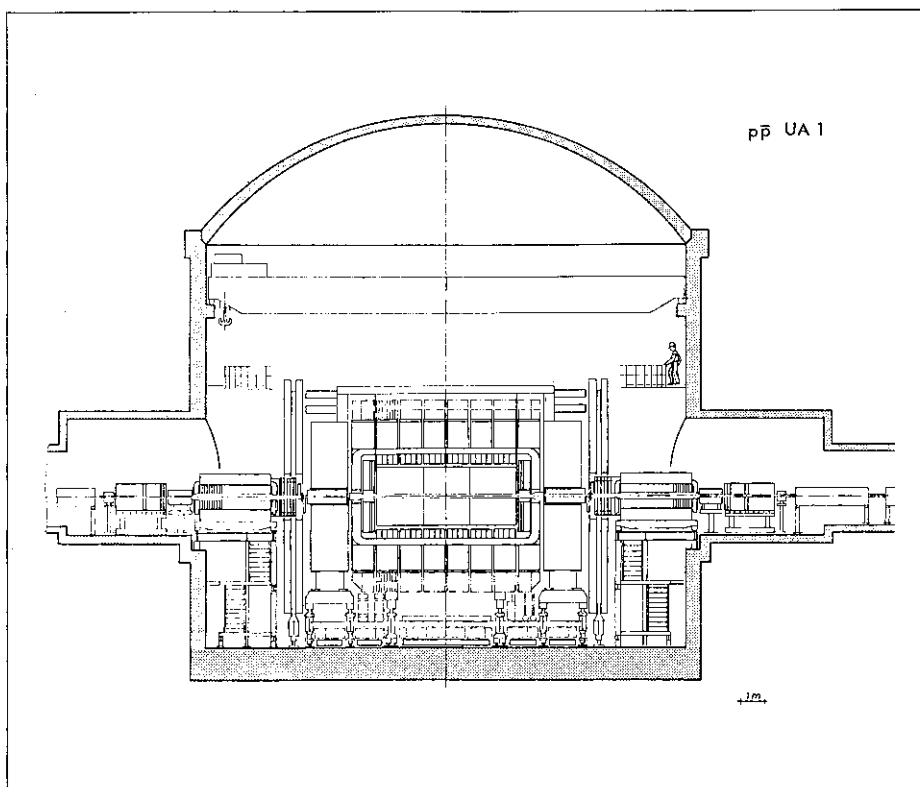
Literally hundreds of man-years of heroic effort went into the design, assembly and testing of the thousands of units for the various sub-assemblies of the detectors. Wire by wire, and crate by crate, the electronics grew, and piece by piece the equipment for the detectors came together. The high efficiency attained during the 1983 run (80 per cent) bears witness to the thoroughness of this preparation and ground-work.

The logistics of this work were far-reaching, and sometimes had to overrule physics requirements. The size of some components, for example, was found to be limited by the transport and handling services available.

In both detectors, different types of particles are identified and studied by looking at their behaviour as they pass through successive layers of the apparatus, each of which has a specific function.

Another problem is posed by the rarity of the phenomena being sought. To be sure of catching a few Z particles over a period of about two months, the detectors would have to be exposed to a few thousand proton-antiproton collisions per second. To examine all this data in detail at once was out of the question, and both experiments use 'triggers' — pre-programmed selection criteria which ensure that potentially valuable physics is recorded on special magnetic tapes for subsequent analysis. Thanks to skilful triggering and subsequent data handling, the captured information can be filtered

Cross-section of the UA1 detector. The collision region is surrounded in turn by the central tracking detector, the electromagnetic calorimeter, the magnet/hadron calorimeter and the muon detectors. On either side are the forward and 'very forward' detectors covering particles emerging close to the beam pipe. Not shown are the 'very very forward' detectors ('Roman pots'), some 20 metres from the central detector.



and analysed even while the experiments are still running.

Most interest lies in the triggers which select out those events producing particles flying out at large angles to the direction of the colliding beams, as these particles characterize the violent frontal collisions which shake the constituents of the protons and antiprotons.

The UA1 experiment

Carlo Rubbia, leader of the UA1 team, describes his immense detector as 'a series of boxes, each one doing what the previous one couldn't do' — a modest description of some 2000 tons of sophisticated precision apparatus packed with advanced technology!

The UA1 detector was designed to cope with large numbers of particles, collecting 'unbiased' information from collision products collected

over a maximum solid angle. Particle energies are measured both by their curvatures in the internal magnetic field, and by energy deposition (calorimetry). Both electrons and muons are sought.

The 7000 gauss magnetic field is supplied by an 800-ton conventional electromagnet using thin aluminium coils and enclosing a region of 85 cubic metres. Inside the magnet and surrounding the beam pipe carrying the particles are six shells of drift chambers containing 6000 sense wires with image readout, providing a reconstruction of the emerging particle tracks in a cylindrical volume 6 m long and 2.6 m in diameter around the beam crossing point. The reconstructions have an uncanny resemblance to classical bubble chamber tracks.

Surrounding this central detector inside the magnet are the 'gondolas' — 48 crescent-shaped modules of

Portrait of UA1

Aachen Technische Hochschule
muon chambers

Annecy (LAPP)
'bouchons' (electromagnetic calorimeter end-caps)

Birmingham
hadron calorimeter,
trigger processor

CERN
magnet, compensators, central detector, experimental area, computing, overall coordination

Queen Mary College, London
hadron calorimeter,
trigger processor

Paris, Collège de France
forward detectors

**Riverside,
University of California**
'very very forward' detectors

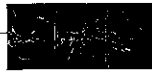
Rome
'very forward' detectors

Rutherford Appleton Laboratory
hadron calorimeter,
trigger processor

Saclay
'gondolas' (electromagnetic calorimeter)

Vienna
electromagnetic calorimeter
electronics and phototubes

This list is not exhaustive, and covers only the initial configuration of the UA1 detector. Helsinki joined later and Harvard and Wisconsin are also contributing to ongoing development.



The UA2 detector, showing the finely segmented barrel-like central detector and the large magnetic spectrometers on either side.

(Photo CERN 293.3.82)

lead-scintillator sandwich to catch electromagnetic energy.

The outer hadron calorimeter gauges energy flow when particle densities become too great for magnetic analysis. It consists of scintillator slabs and associated instrumentation fitted between the C-shaped iron slabs of the magnet return yoke. Both the electromagnetic and hadronic calorimeters are closed by end-caps.

Muons transversing all this are picked up in large slab-like arrays of drift chambers which cover the entire apparatus, giving it a deceptively uninteresting box-like appearance. These muon chambers alone required some 30 kilometres of extruded aluminium! To supplement the detection capabilities of the main detector, additional equipment is installed in the forward/backward regions around the beam pipe on either side of the main detector.

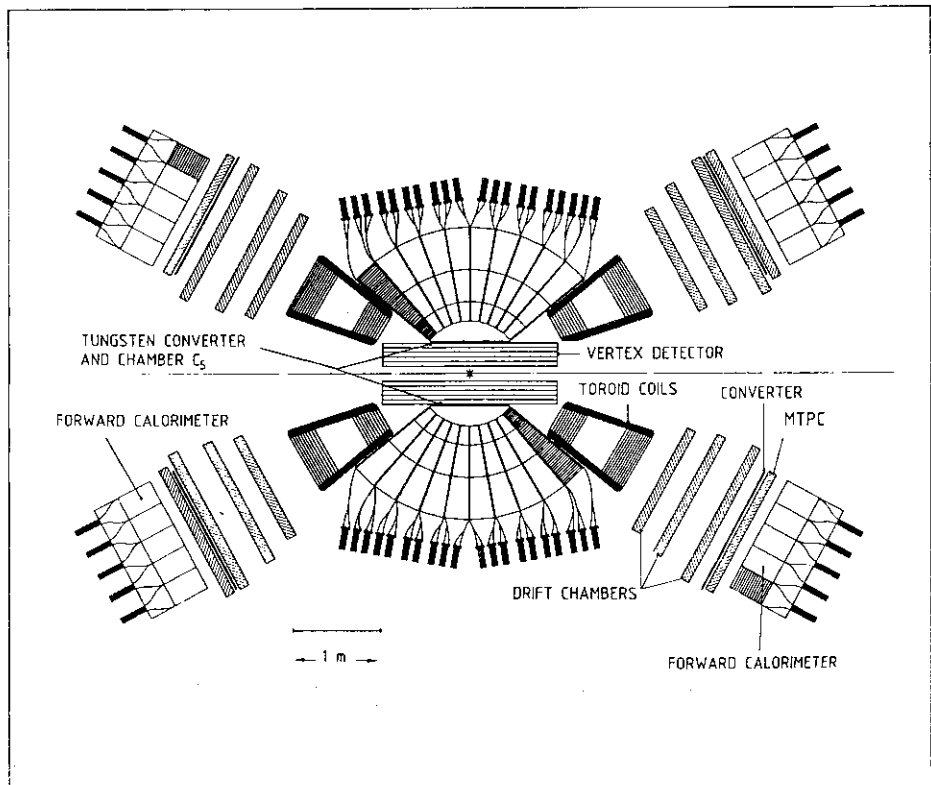
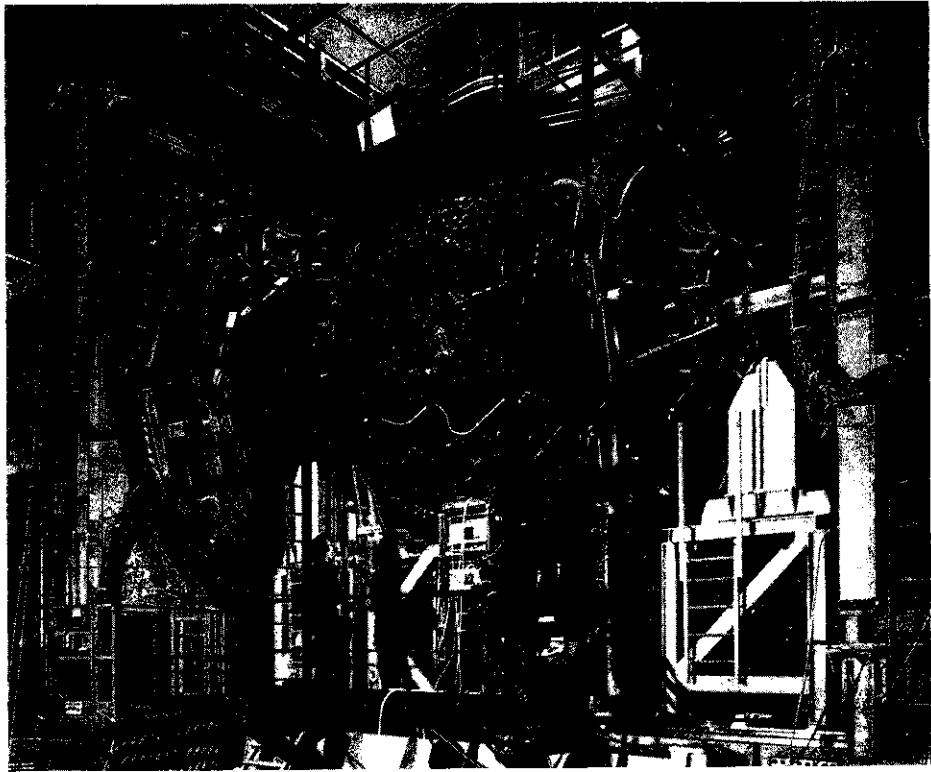
A sophisticated microprocessor-based data handling system has been developed which selects out potentially interesting data and copes with the enormous amounts of information produced by each measured collision (see April issue, page 82).

UA2

The search for W and Z particles was high on the list of priorities in the UA2 design, which concentrates on decays producing electrons. Lead/scintillator sandwich counters identify electrons over a wide solid angle.

Particles emerging from the collisions are picked up in the inner ver-

Schematic diagram of the UA2 detector. The inner vertex detector was made by Orsay, the forward drift chambers by Copenhagen and Pavia, the forward calorimeters by Saclay, the forward multi-tube proportional counters (MTPC) by Bern, and the large central calorimeter and the toroid coils by CERN.



January 1983. One of the events found by the UA1 detector from the October-December 1982 run producing a high transverse energy electron (arrowed). This particle is moreover produced more or less back-to-back with 'missing energy', indicative of the emission of an invisible neutrino. The electron and the neutrino are the decay products of a W particle.

tex detector, equipped with interleaved proportional chambers and drift chambers. From the reconstructed particle tracks, the position of the interaction can be pinpointed.

Surrounding this vertex detector are the central electromagnetic and hadronic calorimeters, segmented into 240 cells, each pointing towards the centre of the interaction region. Each of these cells is divided into electromagnetic (lead/scintillator) and hadronic (iron/scintillator) compartments.

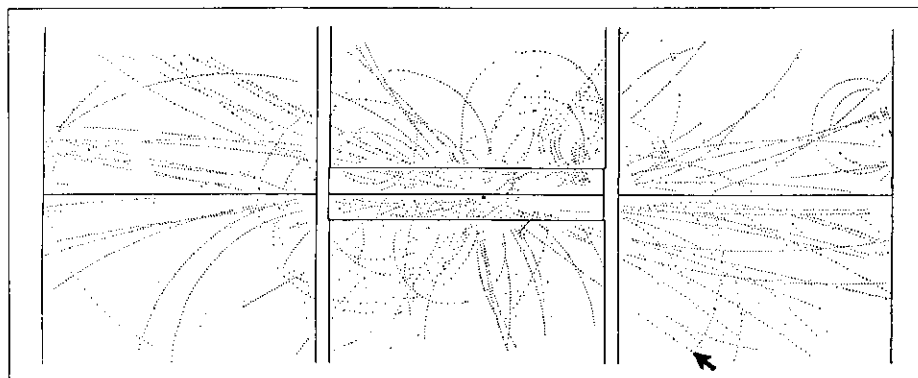
The annular regions on either side of the central detector are equipped with magnetic analysis and segmented arrays of lead-scintillator shower counters for electromagnetic energy measurement, and drift and proportional tube chambers for electron localization.

During its initial runs in 1981 and 1982, the UA2 central calorimeter had a 'wedge' removed to accommodate a magnetic spectrometer which measured the level of neutral pion production.

Hunting Ws and Zs

The new experiments in the SPS ring had their first tentative glimpse of 540 GeV proton-antiproton collisions in the summer of 1981. The first task was to make an initial survey of particle behaviour in this newly available energy range. Cosmic ray experiments had previously reported unexplained behaviour, with events containing large numbers of long-lived particles but remarkably few neutral pions. Physicists were eager to see if this could be reproduced under laboratory conditions. However neither UA1 nor the big streamer chambers of the UA5 experiment (Bonn/Brussels/Cambridge/CERN/Stockholm) saw anything radically new.

For the second antiproton run later



in 1981, the UA5 detector was replaced by UA2, and the UA1 central detector came into action for the first time. In those days, proton-antiproton collision rates were low (best luminosity $5.2 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$), and finding W and Z particles was out of the question. But both UA1 and UA2 were able to make valuable contributions to the study of particle 'jets' — well-defined clusters of emerging particles, interpreted as the results of violent collisions between the quarks and gluons hidden deep inside the protons and antiprotons.

Evidence for such jets had been seen in experiments at lower energy, but the higher energies available in the SPS collider made the jets stand out unmistakably from background effects due to other processes. The SPS collider results on jet production were among the physics highlights of 1982. Another initial collider success was the charting of reaction rates (cross-sections) by the UA4 experiment (Amsterdam / CERN / Genoa / Naples / Pisa), installed with UA2, to see how these compared with what was known from lower energies. (UA1 also measures these cross-sections.)

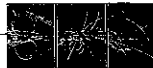
Meanwhile the SPS and the experiments prepared for a major antiproton run, scheduled for the spring of 1982. Then disaster struck. While setting up, the UA1 detector fell victim to a dirty compressed air supply

which contaminated the delicate components of the inner detector. Spirits were low when the detector had to be painstakingly dismantled for cleaning and the run was postponed.

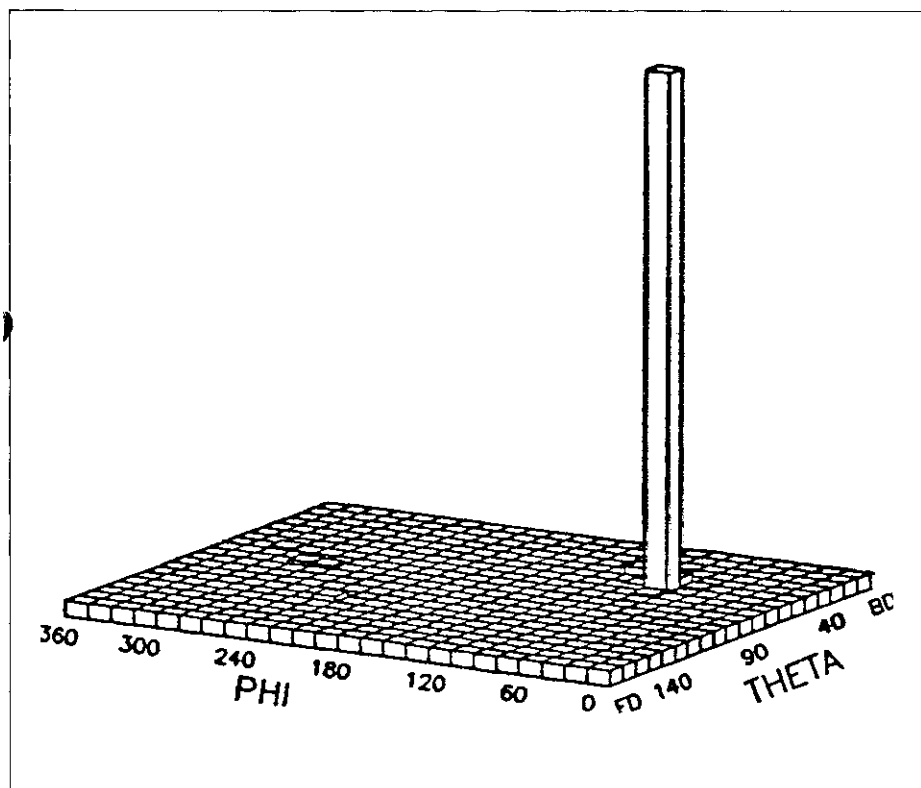
However this setback paid unexpected dividends. Instead of two separate runs, 1982 SPS antiproton operations were merged into one block, which began in October. This was to make for valuable savings in setting-up and running-in.

After a modest start which further tried experimenters' patience, things quickly began to improve. Soon the SPS was supplying what was to become the standard diet of three circulating bunches of protons and of antiprotons. Collision rates improved to give luminosities of around $10^{28} \text{ cm}^{-2} \text{ s}^{-1}$, and experimenters were seen going around with wide smiles. They knew they were logging lots of data with low backgrounds, just what they needed to find W particles.

Luminosity continued to improve, reaching a record level of 5×10^{28} . By the end of the run, UA1 and UA2 had each intercepted a major proportion of the 28 inverse nanobarns of integrated luminosity to which they had been exposed. According to the theory, here was enough data to provide some charged W particles. Eagerly the experimenters turned to the analysis of their data.



The signature of a W particle, from the 1982 run, as recorded in the UA2 detector. A lone high transverse momentum electron towers over a barren landscape.



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OBSERVATION OF SINGLE ISOLATED ELECTRONS OF HIGH TRANSVERSE MOMENTUM IN EVENTS WITH MISSING TRANSVERSE ENERGY AT THE CERN $\bar{p}p$ COLLIDER

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We report the results of a search for single isolated electrons of high transverse momentum at the CERN $\bar{p}p$ collider. Above 15 GeV/c, four events are found having large missing transverse energy along a direction opposite in azimuth to that of the high- p_T electron. Both the configuration of the events and their number are consistent with the expectations from the process $\bar{p} + p \rightarrow W^+ + \text{anything}$, with $W \rightarrow e + \nu$, where W^+ is the charged Intermediate Vector Boson postulated by the unified electroweak theory.

Even during the run, it had been clear that they were seeing something in the events 'triggered' by energetic electrons. After off-line analysis, the UA1 and UA2 teams found several examples where, amongst the clutter of particles emerging from the collisions, a lone high energy electron had been spat out at a wide angle to the beam direction (high transverse momentum). This isolated electron was found to be roughly back-to-back with 'missing' energy in the calorimeters with no visible associated particle track, hinting at a neutrino.

Some thousand million collisions had been seen by the detectors in the 1982 run, but of these, only about one tenth of a per cent were violent enough to provide the right conditions to produce W s and Z s. Each of these selected collisions produced enough detector information to fill a large telephone directory. Thus it was a dazzling feat of detector know-how and data handling skill by both the experiments to sift through this mass of information so quickly and filter out their interesting events — six at UA1 and four at UA2.

The results were first presented at the Workshop on Proton-Antiproton Collider Physics, held in Rome in January. The explanation of these events was then still only a whisper. At the meeting, Fermilab Director Leon Lederman had confessed to being impressed by 'the speed at which data was analysed and physics achieved out of detectors of unprecedented sophistication, viewing collisions of novel complexity'.

It took the physicists just a few weeks to convince themselves that they had found the signature of a W particle decaying into an energetic electron and a neutrino, carrying energy but invisible. The formal announcement of the discovery of the

EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c² AT THE CERN SPS COLLIDER

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We report the observation of four electron-positron pairs and one muon pair which have the signature of a two-body decay of a particle of mass ~ 95 GeV/c². These events fit well the hypothesis that they are produced by the process $p + p \rightarrow Z^0 + X$ (with $Z^0 \rightarrow e^+e^-$ or $\mu^+\mu^-$), where Z^0 is the Intermediate Vector Boson postulated by the electroweak theories as the mediator of weak neutral currents.

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W particle by the UA1 team was made at CERN on 25 January and later confirmed by UA2. As predicted by the theory, its mass was around 80 GeV.

The next step was to track down the companion Z^0 , the carrier of the neutral current of the weak interaction. However the theory said that these would be ten times rarer than the Ws, and at least several times the amount of data collected in the 1982 run would be required to give the experimenters a good chance of finding some.

The SPS operations team were set a goal of 100 inverse nanobarns, roughly four times what was achieved in 1982. Were people being too optimistic in hoping to find the Z^0 so soon after the highly successful 1982 run, which had already smashed all records?

The 1983 SPS antiproton run began on 12 April, again modestly. But improved techniques and methods began to pay dividends. Magnificent reliability assured a steady supply of the precious antiprotons. Luminosities crept higher and a record figure

of 1.6×10^{29} cm⁻² s⁻¹ was achieved, more than a hundred times what was seen in the pioneer runs in 1981. The 100 inverse nanobarn target was duly reached on 6 June, one full month before the end of the run!

The signature of a Z^0 was expected to be much clearer than that of the W. There would be no tricky missing energy to look for. The experiments were looking for clear electron-positron pairs (and, in the case of UA1, oppositely charged muon pairs), carrying more energy than had ever been seen before.

The UA1 team triumphantly unearthed a Z^0 candidate event on 4 May, from data recorded just a few days before. A first estimate of its mass was around 100 GeV, in the region where it was expected. But this first Z candidate was worrisome as one of its electron tracks looked as though it was accompanied by an energetic photon.

But cleaner examples of Z^0 decay into electron and positron (and into two muons) arrived from UA1 in the ensuing weeks. On 1 June, the formal announcement of the discovery of the Z^0 particle was made at CERN.

After the end of the 1983 antiproton run on 3 July, the UA1 and UA2 experiments had between them about a dozen Z^0 s, centred around 93 GeV, and about a hundred Ws at 81 GeV. As well as W decays producing a lone electron plus neutrino, UA1 has also seen decays producing a muon plus neutrino. The analysis of the data is continuing, and more events are turning up.

But whatever else the UA1 and UA2 experiments may find in the SPS collider, it is clear that a new chapter can be added to the history of science. With LEP and other big machines now being built or planned, we are entering a new era of physics.