84-6-172

PHYSICS RESULTS OF THE UA1 COLLABORATION AT THE CERNPROTON-ANTIPROTON COLLIDER

Carlo RUBBIA
CERN, Geneva, Switzerland

1. THE CERN SUPER PROTON SYNCHROTRON (SPS) AS A
PROTON-ANTIPROTON COLLIDER

The conversion of the SPS into a $\bar{p}p$ collider¹⁾ and the associated physics programmes of the UA1 collaboration were motivated by three very specific physics goals, namely :

- (i) the observation of jets and a detailed comparison with predictions of QCD.
- (ii) The discovery of the charged Intermediate Vector Boson (IVB) $W^{\pm}$ in the electron and muon decay modes and the measurement of its fundamental charge asymmetry in the decay.
- (iii) The discovery of the neutral IVB, Z^0 both in the electron and muon decay channels.

These goals are now essentially fulfilled. In addition and perhaps more surprising has been the extreme cleanliness of the events. A modest p_t threshold cut can easily separate the interesting phenomena removing the background due to spectator quarks.

The first collisions between protons and antiprotons at $\sqrt{s}=540$ GeV in the SPS accelerator operating as a storage ring²⁾ were observed in the early summer of 1981, not even

three years after approval of the project. Two years later, a very large amount of information has become available which will be the subject of these lectures. Before discussing these results, it may be worth recalling that the collider has been the first and so far the only storage ring in which bunched protons and antiprotons collide head-on. Although the pp-collider uses bunched beams like e^+e^- colliders, the phase-space damping due to synchrotron radiation is now absent. Furthermore, since antiprotons are scarce one has to operate the collider in conditions of relatively large tune shift which is not the case for the continuous proton beams of the ISR. Therefore the machine itself has been breaking new grounds.

One of the most remarkable results of the $\bar{p}p$ collider has been probably the fact that it has operated at such high luminosity, which in turn means a large beam-beam tune shift. Most serious concern had been voiced in the early days of the construction about the stability of the beams due to beam-beam interactions. The beam-beam force can be approximated as a periodic δ -function of extremely non-linear potential kicks and it is expected to excite a continuum of resonances, in principle with the density of rational numbers. Reduced to bare essentials, we can consider the case of a weak antiproton beam colliding head-on with a strong bunched proton beam. The increment of the action invariant $W = \gamma x^2 + 2\alpha x x' + \beta x'^2$ of an antiproton due to the angular kick $\Delta x'$ is $\Delta W = \beta(\Delta x')^2 + 2(\alpha x + \beta x')\Delta x'$ and can be expressed in terms of the "tune shift" ΔQ as $\Delta x' = 4\pi\Delta Q x / \beta$. If now we assume that the successive kicks are randomized, the second term of ΔW averages to zero and we get :

$$\left\langle \frac{\Delta W}{W} \right\rangle = \frac{1}{2} (4\pi\Delta Q)^2$$

For the design luminosity we need $\Delta Q \sim 0.003$ leading to

$(\Delta W/W) = 7.1 \times 10^{-4}$. This is a very large number indeed giving an e-fold increase of W in only $1/7.1 \times 10^{-4} = 1.41 \times 10^3$ kicks! Therefore the only way in which the antiproton motion remains stable is because these strong kicks are not random but periodic and the beam has a long "memory" which allows one to add them coherently rather than at random. Off-resonances, effects of these kicks then cancel on average, giving a zero overall amplitude growth. The beam-beam effects are very difficult, albeit impossible to evaluate theoretically, since this, apriori purely deterministic problem can exhibit stochastic behaviours and irreversible diffusion-like characteristics.

An old measurement at the electron-positron collider SPEAR had further increased the general concern about the viability of the $\bar{p}p$ collider scheme. Reducing the energy of the electron collider (Figure 1) resulted in a smaller value of the maximum allowed tune shift, interpreted as due to the reduced synchrotron radiation damping. Equating the needed beam lifetime for the $\bar{p}p$ collider (where damping is absent) with the extrapolated damping time of an e^+e^- collider gives a maximum allowed tune shift $\Delta Q = 10^{-5} - 10^{-6}$ which is catastrophically low. This bleak prediction did not find itself confirmed by the experience at the collider, where $\Delta Q = 0.003$ per crossing and six crossing is routinely achieved with a beam luminosity lifetime approaching one day. What is then the cause of such a striking contradiction between the experiments with protons and electrons? The difference is related to the presence of synchrotron radiation in the latter case. The emission of synchrotron photons is a main source of quick randomization between crossings and it leads to a rapid deterioration of the beam emittance. Fortunately the same phenomenon provides us also with an effective damping mechanism. The proton-antiproton collider works since both the randomizing and the damping mechanisms are absent. This

Fig. 1 Maximum allowed tune shift ΔQ at SPEAR as a function of the energy.

unusually favourable combination of effects ensures that proton-antiproton colliders become viable devices. They are capable of substantial improvements in the future. Accumulating more antiprotons would permit us to obtain a substantially large luminosity. A project is on its way at CERN which is expected to be able to deliver enough antiprotons to accumulate in one single day approximately the integrated luminosity on which the results of these lectures have been based ($\sim 100 \text{ nb}^{-1}$). On a longer time scale, a $\bar{p}p$ collider built in the LEP tunnel with superconducting

magnets of high field (10 T) is also conceivable. The luminosity will be further increased because of adiabatic beam damping with energy ($L\gamma/R$). If the proton and antiproton bunches are transferred from the SPS collider to a 10 TeV + 10 TeV collider in the LEP tunnel, a further increase of luminosity of about one order of magnitude is gained. Luminosities of order of $10^{32} \text{ cm}^{-2} \text{ sec}^{-1}$, which are likely to be at the limit of a general purpose detector are therefore quite conceivable. A further, important advantage is provided by the emergence of a significant amount of synchrotron damping, which at 10 TeV has an e-folding time of the order of several hours. This could be very helpful in improving even further the beam lifetimes and to increase significantly the attainable luminosities.

2. JETS

2.1. Introduction. Jets appear as the dominant, new phenomenon at the S $\bar{p}$ pS collider, thus confirming the earlier cosmic ray observations and predictions of QCD. In this lectures we shall make use mostly of UA1 results. Very similar results and analogous conclusions are in general given by the parallel experiment UA2.

As realized very early in the experimentation around the collider a threshold in the transverse energy $E_T = \sum_i E_T^i$ summed over calorimeter cells can be used to trigger on an essentially 100% pure jet sample. The energy flow around the jet axis shows a striking sharp peak on a relatively low background due to other particles. The identification of the jet parameters is therefore very clean.

The energy spectrum covered by jets at the collider greatly exceed the one explored so far with the e^+e^- collider. Invariant masses in excess of 200 GeV have been observed. Also the nature of these jets is different, since the projectiles now are made both of quarks and gluons. In

spite of these differences, however, fragmentation distribution of charged particles appear remarkably similar to the one measured for e^+e^- jets. A significant factor of jet events contain more than two jets. For instance for events with $E_T^{(1)} > 20$ GeV, $E_T^{(2)} > 20$ GeV, about 30% have $E_T^{(3)} > 4$ GeV and $\sim 10\%$ have $E_T^{(3)} > 7$ GeV. The presence of the third jet strongly suggests the gluon events with bremsstrahlung mechanism (roughly α_s times smaller in cross-section) and very similar to the familiar observation at the e^+e^- colliders. Indeed, the acoplanarity distribution for these events is in excellent agreement with QCD predictions which take precisely this effect into account. Appearance of jets at the collider is interpreted as hard scatterings amongst constituents of the proton and the antiproton. Kinematics of this "elementary" process can be derived from the energies and angles of the jets. There are several processes which can concurrently occur, due to the presence of quarks and gluons :

$$\begin{aligned} gg &\rightarrow gg & gq &\rightarrow gq \\ g\bar{q} &\rightarrow g\bar{q} & q\bar{q} &\rightarrow q\bar{q} \\ q\bar{q} &\rightarrow q\bar{q} \end{aligned}$$

Fortunately, in the centre of mass of the parton collision, all processes have almost identical angular distributions. Only cross-sections differ significantly.

2.2. The UA1 detector and the trigger conditions. The UA1 detector has been described in detail elsewhere³⁾, so only the aspects specifically concerned with this study will be presented. The central part of the detector consists of a large cylindrical tracking chamber centered on the collision point, surrounded by a shell of electromagnetic (e.m.) calorimeters and then by the hadronic calorimeter, which also

serves as the return yoke for the 0.7 T dipole magnetic field. There are also tracking chambers and calorimeters in the more forward regions but these were not used in this study. The central detector (CD) and central calorimetry has almost complete geometrical coverage down to 5° to the beam axis. In the variables commonly used for such descriptions, this translates to -3.0 to 3.0 in pseudorapidity ($\eta = -\ln[\tan\theta/2]$, where θ is the polar angle from the beam axis), and nearly 2π coverage in azimuth about the beam axis (ϕ).

The central tracking chamber consists of a 5.8 m long and 2.3 m diameter cylindrical drift chamber. This chamber provides three-dimensional coordinate information, enabling efficient track reconstruction. This, combined with the 0.7 T magnetic field, results in accurate momentum measurement for nearly all charged tracks.

The central calorimetry consists of lead/scintillator sandwich e.m. shower calorimeters surrounded by iron/scintillator sandwich hadronic calorimeters. These calorimeters are highly segmented in order to obtain position information of the energy deposition. Details of the geometry are given in Table 1.

Making use of the knowledge gained from the previous (1981) collider run ")", a localized transverse energy hardware trigger was implemented to select jet-like events for the 1982 run. This trigger required that the transverse energy (E_T) measured within a calorimeter "block" be greater than 15 GeV. A "block" was defined in the central region as two hadron calorimeter units plus the e.m. calorimeter elements in front of them. A "block" in the end-cap region was defined as the hadronic and e.m. elements comprising one quadrant of an end-cap. With this trigger, a data sample of

Table 1

UAl central calorimeters

Calorimeters	Type	Thickness at normal incidence	Rapidity range	Number of cells	Cell size $\Delta\eta \times \Delta\phi$ (approx.)	Comments
Gondolas	Electromag.	$26.4 X_0/1.1 \lambda$	$ \eta < 1.5$	48	$0.11 \times 180^\circ$	Azimuth from light attenuation
C's	Hadronic	5.0λ	$ \eta < 1.5$	232	$0.30 \times 15^\circ$	
Bouchons	Electromag.	$27.0 X_0/1.2 \lambda$	$1.5 \leq \eta < 3$	64	$1.5 \times 11^\circ$	Rapidity from position detector
I's	Hadronic	7.1λ	$1.5 \leq \eta < 3$	128	$0.40 \times 15^\circ$	

(X_0 are radiation lengths, λ absorption lengths).

$\int L dt = 14 \text{ nb}^{-1}$ was obtained in the 1982 collider run, which constitutes the sample used for the jet studies reported in this paper. In the 1983 run, approximately 118 nb^{-1} of data were collected. Only the inclusive jet cross-section will include results from the 1983 data sample.

2.3. Definition of jets. Jets are defined as clusters in pseudorapidity/azimuth (η/ϕ) space by the following procedure⁴⁾. An energy vector is associated to each calorimeter cell. For hadronic cells, the vector points from the interaction vertex to the centre of the cell. For electromagnetic cells, the vector points to the energy centroid determined by pulse height measurements (Gondolas) or by position detectors (Bouchons).

In the subsequent clustering, cells are treated differently depending on their E_T being above or below 2.5 GeV :

- Among the cells with $E_T \geq 2.5 \text{ GeV}$, the highest E_T cell initiates the first jet. Subsequent cells are considered in order of decreasing E_T . Each cell in turn is added vectorially to the jet closest in (η, ϕ) space, i.e. with the smallest $d \equiv \sqrt{(\Delta\eta)^2 + \delta\phi^2}$ (with ϕ in radians), if $d \leq 1.0$. If there is no jet with $d \leq 1.0$, the cell initiates a new jet.

- Cells with $E_T < 2.5 \text{ GeV}$ are finally added vectorially to the jet nearest in (η, ϕ) if their transverse momentum relative to the jet axis is less than 1 GeV and if they are not further than 45° in direction from the jet axis.

The cut at $d = 1.0$ has been derived from the jet energy profile (see below).

All triggers selected previously were fully reconstructed in the central detector, and calorimeter depositions were corrected using detailed light attenuation maps and an average

response correction factor of 1.13 to allow for the hadronic energy in the electromagnetic calorimeters.⁴⁾ After reconstruction of jets according to the procedure above over the full pseudorapidity range $|\eta| < 3$, an E_T threshold was applied requiring at least one jet with $E_T > 30$ GeV in the Gondola region. This jet is called the trigger jet. A threshold was applied to the fraction of jet energy deposited in the electromagnetic calorimeters ($\geq 10\%$), to discard signals from beam halo in the hadronic calorimeters. This leaves $< 1\%$ of events with a potential halo problem, while reducing the good data sample by $< 2\%$. To avoid edge effects due to the calorimeter geometry, the trigger jet axis has to be contained in $\eta = \pm 1.2$ and in $\phi = \pm 60^\circ$ from the horizontal plane. These cuts ensure good energy containment and minimal particle losses due to the narrow dead zones between the calorimeters in the vertical plane.

To understand possible trigger biases, we used a sample of events taken with a global (i.e. $|\eta| < 1.5$) $\Sigma |E_T| > 20$ GeV trigger and studied the efficiency of jet finding. We found that the localized energy trigger and the selection procedure is $\sim 80\%$ efficient for jets with $E_T = 30$ GeV, and more than 95% efficient for jets with $E_T \geq 35$ GeV.

2.4. Jet axis and jet energy. The above jet finding procedure results in jets with energy and axis defined from calorimeter depositions. It is therefore necessary to discuss the precision of these parameters.

The definition of a jet axis is rather independent of the algorithm used for finding the jet, as it is mostly dependent on large energy depositions in few calorimeter cells. To assess the precision of the jet axis we have simulated in our detector high E_T jets using a Monte Carlo program with

fragmentation according to a cylindrical phase space (CPS) model defined below. The result of this study is that the jet axis given by the jet finding procedure agrees with the vectorial sum of the momenta of fragments from the generated jet to within $\pm 6^\circ$ in ϕ and ± 0.04 in η (rms). This shows that the granularity of our calorimeters does not introduce any appreciable error in the jet axis definition. If using the same jet finding algorithm on the charged tracks given by the central detector, determined with superior angular resolution, one obtains a charged jet axis which coincides with the calorimetric jet axis to within ± 0.1 in η and $\pm 10^\circ$ in ϕ (rms). The difference reflects mostly the fluctuations between the charged and neutral parts of jets, and constitutes a lower limit to the precision of the jet axis definition.

The definition of the jet energy, on the other hand, is directly related to the cutoff parameter d in (η, ϕ) space. We use the energy profile and Monte Carlo studies to obtain better understanding of the jet energy.

Given the axis of a jet, the average values per jet of deposited transverse energy and of charged particle transverse momentum can be studied as function of $\Delta\eta$ and $\Delta\phi$ referred to the jet axis. We restrict ourselves here to the pseudorapidity projection, where the granularity is best. We define an average jet profile by superimposing many jets, leaving out from the average any low-acceptance regions in η or ϕ . The hemisphere opposite to the jet axis in ϕ ($|\Delta\phi| > \pi/2$) is not included. All jets found in our event sample are included, if their transverse energy is at least 20 GeV and if their axis lies within the same (η, ϕ) limits as used for the trigger jet.

The transverse energy flow as a function of $\Delta\eta$ is shown in Fig. 2 (a-c) for three ranges of jet E_T . A clear enhancement is observed on top of a flat energy plateau. The

full width of the enhancement at the base is given by $\Delta\eta = \pm 1.0$, independent of the jet energy (this justifies the cutoff value $d \leq 1.0$ in the jet finding algorithm). We distinguish two distinct regions in the average jet, the hard core of the jet ($|\Delta\eta| < 0.2$), and the wings ($0.2 \leq |\Delta\eta| < 1.0$). The relative amount of transverse energy contained in the core increases with the jet E_T . The E_T content of the wings seems rather independent of the jet E_T . Outside the enhancement, for $|\Delta\eta| > 1.0$, a constant E_T plateau is observed, whose height is independent of the jet E_T . Its value is substantially higher than the one observed for minimum bias events⁵⁾. When the events with more than two jets are excluded the plateau height lies between the values for minimum bias events and for all events. Hence the origin of the plateau is in two distinct phenomena. The first is due to the debris of the beam particles, namely spectator jets. The second one is the production of multijet events, clearly observed in the present data sample. In this case more than one jet can be emitted in the same azimuthal hemisphere, thus increasing the height of the plateau. It should be noted, though, that an absolute measurement of this plateau is difficult : the particles outside the hard core of the jet are mostly of low momentum, and are not measured with good precision due to the non-linear response of the calorimeters at low energy⁶⁾.

We have therefore used the information coming from the central detector for a more quantitative assessment of the jet and plateau composition. The jet profile is now studied with respect to the charged jet axis. Again, particle losses in the small regions of low acceptance in the central detector are corrected for by our averaging procedure. Figs. 2 (d-f) show the mean charged transverse momentum flow in the same slices of jet E_T as before. The same conclusions are reached as for the transverse energy flow. This demonstrates

Fig. 2 (a-c): Transverse energy flow as function of $\Delta\eta$, i.e. pseudorapidity distance from the jet axis, for 3 slices of jet E_T . Cells inside $\Delta\phi=\pm 90^\circ$ are used.

(d-e): Charged transverse momentum flow as function of $\Delta\eta$.

(g-i): Charged multiplicity flow as function of $\Delta\eta$.

in particular that the granularity of our calorimeters does not influence our measurement of the jet width. The distributions also show that calorimetric measurements for energetic jets are not significantly distorted by the magnetic field.

2.5. Multiplicities. The multiplicity flow is obtained by the same averaging procedure as the energy flow, counting tracks reconstructed in the central detector and excluding regions of low acceptance. In Figs. 2 (g-i) the average multiplicity flow of charged tracks around the charged jet axis is shown, again as function of the jet E_T . The multiplicity in the jet increases only slowly with E_T , implying that the leading particles of the jet carry an increasing transverse momentum.

Outside the jet a flat plateau is observed. The mean multiplicity for the plateau depends on the topology of the events. A definite increase in the average multiplicity is observed over the minimum bias level⁷⁾. For pure 2-jet events the rise is 40%, and is almost a factor of 2 when the multijet events are included. A similar increase is observed in the mean p_t per charged particle over the minimum bias value, 14% for 2-jet events and 25% when including the multijet events.

The increase observed in the transverse energy flow plateau over minimum bias events can therefore be attributed to an increase of both the average multiplicity and the mean p_t per particle, due to the multijet production. The precise determination of charged particle multiplicities inside the jet is difficult. It is not possible to separate low-momentum fragments of the jet which contribute sizeably to the jet multiplicity, from the multiplicity background arising from spectator or additional jets, on an event-by-event basis. To estimate losses of low-momentum fragments from the

jet by the jet finding algorithm, we rely upon a fragmentation model and a full Monte Carlo simulation of the detector.

Fig. 3 Transverse energy flow for jets with $E_T > 35 \text{ GeV}$ as function of $\Delta\eta$. Dashed curve: Cylindrical Phase Space model. Full curve: ISAJET model.

2.6. Monte Carlo studies. Two Monte Carlo programs with different hadronization models have been compared with the data. The first one is a naive parton-parton hard scattering model without QCD radiative effects, in which the systems of hard scattered partons and spectator jet fragment independently according to cylindrical phase space (CPS). The mean multiplicity of fragments is obtained as a function of s (square of c.m.s. parton-parton energy) from a phenomenological fit to multiplicity measurements in hadronic events from e^+e^- collisions⁸⁾:

$$\langle n(s) \rangle = 2.0 + 0.027 \exp\{2\sqrt{\ln(s/\Lambda^2)}\} \quad (1)$$

with $\Lambda = 0.3$ GeV.

The second program is ISAJET⁹⁾, which incorporates QCD radiated gluons in the final state. The fragmentation model used for the spectators is ISAJET tuned to reproduce minimum bias events. For both models, generated particles are tracked through the magnetic field and the showers in the calorimeters are simulated¹⁰⁾. In Fig. 3 the experimental transverse energy flow for jets with $E_T > 35$ GeV is compared to the Monte Carlo results. ISAJET gives a better description of the jet shape than CPS: Both programs fail to reproduce the plateau region as they do not include a complete multijet production, in particular through initial state bremsstrahlung. The charged multiplicity flow is shown in Fig. 4, again for jets with $E_T > 35$ GeV. The multiplicity given by ISAJET is low and coincides with the minimum bias level. CPS gives a good overall description of the multiplicity flow.

To measure charged jet multiplicities, we sum up average track multiplicities in the window $\Delta\eta = \pm 1$, apply a flat background subtraction obtained from the region $1 \leq |\Delta\eta| < 2$, and correct for the loss of jet-associated particles outside $\Delta\eta = \pm 1$ according to CPS. As in our

data, low acceptance regions are excluded and corrected for. A further correction is applied for unreconstructed low-momentum particles. The final corrected results on charged track multiplicities in jets are shown in Table 2.

Fig. 4 Charged Multiplicity flow for jets with $E_T > 35$ GeV as function of $\Delta \eta$. Dashed curve: Cylindrical Phase Space model. Full curve: ISAJET model.

Table 2

Jet population used for the present study
after the cuts mentioned in the text
for different $E_T(\text{jet})$ ranges

N(jets)	$E_T(\text{jet})$ range
	(GeV)
853	30-35
323	35-40
195	40-50
64	> 50

It should be noted that ISAJET when tuned to fit the plateau multiplicity results in larger corrections to the multiplicity inside the jet window, as more fragments are generated far from the jet axis. The 10% systematic error in Table 2 is an attempt to account for this model dependence of the correction.

Using the multiplicity extrapolation (1) from e^+e^- for our energy range would also result in higher multiplicities, of the order of 9.0 charged particles for a jet of 25 GeV. A more detailed comparison with e^+e^- jets can be found in the discussion of jet fragmentation.

2.7. Jet cross-sections. To measure the inclusive jet yield, all events are selected as above, imposing additional constraints on the vertex position (± 40 cm from the detector's centre, for a measured rms spread of ± 12 cm) and on the jet axes (± 1 in pseudorapidity, $\pm 60^\circ$ in ϕ

from the horizontal plane). All jets with $E_T > 35$ GeV are considered. Events containing jets with transverse energy above 55 GeV were, in addition, inspected visually on a MEGATEK 3-dimensional display, and a small number of badly reconstructed or background events were rejected, typically events in which cosmic showers or beam halo overlap with collisions.

The inclusive E_T distribution thus obtained is further corrected for geometrical acceptance, experimental procedure and detector resolution using a Monte Carlo method. Jets are simulated using the models discussed above. The comparison between the reconstructed E_T spectrum and the Monte Carlo input results in a correction factor for each bin of E_T . The global correction is not strongly dependent on E_T and does not exceed a factor 1.25. The inclusive cross-section $d\sigma/dE_T d\eta$ obtained after correction is shown in Fig. 5, together with the data from 1981 published in Ref. 4. In the small region of overlap the measurements agree. All errors shown are purely statistical. The following systematic errors are not included :

- The uncertainty of the absolute luminosity ($\pm 15\%$) ;
- Uncertainties in geometrical acceptance due to the choice of the fiducial region, of the jet finding algorithm and of the fragmentation model used in the Monte Carlo programs ($\pm 5\%$) ;
- An uncertainty in the jet energy which for a given event varies when changing the angular aperture in the jet finding algorithm. This translates into a $\pm 20\%$ uncertainty in cross-section ;
- The dependence of the jet acceptance and jet finding efficiency on the production and fragmentation models used in the Monte Carlo programs ($\pm 20\%$) ;
- The uncertainty arising from the definition of the

energy scale : the absolute energy calibration is known to $\pm 5\%$;

Fig. 5 Inclusive Jet cross section $d\sigma/dE_T d\eta$ ($\eta=0$) as function of E_T . 1981 data (x) and 1982 data (+). The hatched band corresponds to possible QCD predictions [15].

- The additional uncertainty in energy scale due to the poorly known particle composition of jets : electromagnetic and hadronic calorimeters exhibit a different response to electromagnetic particles and hadrons, and this response difference is strongly dependent on the particle momenta for $p < 5 \text{ GeV}^6$). The uncertainty in the average response correction used is estimated at $\pm 5\%$. We combine these energy effects into an overall error of $\pm 7.5\%$ of the energy scale, which translates into an uncertainty of a factor 1.5 in the cross-section.

Our overall systematic uncertainty in the cross-section can therefore be given as a factor of 1.65, essentially independent of the jet transverse energy. The measured cross-section is compared in the figure to a band of QCD predictions with a width corresponding to uncertainties in the theory¹¹⁾. Note that QCD predicts transverse momentum distributions for partons, while our measurements refer to the sum of the jet fragment momenta. Despite large experimental and theoretical uncertainties, the agreement observed is excellent. The large increase in jet cross-section from ISR to collider energies, by three orders of magnitude, is thus confirmed. In order to obtain the cross-sections for producing several jets in an event, we now consider, in addition to the trigger jet, all jets with $E_T > 15 \text{ GeV}$ reconstructed with a jet axis inside $|\eta| < 2.5$, again attempting to avoid edge effects and jets that might be faked by spectator background.

In Fig. 6 we show the fraction of events with 1, 2 and 3 jets (trigger jets included) as function of the E_T of the trigger jet. The 2-jet topology dominates over the full range in E_T at a level of $\sim 80\text{--}85\%$. The fraction of 1-jet events becomes negligible at high trigger jet E_T , whereas the fraction of 3-jet events rises in the region of low E_T and levels off at $\sim 15\%$. We should stress that our jet

Fig. 6 Fraction of events with 1,2 and 3 jets of $E_T > 15$ GeV, found by the jet algorithm in a pseudorapidity window $|\eta| < 2.5$, as function of the trigger jet E_T .

finding algorithm, with the window $\Delta\eta = \pm 1$, and the additional requirement $E_T > 15$ GeV, can be expected to have a direct influence on the number of jets found, and that the topological cross-sections as presented here have to be understood in relation to a given jet finding procedure. We also have not corrected these cross-sections in any way for geometrical acceptance.

The occasional presence of a third jet strongly suggests a gluon bremsstrahlung mechanism similar to what has been observed in hadronic e^+e^- events. QCD predicts multijet events due to quark-gluon and gluon-gluon couplings with rates that are proportional to the products of coupling constants appearing in the bremsstrahlung processes of the original parton. 3-jet events would then, for instance, be produced with a cross-section roughly α_s times the cross-section for 2-jet production. The rate of multijet events can be estimated by measuring the differential cross-section in terms of some suitable parameter describing the non-coplanarity. One such parameter is p^{out} , the momentum perpendicular to the plane defined by the trigger jet and the beam momentum. For large enough p^{out} the 3-jet production rate can be calculated perturbatively from QCD^{14),15)} and be compared with the data.

For the study of non-coplanarity we used events with a trigger jet as defined in 2.3. above. In order to minimize any effects coming from problems in jet finding we first calculate p^{out} directly from all E_T -vectors not belonging to the trigger jet. To avoid contamination from the spectator jets we require these E_T -vectors to have $|\eta| < 2.5$. The p^{out} is reconstructed by adding the E_T -vector components perpendicular to the plane defined by the energy axis of the trigger jet and the beam direction, separately on both sides of the plane. If the energies of the jets are balanced, the two $|p^{\text{out}}|$ values should be the same. The difference shows

a width which is consistent with the experimental resolution. We therefore take as p^{out} the average value of $|p^{\text{out}}|_{\text{left}}$ and $|p^{\text{out}}|_{\text{right}}$. The resulting p^{out} distribution is shown in Fig. 7a. This distribution has a contribution from the p_t of the background, i.e. from particles not belonging to the jets, which is difficult to estimate accurately. From the transverse energy flow in minimum bias events one can roughly estimate the contribution to be about 5 GeV. To understand further the size of the background we have repeated the analysis using the jets as found by the jet algorithm. The results are shown in Fig. 7b. One sees that the p^{out} distributions obtained have the same slope but are shifted by about 5 GeV down in p^{out} when compared with the distribution obtained all E_T -vectors. This shift is consistent with the estimate from minimum bias events. In the same figure is also shown the p^{out} distributions obtained from events with two back-to-back jets generated with our CPS Monte Carlo. In this model the partons are strictly coplanar, the non-zero p^{out} comes from the hadronization model and the resolution of the apparatus. It is clear from the figure that this 2-jet model cannot reproduce the observed large p^{out} tail.

Instead the distribution obtained from a complete QCD calculation for 3-jet production¹²⁾ as shown in Fig. 7b agrees much better with the data. The band reflects again the theoretical uncertainties, which are of the same origin as for the inclusive jet cross-section. Note that the QCD calculation is for partons, i.e. there is no broadening due to fragmentation and no background from spectator partons either. We conclude from our study that we observe multijet events with a rate that is roughly consistent with the expectation from QCD.

Fig. 7 p^{out} distribution from calorimeter cells (a) and from jets (b), compared to a 2-jet model and to a perturbative QCD 3-jet calculation [16].

2.8. Studies on jet fragmentation in charged particles. So far the jets are found by using exclusively the information coming from the electromagnetic and hadronic calorimeters, via

the clustering method explained above and in Refs. 4,14,18. The axis and the total energy of the jet are known from the vectorial sum of all its cell energy vectors. Charged particles are then associated with a particular jet, provided they are confined inside a cone centered around the jet axis. The jet axis and directions of charged particles show obvious correlation up to an angle of 35° , as shown in Fig. 8. The half aperture of the cone is then fixed to that value. The dashed curve is an estimate of the background of the beam fragments (spectators) not associated with the jet, by a simple Monte Carlo where the particles are generated uncorrelated according to a cylindrical phase-space model.

Owing to the fixed opening angle of the cone, only the central region of the calorimeters is used. This region extends from -1.5 to $+1.5$ in pseudorapidity η . To minimize edge effects, we restrict the jet-axis direction to be contained in $-1.25 \leq \eta \leq 1.25$. In order to consider only charged particles pointing to the central calorimeter cells, and consequently depositing their energy in those cells, the pseudorapidity range of charged particles is within the limits $-1.5 \leq \eta \leq +1.5$. If the jet axis is close to its pseudorapidity limit of 1.25 , charged particles can be emitted in the region $|\eta| > 1.5$. The loss of particles due to this situation is small, of the order of 7%.

Because of the horizontal orientation of the magnetic field and the presence of gaps between the two halves of the calorimeters in the vertical plane, the azimuthal angle about the beam line of the jet axis is restricted to lie within four sectors of a 15° half opening angle centered on $\pm 45^\circ$ axes. This restriction in solid angle does not affect any result of the present fragmentation study, as everything is normalized to the final jet population obtained after the above-mentioned cuts.

A loss of 13% is estimated for charged particles emitted

outside the sectors. Including the rapidity acceptance, the overall geometrical acceptance is, then, of the order of 80%. A systematic uncertainty of 10% has been added to the statistical errors. No correction has been introduced for track-finding efficiency within jets. However, visual scanning of a reduced population of events did not show any evidence of unfitted straight tracks. The percentage of tracks giving an ionization larger than 1.7 times that of minimum ionizing particles has been measured in the central drift chamber volumes. The small percentage observed, 4.5%, is compatible with the tail of the dE/dx distribution. We deduce that no undetected multi-tracks are contained in the data sample. A small fraction of the tracks within the 35° cone ($< 5\%$) has been discarded because of non-association with the main vertex of the interaction. After the acceptance cuts listed above, the jet population used for the present analysis is given in table 2.

2.9. Jet fragmentation function. The inclusive variable used for the jet fragmentation study has been chosen to be :

$$z = p_L^{\pm}(\text{jet axis})/E(\text{jet}), \quad 0 \leq z \leq 1,$$

where $p_L^{\pm}(\text{jet axis})$ is the momentum of the charged particle projected on the jet axis. The energy of the jet, $E(\text{jet})$, is defined as the modulus of the vectorial sum of all energy cell vectors belonging to the jet.

The distribution of the variable z - the fragmentation function - is defined as :

$$D(z) = (1/N_{\text{jets}})(dN_{\text{ch}}/dz)$$

The integral of $D(z)$ is then the mean charged multiplicity contained in the jet :

$$N_{ch}(jet) = \int_0^1 D(z) dz$$

Several corrections have been applied to $D(z)$. These are discussed below.

The form of the background below $D(z)$ is obtained in the control region $52.5^\circ \leq \theta \leq 70^\circ$, where θ is the spatial angle between the jet axis and the charged particles. Background normalization is given by the Monte Carlo prediction of the number of particles uncorrelated with the jet for $\theta < 35^\circ$ (dashed curve in Fig. 8).

For relatively high z 's, all the charged particles are contained in the 35° cone around the jet axis. At low values of z this is no longer true. Many soft particles are emitted at large angles. In particular, below 0.02 the emission of particles looks so isotropic that the correlation of the particles with the jet is no longer obvious. Loss of jet particles emitted outside the cone varies from 35% for z between 0.02 and 0.03, to 5% for z around 0.07.

The jets we are dealing with in this paper are very energetic ; they have a total energy above 30 GeV. Associated charged particles with a high z value (therefore a high momentum) have then a large momentum uncertainty. The smearing in z which creates an important deformation of $D(z)$ for values above 0.7 has been removed from the data, assuming an exponential law for $D(z)$ at large z .

Monte Carlo studies with full calorimeter reconstruction indicate that the uncertainty in the measurement of the jet energy is more or less constant between 30 and 50 GeV, and is of the order of 15%. Five percent of the resolution comes strictly from cell association of the jet cluster algorithm, the rest of it being due to the finite resolution and granularity of the calorimeters. No correction has been applied to the data in order to take into account the jet energy smearing.

Fig. 8 Distribution of the spatial angle between the jet axis as given by the calorimeters and the directions of charged particles. Arrows indicate the 35° cut. The dashed line is the result of a Monte Carlo assuming no correlation between jet axes and charged particles.

Figure 9 shows the plot for $D(z)$ with $z > 0.02$. This distribution falls rapidly with z at low z values. At higher z values its form is approximately exponential.

We can compare the shape and the normalization of $D(z)$ for the present experiment with $(1/\sigma_{\text{tot}}) \times (d\sigma/dx_L)$

Fig. 9 Charged-Particle fragmentation function for $E_T(\text{jet}) > 30 \text{ GeV}$, compared with similar results from the TASSO detector at PETRA at $W = 34 \text{ GeV}$.

obtained by the TASSO Collaboration for jet energies of 17 GeV, where $x_L = p_L^\pm / p_{\text{beam}}$, and $p_L^\pm$ is the momentum of the charged particles projected on the jet axis whose direction is determined from minimizing the sphericity of the e^+e^- events⁸⁾. The energies of the jets are of course different for both cases. However, the comparison is meaningful because scaling violations in e^+e^- annihilations are known to be small¹³⁾. No striking differences can be observed between these two sets of data, as can be seen in Fig. 9. This means that quark-dominated and gluon-dominated fragmentation functions are, on the whole, not different from each other, at least for values of $z > 0.02$.

Within our own data we can look for possible variations of $D(z)$ as a function of the transverse energy of the jet. After background subtractions and corrections, $D(z)$ is plotted in Fig. 10 for three E_T bands : 30-35 GeV, 40-45 GeV, and > 50 GeV ; $D(z)$ is approximately independent of the jet energy. A possible tendency for $D(z)$ to shrink at low z with increasing $E_T(\text{jet})$ cannot be excluded. This is not observed in the high- z region, probably on account of the very large uncertainties in the data introduced by the track momentum smearing, which are difficult to remove entirely owing to the lack of statistics¹⁴⁾.

2.10. Transverse momentum with respect to the jet axis. The jet axis given by the calorimeters is not precise enough for studying the transverse momentum p_t of the charged particles with respect to the jet axis. For this reason it is replaced by a charged jet axis whose direction is given by the vectorial sum of all charged-particle momenta. The charged particles used to define this axis are inside the cone of 35° half aperture around the calorimeter jet axis. Of course, the charged jet axis is correct only if we assume that the charged and neutral axes are aligned evenly. If this

Fig. 10 Charged-particle fragmentation functions for $E_T(\text{jet}) = 30\text{--}35 \text{ GeV}$, $40\text{--}50 \text{ GeV}$, and $> 50 \text{ GeV}$.

assumption is not valid on an event-by-event basis, it is probably true statistically.

As we have seen before, the association of particles with the jet is questionable at lower z values. For this reason a cut $z > 0.1$ is applied to select particles unambiguously associated with the jet. Owing to the "seagull effect" discussed below (Fig. 11), this cut will result in a higher

Fig. 11 Variation of $\langle p_T \rangle$ with respect to the jet axis for charged particles as a function of z . Errors are due to statistics only.

mean p_t within the jet, compared with a mean p_t value obtained for all particles belonging to the jet regardless of their z value. For all jets with $E_T > 30 \text{ GeV}$, the

variation in the average transverse momentum of charged particles measured with respect to the jet axis is plotted in Fig. 11 as a function of z . A "seagull effect" is observed, showing the increase of $\langle p_t \rangle$ from a value of 0.5 GeV/c at a z value around 0.1 to a value approaching 1 GeV/c for z values above 0.5.

The invariant p_t spectrum, $(1/p_t)(dN/dp_t)$, is shown in Fig. 12 together with the results of a fit :

$$(1/p_t)(dN/dp_t) = A/(p_t + p_{t_0})^n$$

for all jets with $E_T > 30$ GeV. The above function was shown to reproduce well the p_t spectrum of charged particles in minimum bias events¹⁵⁾. The p_t spectrum is well fitted by the values $p_{t_0} = 4$ GeV/c, $n = 14.8$. The observed mean p_t value internal to the jet is $\langle p_t \rangle = 600$ MeV/c, after having applied the cut $z > 0.1$ on all particles. A large p_t tail is observed up to $p_t = 4$ GeV/c. This tail could well be an indication of gluon bremsstrahlung. On the other hand, it could also be due to an experimental misalignment of the jet axis, or to events whose leading particles are neutrals.

Evolution of the mean p_t within the jet has been studied for the following regions of $E_T(\text{jet})$: 30-35, 40-50, and > 50 GeV. Fig. 13 shows the p_t spectrum obtained for each of these transverse energy bands. The mean p_t increases from 600 MeV/c at $E_T = 30$ GeV to 700 MeV/c for $E_T > 50$ GeV.

Fig. 12 $(1/p_T)(dN/dp_T)$ spectrum (p_T with respect to the jet axis) for charged particles with $z > 0.1$. The solid line is the result of a fit $1/p_T + p_T)^N$ with $p_{T0} = 4.0 \text{ GeV/c}$, $N = 14.8$.

Fig. 13 $(1/p_T)(dN/dp_T)$ spectra (p_T with respect to the jet axis) for charged particles with $z > 0.1$ and for three ranges of $E_T(\text{jet}) = 30\text{--}35 \text{ GeV}$, $40\text{--}50 \text{ GeV}$, and $> 50 \text{ GeV}$.

2.11. Structure functions. So far nucleon structure functions were the exclusive domain of lepton-hadron scattering experiments. The observation of well defined two-jet events in proton-antiproton collisions at high energy opens up the possibility of proton structure function measurements at values of four-momentum transfer squared (Q^2) in excess of 2000 GeV^2 , far higher than previously accessible using lepton beams. In the parton model two-jet events result when an incoming parton from the antiproton and incoming parton from the proton interact with each other to produce two outgoing high transverse momentum partons which are observed as jets.

If $d\sigma/d\cos\theta$ is the differential cross-section for a particular parton-parton subprocess as a function of the c.m.s. scattering angle θ , the corresponding contribution to the two-jet cross-section may be written :

$$d^3\sigma/dx_1 dx_2 d\cos\theta = [F(x_1)/x_1][F(x_2)/x_2] d\sigma/d\cos\theta \quad (1)$$

where $[F(x_1)/x_1][F(x_2)/x_2]$ is a structure function representing the number density of the appropriate partons in the antiproton [proton] as a function of the scaled longitudinal momentum $x_1[x_2]$ of the partons.

The differential cross-sections for the possible subprocesses have been calculated to leading order in QCD¹⁶⁾. The elastic scattering subprocesses [gluon-gluon, gluon-quark(antiquark) and quark(antiquark)-quark(antiquark)] have a similar angular dependence and become large as $\cos\theta \rightarrow 1$ [like $(1-\cos\theta)^{-2}$] as a consequence of vector gluon exchange. In the approximation that the elastic subprocesses dominate and have a common angular dependence, the total two-jet cross-section may be written¹⁷⁾ in the form of eq. (1). In particular, if $d\sigma/d\cos\theta$ is taken to be the differential cross-section for gluon-gluon elastic scattering :

$$d\sigma/d\cos\theta = (9/8)[\pi\alpha_s^2/2x_1x_2s](3+\cos^2\theta)^3(1-\cos^2\theta)^{-2} \quad (2)$$

where α_s is the QCD coupling constant and s is the total c.m.s. energy squared, then the structure function $F(x)$ becomes :

$$F(x) = G(x) + (4/9)[Q(x) + Q(x)] \quad (3)$$

where $G(x)$, $Q(x)$, and $Q(x)$ are respectively the gluon, quark, and antiquark structure functions of the proton. In eq. (3) the factor 4/9 reflects the relative strengths of the quark-gluon and gluon-gluon couplings predicted by QCD.

The experimental angular distribution of jet pairs produced in $\bar{p}p$ collisions is analysed as a test of vector gluon exchange and results are presented on the structure function $F(x)$ defined by eqs. (1)-(3).

A set of Monte Carlo events¹⁰⁾ generated using ISAJET⁹⁾ has been analysed in parallel with the real data. Isajet generates two jet events and simulates the fragmentation of each jet into hadrons including the effects of QCD bremsstrahlung. The Monte Carlo program simulates in detail the subsequent behaviour of the hadrons in the UA1 apparatus. The Monte Carlo events are used to calculate various corrections which are discussed below, and to estimate the jet energy resolution and the uncertainty in the determination of the jet direction.

After full calorimeter reconstruction jets are defined using the UA1 jet algorithm¹⁸⁾. The energy and momentum of each jet is computed by taking respectively the scalar and vector sum over the associated calorimeter cells. A correction is applied to the measured energy ($\sim +10\%$) and momentum ($\sim +6\%$) of each jet, as a function of the pseudorapidity and azimuth for the jet, on the basis of the Monte Carlo analysis, to account for the effect of

uninstrumented material and containment losses.

After jet finding, events are selected with ≥ 2 jets, within the acceptance of the central calorimetry $|\eta| < 3$. While the majority of these events have a topology consistent with two balanced high E_T jets, some 10-15% of the events have additional jets with $E_T > 15 \text{ GeV}^{18)$. A preceding analysis has shown that multijet events are largely accounted for in terms of initial-and final-state bremsstrahlung processes¹⁹⁾. For this analysis, in order to compare with theoretical expectations for the two-jet cross-section, additional jets, apart from the two highest E_T jets, are ignored. The r.m.s. transverse momentum of the two-jet system (taking account of resolution) is then $\sim 10 \text{ GeV}$. A further correction is then applied, on the basis of the Monte Carlo analysis, to the energy ($\sim +12\%$) and momentum ($\sim +7\%$) of the two highest E_T jets in order to account for final state radiation falling outside the jet, as defined by the jet algorithm. After all corrections, averaged over the full acceptance, the jet energy resolution $\delta E/E \sim \pm 26\%$ and the uncertainty in the jet direction (in pseudorapidity) $\delta \eta \sim \pm 0.05$.

For each event the x_1 and x_2 of the interacting partons are computed as follows :

$$x_1 = [x_F + \sqrt{(x_F^2 + 4\tau)}]/2 \quad (4)$$

$$x_2 = [-x_F + \sqrt{(x_F^2 + 4\tau)}]/2$$

where

$$x_F = (p_{3L} + p_{4L})/(\sqrt{s}/2) \quad (5)$$

$$\tau = (p_3 + p_4)^2/s$$

In eq. (6), p_3 and p_4 are the 4-momenta of the final two jets and p_{3L} and p_{4L} are the longitudinal momentum

components measured along the beam direction in the laboratory frame.

The c.m.s. scattering angle is computed in the rest frame of the final two jets $[(p_3 + p_4)]$ relative to the axis defined by the interacting partons $[(p_1 - p_2)]$ assumed massless and collinear with the beams²⁰⁾:

$$\cos\theta = (p_3 - p_4) \cdot (p_1 - p_2) / (|p_3 - p_4| |p_1 - p_2|). \quad (6)$$

The finite angular acceptance of the apparatus and the trigger E_T threshold requirement discriminates against events with small scattering angles (i.e. large $\cos\theta$), and restricts the range of $\cos\theta$ over which the trigger is fully efficient. Events which are close to the limits of the acceptance in $\cos\theta$ are rejected by applying a fiducial cut in $\cos\theta$. This fiducial cut ($\cos\theta_{\max}$) is defined for each event as the maximum value of $\cos\theta$ for which both the final two jets would fall in the acceptance region $|\eta| < 2.5$ (with at least one jet having $|\eta| < 1.0$) and for which the mean of the transverse energies of the final two jets would exceed (20)35 GeV [in the (un)filtered data set]. Events with azimuthal angle ϕ (defined by the final two jets) within $\pm 45^\circ$ of the vertical, where the two halves of the calorimeter are joined, are also rejected. The final event sample consists of 2432 events satisfying the above cuts, for which the acceptance is essentially uniform.

Figures 14 a-d show the raw histograms in $|\cos\theta|$ for various x_1, x_2 intervals. In each case a cut has been applied on $\cos\theta_{\max}$ as indicated. The curve, which has been normalized to the number of events in each histogram, shows the expected angular dependence [eq. (2)] assuming vector gluon exchange (QCD). The data are consistent with the curve independent of x_1, x_2 in accordance with eq. (2).

Figure 15 shows the angular distribution obtained using

Fig. 14 a-d) Histograms in $\cos \theta$ for various x_1 , x_2 intervals. A cut on $\cos \theta_{\max}$ has been applied as indicated. The curve, which has been normalized to the number of events in each histogram, is the expected angular dependence [eq. (2)] assuming vector gluon exchange (QCD).

all the events in the sample, on the assumption that the angular dependence is independent of x_1 and x_2 . The distribution is computed starting from the raw distributions in $\cos\theta$, classified in intervals of $\cos\theta_{\max}(\Delta \cos\theta_{\max} = 0.1)$, normalizing one distribution to another in the region of overlap. The final distribution is divided by the number of events with $\cos\theta < 0.1$ to obtain $(d\sigma/d\cos\theta)(d\sigma/d\cos\theta)_{\cos\theta=0}$. Monte Carlo studies demonstrate that, for the range of $\cos\theta$ shown, the angular distribution is not appreciably modified by the effects of resolution smearing. In Fig. 15 the data are compared with theoretical forms for gluon-gluon, gluon-quark(antiquark)-quark(antiquark) elastic scattering in QCD (i.e. assuming vector gluon exchange). Theoretical forms for quark(antiquark)-(quark(antiquark) and gluon-quark(antiquark) scattering in an Abelian scalar gluon theory²¹⁾ are also shown. The data are clearly consistent with the predictions of the vector gluon theory (QCD) and the Abelian scalar gluon theory is excluded. The data are not yet sufficiently accurate, however, to discriminate between the various subprocesses. A fit to the data of the form $(1-\cos\theta)^{-n}$ for $\cos\theta > 0.4$ yields $n=2.08 \pm 0.10$. This result is consistent with $n=2$ and, in analogy with the case of Rutherford scattering at low energy, may be regarded as a test of the inverse square law for the interaction between the partons.

In order to extract the structure function $F(x)$ [eq. (3)] the quantity $S(x_1, x_2)$ is defined in terms of the measured differential cross-section $d^2\sigma/dx_1 dx_2$ as follows :

$$S(x_1, x_2) = x_1 x_2 (d^2\sigma/dx_1 dx_2) / \int_0^{\cos\theta_{\max}} K(d\sigma/d\cos\theta) d\cos\theta. \quad (7)$$

If eq. (1) is valid then : $S(x_1, x_2) = F(x_1)F(x_2) \cdot S(x_1, x_2)$

Fig. 15 The angular distribution obtained using all the events in the sample on the assumption that the angular dependence is independent of x_1 and x_2 . The data are compared with theoretical forms for parton-parton elastic scattering in QCD and in an Abelian scalar gluon theory [9].

is determined from the data by weighting the events individually as a function of x_1, x_2 , and $\cos\theta_{\max}$. The parton-parton differential cross-section $d\sigma/d\cos\theta$ is taken from eq. (2) with $\alpha_s = 12\pi/[23 \ln(Q^2/\Lambda^2)]$, i.e. assuming five effective quark flavours and $\Lambda = 0.2$ GeV. For this analysis Q^2 is defined by $Q^2 = -t$, where $t = (p_1 - p_3)^2$ [or $t = (p_1 - p_4)^2$, whichever is numerically smaller] in analogy with deep inelastic scattering. A factor K has been introduced in eq. (7) to allow for the effect of higher order QCD corrections, which may change the effective Q^2 scale and hence the normalization of the parton-parton cross-section. These corrections have been computed theoretically^{22), 23)}, and are expected to be appreciable even at the energy of the SPS Collider. The results given below have been computed assuming $K = 2$.

The experimental results for $S(x_1, x_2)$ are tabulated in Table 3. The data are symmetric in x_1 and x_2 and have been folded appropriately. The raw event numbers in each bin are given. The data for $\sqrt{\tau} < 0.2$ are based entirely on the unfiltered data set. The data have been corrected for the effects of resolution smearing. This correction varies from - 24% at small x to - 70% at the largest x values. The quoted errors are statistical only : the systematic error affecting mainly the overall normalization is $\sim \pm 65\%$, due largely to the uncertainty in the jet energy scale. If factorization holds then $S(x_1, x'_2)/S(x_1, x_2)$ will be independent of x_1 for any choice of x_2 and x'_2 . This ratio is plotted in Fig. 16a for $x_2 = 0.1-0.2$, $x'_2 = 0.05-0.1$ and in Fig. 16b for $x_2 = 0.1-0.2$, $x'_2 = 0.2-0.3$. Since the data are symmetric in x_1 and x_2 the folded data (Table 3) have been used to compute the ratio. In each case the ratio is consistent with a constant (broken line) independent

Table 3

The experimental result for $S(x_1, x_2)$ (see text). The raw event numbers in each x_1, x_2 -bin are also given.

The quoted errors are statistical only: the systematic error affecting mainly the overall normalization $\sim \pm 65\%$.

The corresponding results for $F(x)$ are also tabulated, together with the mean value of $-t$ in each bin.

$S(x_1, x_2)$

x_1 or x_2	0.05-0.10	0.10-0.20	0.20-0.30	0.30-0.40	0.40-0.50	0.50-0.60	0.60-0.80
0.05-0.10	-	-	3.053 ± 0.276 (340)	1.224 ± 0.207 (225)	0.449 ± 0.122 (145)	0.298 ± 0.134 (66)	0.064 ± 0.038 (38)
0.10-0.20	-	2.541 ± 0.247 (263)	0.842 ± 0.118 (392)	0.373 ± 0.061 (202)	0.218 ± 0.047 (115)	0.055 ± 0.027 (30)	0.024 ± 0.015 (16)
0.20-0.30	-	-	0.391 ± 0.080 (75)	0.117 ± 0.044 (28)	0.038 ± 0.029 (13)	0.032 ± 0.038 (11)	0.005 ± 0.011 (1)
0.30-0.40	-	-	-	0.042 ± 0.053 (3)	0.022 ± 0.040 (3)	0.009 ± 0.028 (1)	0.000 ± 0.000 (0)

$F(x)$

$F(x)$	5.497 $\pm$ 0.578	1.607 $\pm$ 0.082	0.542 $\pm$ 0.049	0.222 $\pm$ 0.030	0.112 $\pm$ 0.027	0.038 $\pm$ 0.017	0.012 $\pm$ 0.006
$\langle -t \rangle$ GeV ²	1500	2200	3000	4100	4100	4600	5100

Fig. 16 The ratio $S(x_1, x_2')/S(x_1, x_2)$ for a) $x_2 = 0.1-0.2$, $x_2' = 0.05-0.1$ and b) $x_2 = 0.1-0.2$, $x_2' = 0.2-0.3$. In each case the data are consistent with a constant (broken line) independent of x_1 .

of x_1 . The data are therefore consistent with factorization in x_1 and x_2 .

Figure 17 shows the structure function $F(x)$ [eq. (3)] obtained from $S(x_1, s_2)$ assuming factorization in x_1 and x_2 . The results for $F(x)$ are also tabulated in Table 3, together with the mean value of $-t$ in each x -bin. The measured integral of $F(x)$ over the range $x=0.05-0.80$ is 0.53 ± 0.03 . The errors quoted are statistical only. Since the cross-section takes the form of a product of structure functions the errors in the structure function are roughly one half the errors in $S(x_1, x_2)$. In particular, the systematic uncertainty in the overall normalization of the structure function is $\sim \pm 30\%$. Over the range $x=0.1-0.8$, the data show an exponential x dependence and may be parametrized by the form $F(x) \sim 6.2 e^{-9.5x}$ (broken line). Over the same range the data cannot be described by a single term of the form $(1-x)^n$ for any choice of n but may be parametrized as the sum of two such terms e.g. $F(x) \sim 8.0(1-x)^{1.3} + 1.1(1-x)^4$. Changing the assumed value of Λ by a factor of two (up or down) changes the structure function by $\sim \pm 15\%$. Changing the assumed value of the K-factor [eq. (7)] from $K = 2$ to $K = 1$ increases the structure function by a factor of $\sqrt{2}$, i.e. by an amount comparable to the systematic error.

In Fig. 17 the measured $F(x)$ is compared with expectations based on QCD fits to deep inelastic scattering data²⁴⁾. The solid curve represents the structure function $G(x) + (4/9)[Q(x)+Q(x)]$ at $Q^2 = 20 \text{ GeV}^2$ based on a QCD parametrization of CDHS measurements of $G(x)$ and $[Q(x)+Q(x)]$ at low Q^2 ($Q^2 = 2-200 \text{ GeV}^2$) using a neutrino beam on an iron target. The broken curve shows the expected modification of the structure function, at the value of Q^2 appropriate in this experiment, due to QCD scaling violations (assuming $\Lambda = 0.2 \text{ GeV}$). The expected contribution due to

Fig. 17 The structure function of $F(x)$ [eq. (3)]. The errors are statistical only: the systematic error affecting mainly the over-all normalization is $\sim \pm 30\%$. The broken line represents the parametrization $F(x) = 6.2 \cdot 10^{-2} x^{-0.5}$ (see text). The solid curve represents a QCD parametrization of the structure function $G(x) + (4/9)[Q(x) + \bar{Q}(x)]$ at $Q^2 = 20 \text{ GeV}^2$ based on the CDHS [13] measurements at low Q^2 ($Q^2 = 2-200 \text{ GeV}^2$). The broken curves show the expected modification of the structure function at the values of Q^2 appropriate in this experiment. The expected contribution of quarks and antiquarks is shown separately.

the quarks and the antiquarks is shown separately. The two-jet data measure directly, for the first time, the very large flux of gluons in the proton at small x ($x \leq 0.3$) and also demonstrate the existence of QCD scaling violations at large Q^2 relative to the low Q^2 data. The present data suggest somewhat softer parton distributions than would be expected based on the CDHS parametrization.

Finally, our result for the integral of $F(x)$ given above may be reinterpreted to yield information on σ_s and K . Assuming the validity of the parton model momentum sum-rule we have $\int_0^1 F(x) dx \leq 1$, from which we obtain $\alpha_s \sqrt{K} \geq 0.12$ ($\pm 30\%$ systematic error, due to the uncertainty in the energy scale). It is emphasized that this result is independent of the comparison with deep inelastic scattering data.

3. OBSERVATION OF CHARGED INTERMEDIATE VECTOR BOSONS

3.1. Introduction. The observation of the charged intermediate vector boson (IVB) was reported by the UA1 Collaboration in January 1983²⁵⁾ on the basis of the observation of five high energy isolated electrons. These events all exhibited a very large missing energy, interpreted as neutrino emission. The transverse vector momenta of the electron and neutrino share a strong correlation in angle and energy, indicating the same physical origin and are consistent with the assumption of the process :

$$\begin{array}{c} \bar{p}p \rightarrow W^\pm + X \\ \quad \quad \quad \downarrow \\ \quad \quad \quad e^\pm \nu_e \end{array} \quad (1)$$

Since no other background could be formulated they were interpreted as evidence for IVB. Mass values were also given, $m_W = (80 \pm 5) \text{ GeV}/c^2$ (UA1) and $m_W = (80_{-6}^{+10}) \text{ GeV}/c^2$ (UA2).

Since then the CERN sample has been considerably increased :

UA1 ²⁶⁾	53 $W^{\pm} \rightarrow e^{\pm} \nu$ events
	14 $W^{\pm} \rightarrow \mu^{\pm} \nu$ events
UA2 ²⁷⁾	36 $W \rightarrow e \nu$ events
<hr/>	
Total	103 events

Such a comparatively large sample of events can now be used to proceed further in understanding the phenomenon. In particular the assignment the reaction (1) can now be "proven" rather than "postulated".

(i) The transverse decay kinematics is incompatible with emission of two or more neutrinos and it indicates the two body decay ($\nu_e e$). A greatly improved value for the mass is also obtained.

(ii) A subset (80% of the sample) of events from UA1 can be completely reconstructed, the two fold ambiguity for the unmeasured longitudinal momentum of neutrino being removed by the overall calorimetric information from the event. Using the well known relation $x_W = x_p - x_{\bar{p}}$ and $x_p x_{\bar{p}} = m_W^2/s$ we can determine the distribution of the partons participating into the process. One can see that the distributions are in excellent agreement with the assumptions of quarks and antiquarks for the proton and antiproton respectively and exclude "sea" effects and gluons. Therefore the production mechanism is proven to be valence quark-antiquark annihilation.

(iii) A subsample of the fully reconstructed events have the sign of the lepton determined by magnetic curvature. Weak interactions should act as a longitudinal polarizer of the W particles since quarks(antiquarks are provided by the proton(antiproton) beam. Likewise decay angular distributions from a polarizer are expected to have a large

asymmetry, which acts as a polarization analyser. A strong backward-forward asymmetry is therefore expected, in which electrons(positrons) prefer to be emitted in the direction of the proton(antiproton). In order to study this effect independently of W-production mechanism, one has looked at the angular distribution of the emission angle θ^* of the electron(positron) with respect to the proton(antiproton) direction in the W centre of mass. According to expectation of V-A theory the distribution should be of the type $(1+\cos\theta^*)^2$, in excellent agreement with the experimental data. More generally it has been shown by Jacob that for a particle of arbitrary spin J produced with average polarization $\langle\mu\rangle$ and decaying with an asymmetry parameter $\langle\lambda\rangle$ one expects :

$$\langle\cos\theta^*\rangle = \frac{\langle\lambda\rangle\langle\mu\rangle}{J(J+1)}$$

For V-A theory one expects $\langle\lambda\rangle = \langle\mu\rangle = -1$ and $J=1$, leading to the maximal value $\langle\cos\theta^*\rangle = 0.5$. For $J = 0$ one obviously expects $\langle\cos\theta^*\rangle = 0$ and for any other spin value $J > 2$, $\langle\cos\theta^*\rangle \leq 1/6$. Experimentally, we find $\langle\cos\theta^*\rangle = 0.5 \pm 0.1$ close to its maximal value, which supports both the $J=1$ assignment and maximal helicity states at production and decay. Note that the choice of sign $\langle\mu\rangle=\langle\lambda\rangle=\pm 1$ cannot be separated, i.e. right-and left-handed currents at production and decay cannot be resolved without a polarization measurement.

(iv) Finally the production cross-section can be determined: $(\sigma.B)_W = 0.53 \pm 0.08$ (± 0.09) nb, where the last error takes into account systematic errors. This value is in excellent agreement with the expectations of the V-A theory $(\sigma.B)_W = 0.39$ nb.

All these results can be used now to perform the interesting

exercise of deducing classic weak interactions from $W^\pm$ particle observation. Indeed we know that $W^\pm$ must couple to valence quarks at production and to $(e\nu)$ pairs at decay, which implies the existence of the beta decay processes $n \rightarrow p + e^- + \nu_e$ and $(p) + (n) \rightarrow e^+ + \nu_e$. The mass value m_W and the cross-section measurement can be then used to calculate G_F , the Fermi coupling constant. The interaction must be Vector since $J = 1$ and parity is maximally violated since $\langle\mu\rangle = \langle\lambda\rangle = \pm 1$. The only missing element is the separation between $V + A$ and $V - A$ alternatives. For this purpose a polarization measurement is needed. It may be accomplished in the near future by studying for instance the decay $W \rightarrow \tau + \nu_\tau$ and using the τ decay as polarization analyser or producing IVB with longitudinally polarized protons. Isn't this a nice way of teaching weak interactions to young students?

3.2. Event selection for $W \rightarrow e\nu$ decays. Results are based on an integrated luminosity of 0.136 pb^{-1} , which is corrected for dead-time and other similar losses and which includes the exposure for which results have been initially reported²⁵⁾. The trigger selection used throughout the investigation required the presence of an electromagnetic cluster at angles larger than 5° , with transverse energy in excess of 10 GeV. After on-line filtering and complete off-line reconstruction, about 1.5×10^5 events had at least one electromagnetic (e.m.) cluster with $E_T > 15$ GeV. By requiring the presence of an associated, isolated²⁵⁾ track with $p_t > 7$ GeV/c in the central detector, we reduce the sample by a factor of about 100. Next, a maximum energy deposition (leakage) of 600 MeV is allowed in the hadron calorimeter cells after the e.m. counters, leading to a sample of 346 events. We then classify events according to whether there is prominent jet activity.

We find that in 291 events there is a clearly visible jet within an azimuthal angle cone $|\Delta\phi| < 30^\circ$ opposite to the "electron" track. These events are strongly contaminated by jet-jet events in which one jet fakes the electron signature and must be rejected. We are left with 55 events without any jet or with a jet not back-to-back with the "electron" within 30° .

The bulk of these events is characterized by the presence of neutrino emission, signalled by a significant missing energy (see Fig. 18). According to the experimental energy resolutions, at most the three lowest missing energy events are compatible with no neutrino emission. They are excluded by the cut $E_T^{\text{miss}} > 15 \text{ GeV}$. We are then left with 52 events. These events have a very clean electron signature (Figs. 19a-c) and a perfect matching between the point of electron incidence and the centroid in the shower detectors, further supporting the absence of composite overlaps of a charged track and neutral π^0 's expected from jets.

In order to ensure the best accuracy in the electron energy determination, only events in which the electron track hits the electromagnetic detectors more than $\pm 15^\circ$ away from their top and bottom edges have been retained. The sample is then reduced to 43 events.

We have estimated, in detail, the possible sources of background coming from ordinary hadronic interactions with the help of a sample of isolated hadrons at large transverse momenta and we conclude that they are negligible (< 0.5 events). For more details on background we refer the reader to Ref. 25. We may, however, detect some background events from other decays of the W, namely :

$$W \rightarrow \tau \nu \quad (< 0.5 \text{ events})$$

$$\quad \quad \quad \left| \begin{array}{l} \tau_{\pm}^0 \\ \rightarrow \pi^0 (\pi^0) \nu_{\tau} \end{array} \right.$$

Fig.18 The distribution of the missing transverse energy for those events in which there is a single electron with $E_T > 15$ GeV, and no co-planar jet activity. The curve represents the resolution function for no missing energy normalized to the three lowest missing-energy events.

or

$$W \rightarrow \begin{array}{c} \tau \nu_\tau \\ | \\ e \nu_e \nu_\tau \end{array}$$

(= 2 events)

Fig. 19 Distributions showing the quality of the electron signature:

- a) The energy deposition in the hadron calorimeter cells behind the 27 radiation lengths (r.l.) of the e.m. shower detector.
- b) The fraction of the electron energy deposited in the fourth sampling (6 r.l. deep, after 18 r.l. converter) of the e.m. shower detector. The curve is the expected distribution from test-beam data.

These events are expected to contribute only at the low p_t part of the electron spectrum and they can be eliminated in a more restrictive sample.

3.3. Origin of the electron-neutrino events. We proceed to a detailed investigation of the events in order to elucidate their physical origin. The large missing energy observed in all events is interpreted as being due to the emission of one or of several non-interacting neutrinos. A very strong correlation in angle and energy is observed (in the plane normal to the colliding beams, where it can be determined accurately), with the corresponding electron quantities, in a characteristic back-to-back configuration expected from the decay of a massive, slow particle (Figs. 20a and b). This suggests a common physical origin for the electron and for one or several neutrinos. In order to understand better the transverse motion of the electron-neutrino(s) system one can study the experimental distribution of the resultant transverse momentum $p_t^{(W)}$ obtained by adding neutrino(s) and electron momenta (Fig. 21). The average value is $p_t^{(W)} = 6.3 \text{ GeV}/c$. Five events which have a visible jet have also the highest values of $p_t^{(W)}$. Transverse momentum balance can be almost exactly restored if the vector momentum of the jet is added. The experimental distribution is in good agreement with the many theoretical expectations from QCD for the production of a massive state via the Drell-Yan quark-antiquark annihilation²⁸⁾. The small fraction (10%) of events with a jet are then explained as hard gluon bremsstrahlung in the initial state²⁹⁾.

Several different hypotheses on the physical origin of the events can be tested by looking at kinematical quantities constructed from the transverse variables of the electron and the neutrino(s). We retain here two possibilities, namely (i) the two-body decay of a massive particle into the electron and

Fig. 20 a) Two-dimensional plot of the transverse components of the missing energy (neutrino momentum). Events have been rotated to bring the electron direction pointing along the vertical axis. The striking back-to-back configuration of the electron-neutrino system is apparent.

Fig. 20 b) Correlation between the electron and neutrino transverse energies. The neutrino component along the electron direction is plotted against the electron transverse energy.

one neutrino, $W \rightarrow e \nu_e$; and (ii) the three-body decay into two, or possibly more, neutrinos and the electron. One can see from Figs. 5a and b that hypothesis (i) is strongly favoured. At this stage, the experiment cannot distinguish between one or several closely spaced massive states.

Fig. 21 The transverse momentum distribution of the W derived from our events using the electron and missing transverse-energy vectors. The highest $p_T^{(W)}$ events have a visible jet (shown in black in the figure). The data are compared with the theoretical predictions of Halzen et al. for W production (a) without $[O(\alpha_s)]$ and (b) with QCD smearing; and predictions by (c) Aurenche et al., and (d) Nakamura et al. (see ref. 4).

3.4. Determination of the invariant mass of the $(e\nu_e)$ system. A (common) value of the mass m_W can be extracted from the data in a number of ways, namely :

i) It can be obtained from the inclusive transverse-momentum distribution of the electrons (Fig. 22a). The drawback of this technique is that the transverse momentum of the W particle must be known. Taking the QCD predictions^{2,8)}, in reasonable agreement with experiment, we obtain $m_W = (80.5 \pm 0.5) \text{ GeV}/c^2$.

ii) We can define a transverse mass variable, $m_T^2 = 2p_t^{(e)} p_t^{(\nu)} (1 - \cos\phi)$, with the property $m_T \leq m_W$, where the equality holds only for events with no longitudinal momentum components. Fitting Fig. 22b to a common value of the mass can be done almost independently of the transverse motion of the W particles, $m_W = (80.3_{-1.3}^{+0.4}) \text{ GeV}/c^2$. It should be noted that the lower part of the distribution in $m_T^{(W)}$ may be slightly affected by $W \rightarrow \tau\nu_\tau$ decays and other backgrounds.

iii) We can define an enhanced transverse mass distribution, selecting only events in which the decay kinematics is largely dominated by the transverse variable with the simple cuts $p_t^{(e)}, p_t^{(\nu)} > 30 \text{ GeV}/c$. The resultant distribution (Fig. 22c) shows then a relatively narrow peak, at approximately $76 \text{ GeV}/c^2$. Model-dependent corrections contribute now only to the difference between this average mass value and the fitted m_W value, $m_W = (80.0 \pm 1.5) \text{ GeV}/c^2$. An interesting upper limit to the width of the W can also be derived from the distribution, namely $\Gamma_T \leq 7 \text{ GeV}/c^2$ (90% confidence level).

The three mass determinations give very similar results. We prefer to retain the result of method (iii), since we believe it is the least affected by systematic effects, even if it gives the largest statistical error. Two important contributions must be added to the statistical errors :

Fig. 22 a) The electron transverse-energy distribution. The two curves show the results of a fit of the enhanced transverse mass distribution to the hypothesis $W \rightarrow e\nu$ and $X \rightarrow e\nu\nu$. The first hypothesis is clearly preferred.

Fig. 22 b) The distribution of the transverse mass derived from the measured electron and neutrino vectors. The two curves show the results of a fit to the hypothesis $W \rightarrow e\nu$ and $X \rightarrow e\nu\nu$.

i) Counter-to-counter energy calibration differences. They can be estimated indirectly from calibrations of several units in a beam of electrons; or, and more reliably, by comparing the average energy deposited by minimum bias events recorded periodically during the experiment. From these measurements we find that the r.m.s. spread does not exceed 4%. In the determination of the W mass this effect is greatly

Fig. 22 c) The enhanced electron-neutrino transverse-mass distribution (see text). The two curves show the results of a fit to the hypotheses $W \rightarrow e\nu$ and $X \rightarrow e\nu\nu$.

attenuated, to the point of being small compared to statistical errors, since many different counter elements contribute to the event sample.

ii) Calibration of the absolute energy scale. This has been performed using a strong ^{60}Co source in order to transfer test-beam measurements to the counters in the experiment. Several small effects introduce uncertainties in such a procedure, some of which are still under

investigation. At the present stage we quote an overall error of $\pm 3\%$ on the energy scale of the experiment. Of course this uncertainty influences both the $W^\pm$ and Z^0 mass determinations by the same multiplicative correction factor.

3.5. Longitudinal motion of the W particle. Once the decay reaction $W \rightarrow e\nu_e$ has been established, the longitudinal momentum of the electron-neutrino system can be determined with a two-fold ambiguity for the unmeasured longitudinal component of the neutrino momentum. The overall information of the event can be used to establish momentum and energy conservation bounds in order to resolve this ambiguity in 70% of the cases. Most of the remaining events have solutions which are quite close, and the physical conclusions are nearly the same for both solutions. The fractional beam energy x_W carried by the W particle is shown in Fig. 23a and it appears to be in excellent agreement with the hypothesis of W production in $q\bar{q}$ annihilation³⁰⁾. Using the well-known relations $x_W = x_p - x_{\bar{p}}$ and $x_p \cdot x_{\bar{p}} = m_W^2/s$, we can determine the relevant parton distributions in the proton and antiproton. One can see that the distributions are in excellent agreement with the expected x distributions for quarks and antiquarks respectively in the proton and antiproton (Fig. 23b and c). Contributions of the u and d quarks can also be neatly separated, by looking at the charges of produced W events, since $(u\bar{d}) \rightarrow W^+$ and $(\bar{u}d) \rightarrow W^-$ (Figs. 23d and e).

3.6. Effects related to the sign of the electron charge. The momentum of the electron is measured by its curvature in the magnetic field of the central detector. Out of the 52 events, 24 (14) have a negative (positive) charge assignment ; 14 events have a track topology which makes charge determination uncertain. Energy determinations by calorimetry and momentum

Fig. 23 a) The fractional beam energy x_W carried by the W . The curve is the prediction obtained by assuming the W has been produced by qq fusion. Note that in general there are two kinematic solutions for x_W (see text), which are resolved in 70% of the events by consideration of the energy flow in the rest of the event. Where this ambiguity has been resolved the preferred kinematic solution has been the one with the lowest x_W . In the 30% of the events where the ambiguity is not resolved the lowest x_W solution has therefore been chosen.

Fig. 23 b)The x-distribution of the proton quarks producing the W by qq fusion. The curve is the prediction assuming qq fusion.
c)The same as (b) for the antiproton quarks.

Fig. 23 d) The same as Fig. 23b) but for u(u) quarks in the proton (antiproton).
e) The same as Fig. 23b) for for d(d) quarks in the proton (antiproton).

measurements are compared in Fig. 24a, and they are, in general, in quite reasonable agreement with what is expected from isolated high-energy electrons. A closer examination can be performed, looking at the difference between curvature observed and expected from the calorimeter energy determination, normalized to the expected errors (Fig. 24b). One can observe a significant deviation from symmetry (corresponding to $p < E$), which can be well understood once

Fig. 24 a) $1/E$ plotted against Q/p_{CD} where E is the electron energy determined by the calorimeter, p_{CD} the momentum determined from the curvature of the central detector track, and Q the charge of the track.

the presence of radiative losses of the electron track (internal and external bremsstrahlung), is taken into account³¹⁾.

Weak interactions should act as a longitudinal polarizer of the W particles since quarks(antiquarks) are provided by the proton(antiproton) beam. Likewise decay angular distributions from a polarizer are expected to have a large asymmetry, which acts as a polarization analyser. A strong backward-forward asymmetry is therefore expected, in which electrons(positrons) prefer to be emitted in the direction of the proton(antiproton). In order to study this effect

Fig. 24 b) $(1/E - 1/p)$ normalized by the error on the determination of this quantity. The curve is a Monte Carlo calculation, in which radiative losses due to internal and external bremsstrahlung have been folded with the experimental resolution [6].

independently of W-production mechanisms, we have looked at the angular distribution of the emission angle θ^* of the electron(positron) with respect to the proton(antiproton) direction in the W centre of mass. Only events with no

reconstruction ambiguity can be used. It has been verified that this does not bias the distribution in the variable $\cos \theta^*$. According to the expectations of V-A theory the distribution should be of the type $(1 + \cos \theta^*)^2$, in excellent agreement with the experimental data (Fig. 25).

3.7. Determination of the parity violation parameters and of the spin of the W-particle. It has been shown by Jacob³²⁾ that for a particle of arbitrary spin J one expects :

$$\langle \cos \theta^* \rangle = \frac{\langle \lambda \rangle \langle \mu \rangle}{J(J+1)} ,$$

where $\langle \mu \rangle$ and $\langle \lambda \rangle$ are, respectively, the global helicity of the production system (ud) and of the decay system (ev).

The detailed derivation follows closely the paper of reference. Let θ be the angle between the direction of the electron and the spin of the W particle in the rest system of the W-particle. The decay amplitude of W into a ν is proportional to :

$$D_{\mu\lambda}^{J*}(\varphi, \theta, -\varphi)$$

The decay angular distribution is given by :

$$I(\theta, \varphi) = \sum_{\mu\mu'} \rho_{\mu\mu'} \frac{2J+1}{4\pi} \sum_{\lambda_1 \lambda_2} |c_{\lambda_1 \lambda_2}|^2 D_{\mu\lambda}^{J*}(\varphi, \theta, -\varphi) D_{\mu', \lambda}^J(\varphi, \theta, -\varphi)$$

with $\lambda = \lambda_1 - \lambda_2$ and $\rho_{\mu\mu'} = \delta_{\mu\mu'}$,
 p_μ the matrix density for the W in absence of polarization of the p and p beams ; p_μ is the probability that the W is the state of helicity μ .

Combining the two D functions making use of the Clebsch-Gordon series :

Fig. 25 The angular distribution of the electron emission angle θ^* in the rest frame of the W after correction for experimental acceptance. Only those events in which the electron charge is determined and the kinematic ambiguity (see text) has been resolved have been used. The latter requirement has been corrected for in the acceptance calculation.

$$I(\theta, \varphi) = \frac{2J+1}{4\pi} \sum_{\mu} (-1)^{\mu} P_{\mu} \sum_{\lambda_1 \lambda_2} (-1)^{\lambda_1 \lambda_2} |c_{\lambda_1 \lambda_2}|^2$$

$$\sum_{\ell=0}^{2J} c(JJ\ell | \mu - \mu) c(JJ\ell | \lambda - \lambda) P_{\ell}(\cos \theta)$$

We now take the average value of $\cos \theta$. This gives a particularly simple expression :

$$\langle \cos \theta \rangle = \frac{1}{J(J+1)} \left(\sum_{\mu} \mu P_{\mu} \right) \left(\sum_{\lambda_1 \lambda_2} \lambda |c_{\lambda_1 \lambda_2}|^2 \right)$$

The two terms within parenthesis are the average helicities, therefore :

$$\langle \cos \theta \rangle = \frac{\langle \mu \rangle \langle \lambda \rangle}{J(J+1)}$$

For V-A one then has $\langle \lambda \rangle = \langle \mu \rangle = -1$, $J = 1$, leading to the maximal value $\langle \cos \theta^* \rangle = 0.5$. For $J = 0$ one obviously expects $\langle \cos \theta^* \rangle = 0$ and for any other spin value $J \geq 2$, $\langle \cos \theta^* \rangle \leq 1/6$. Experimentally, we find $\langle \cos \theta^* \rangle = 0.5 \pm 0.1$, which supports both the $J = 1$ assignment and maximal helicity states at production and decay. Note that the choice of sign $\langle \mu \rangle = \langle \lambda \rangle = \pm 1$ cannot be separated, i.e. right- and left-handed currents both at production and decay cannot be resolved without a polarization measurement.

3.8. Total cross-section and limits to higher mass W's. The integrated luminosity of the experiment was 136 nb^{-1} and it is known to about $\pm 15\%$ uncertainty. In order to get a clean $W \rightarrow e \nu_e$ sample we select 47 events with $p_t^{(e)} > 20 \text{ GeV/c}$. The $W \rightarrow \tau \nu_{\tau}$ contamination in the sample is estimated to be 2 ± 2 events. The event acceptance is estimated to be 0.65, due primarily to : (i) the $p_t^{(e)} > 20 \text{ GeV/c}$ cut (0.80) ; (ii) the jet veto requirement within $\Delta\phi = \pm 30^\circ$ (0.96 ± 0.02) ; (iii) the electron-track

isolation requirement (0.90 ± 0.07) ; and (iv) the acceptance of events due to geometry (0.94 ± 0.03) . The cross-section is then :

$$(\sigma.B)_W = 0.53 \pm 0.08 (\pm 0.09) \text{ nb},$$

where the last error takes into account systematic errors. This value is in excellent agreement with the expectations for the Standard Model ³⁰⁾ $(\sigma.B)_W = 0.39 \text{ nb}$.

No event with $p_t^{(e)}$ or $p_t^{(\nu)}$ in excess of the expected distribution for $W \rightarrow e\nu$ events has been observed. This result can be used in order to set a limit to the possible existence of very massive W-like objects (W') decaying into electron-neutrino pairs. We find $(\sigma.B)_W' \leq 30 \text{ pb}$ at 90% confidence level, corresponding to $m_{W'} > 170 \text{ GeV}/c^2$, if standard couplings and quark distributions are used to evaluate the cross-sections.

3.9. Observation of the decay mode $W \rightarrow \mu + \nu$.

Muon-electron universality predicts an equal number of events in which the electron is replaced by its heavy counterpart, the muon :

$$p\bar{p} \rightarrow W^\pm X ; W^\pm \rightarrow \mu^\pm \nu_\mu^{(-)}$$

Although almost identical with decays with electrons (1) in theory, the muonic decay has a completely different experimental signature. Whereas an electron produces an electromagnetic shower (detected in the electromagnetic calorimeters), a high momentum muon traverses the whole detector with almost minimum energy loss. Muons are identified by their ability to penetrate many absorption lengths of material. Thus potential backgrounds for muons are radically different from those for electrons. The observation

of the same rate for processes $e\nu$ and $\mu\nu$ is therefore not only the most direct confirmation of muon-electron universality in charged-current interactions, but it also provides an important experimental verification of the previous results.

We now briefly describe the muon detection. A fast muon, emerging from the $\bar{p}p$ interaction region, will pass in turn through the central detector, the electromagnetic calorimeter and the hadron calorimeter, which consists of the instrumented magnet return yoke. After 60 cm of additional iron shielding (except in the forward region), it will then enter the muon chambers, having traversed about $8/\sin\theta$ nuclear interaction lengths, where θ is its emission angle with respect to the beam axis. The number of hadrons penetrating this much material is negligible ; however there are two sources of hadron-induced background :

- i) stray radiation leaking through gaps and holes ;
- ii) genuine muons from hadron decays, such as $\pi \rightarrow \mu\nu$, $K \rightarrow \mu\nu$, etc.

It is therefore essential to follow the behaviour of all muon candidates throughout the whole apparatus. Tracks are recorded in the central detector. The momenta of muons are determined by their deflection in the central dipole magnet, which generates a field of 0.7 T over a volume of $0.7 \times 3.5 \times 3.5 \text{ m}^3$. The momentum accuracy for high-momentum tracks is limited by the localization error inherent in the system ($\leq 100 \text{ } \mu\text{m}$) and by the diffusion of electrons drifting in the gas, which is proportional to $\sqrt{l}$ and amount to about $350 \text{ } \mu\text{m}$ after the maximum drift length of $l = 19.2 \text{ cm}$. This results in a momentum accuracy of about $\pm 20\%$ for a 1 m long track at $p = 40 \text{ GeV/c}$, in the best direction with respect to the field. In general, the precision depends greatly on the length and orientation of the track. For the muon sample under discussion, the typical error is around $\pm 30\%$.

In the present investigation the calorimeters have a fourfold purpose : (i) they provide enough material to attenuate hadrons, and constitute a threshold for muon detection of $p_t > 2 \text{ GeV/c}$; (ii) they identify hadronic interactions and/or accompanying neutral particles by an excess in the energy deposition ; (iii) they ensure a continuous tracking of the muon over six segments in depth ; (iv) they provide an almost hermetically closed energy flow measurement around the collision point, which makes possible the determination of the transverse components of the neutrino momentum by transverse energy conservation.

Fifty muon chambers³³⁾, nearly 4 m x 6 m in size, surround the whole detector, covering an area of almost 500 m². A graphical display of a $W \rightarrow \mu\nu$ event is shown in Fig. 26, with an expanded view of the muon chambers shown as an insert. Each chamber consists of four layers of drift tubes, two for each projection. The tubes in adjacent parallel layers are staggered. This resolves the left-right drift time ambiguity and reduces the inefficiency from the intervening dead spaces. The extruded aluminium drift tubes have a cross-section of 45 mm x 150 mm, giving a maximum drift length of 70 mm. An average spatial resolution of 300 μm has been achieved through the sensitive volume of the tubes³⁴⁾. In order to obtain good angular resolution on the muon tracks, two chambers of four planes each, separated by 60 cm, are placed on five sides of the detector. This long lever-arm was chosen in order to reach an angular resolution of a few milliradians, comparable to the average multiple scattering angle of high-energy muons (3 mrad at 40 GeV/c). Because of space limitations, the remaining side, beneath the detector, was closed with special chambers consisting of four parallel layers of drift tubes.

The track position and angle measurements in the muon chambers permit a second, essentially independent, measurement

Fig. 26 A graphical display of a $W^+ + \mu^+ \nu$ event. The vertical arrow show the trajectory of the 25 GeV/c μ^+ up to the muon chamber while the other arrow shows the transverse direction of the neutrino. The curved lines from the vertex are the charged tracks seen by the central detector, and the petals and boxes illustrate the electromagnetic and hadronic energy depositions. An expanded view of a muon module is shown as an insert.

Fig. 27 Distribution of $1/p_{\mu} - 1/p_{CD}$ for vertical cosmic-ray muons with $p_{CD} > 10 \text{ GeV/c}$, where p_{μ} and p_{CD} are the momenta measured in the muon chambers and central detector respectively.

of momentum. The statistical and systematic errors in this second momentum determination were carefully checked with high-momentum cosmic-ray muons ; Fig. 27 compares the momentum measurements in the central detector and muon chambers. Because of the long lever-arm to the muon chambers, a significant increase in precision is achieved by combining the two measurements.

The presence of neutrino emission is signalled by an apparent transverse energy imbalance when the calorimeter measurement of missing transverse energy is combined with the muon momentum measurement. This determines the neutrino transverse momentum error perpendicular to the muon p_t whereas the error parallel to the muon p_t is dominated by the track momentum accuracy.

The muon sample is contaminated by several background sources such as leakage through the absorber, beam halo, meson decays, and cosmic rays. Some of the background can be eliminated by requiring a matching central detector track with sufficiently high momentum to penetrate to the muon chambers. All events were therefore passed through a fast filter program which selected muon candidates with $p_t > 3$ GeV/c or $p > 6$ GeV/c. This filter program reconstructed tracks in the muon chambers. For each track pointing roughly towards the interaction region, the central detector information was decoded along a path from the muon chamber track to the interaction region. Track finding and fitting were performed in this path. Events were kept if a central detector track satisfied the above momentum cut and matched the muon chamber track within generous limits. The filter program selected about 72000 events. Since only limited regions of the central detector were considered, the program took about 10% of the average reconstruction time of a full event.

The 17326 events from the fast filter which contained a muon candidate with $p_t > 5$ GeV/c were passed through the standard UAl processing chain. Of these, 713 events had a muon candidate with $p_t > 15$ GeV/c or $p > 30$ GeV/c. These events were passed through an automatic selection program which eliminated most of the remaining background by applying strict track quality and matching cuts. Independently of this, all events were examined on an

interactive scanning facility. This confirmed that no W-candidate events were rejected by the selection program.

The selection program imposed additional requirements on event topology in order to reject events with muons in jets or back-to-back with jets.

Events were also rejected if the jet algorithm found a calorimeter jet with $E_T > 10$ GeV or a central detector jet with $p_T > 7.5$ GeV/c back-to-back with the muon to within $\pm 30^\circ$ in the plane perpendicular to the beam. Thirty-six events survived these cuts, and were carefully rescanned. After eliminating additional cosmics and probable $K \rightarrow \mu\nu$ decays, 18 events remained. The final W-sample of 14 events was obtained after the additional requirement that the neutrino transverse energy exceed 15 GeV. The effects of the different cuts are shown in table 4.

The most dangerous background to the $W \rightarrow \mu\nu$ sample comes from the decay of medium-energy kaons into muons within the volume of the central detector such that the transverse momentum kick from the decay balances the deflection of the particle in the magnetic field. This simulates at the same time a high-momentum muon track and, in order to preserve momentum balance in the transverse plane, a recoiling "neutrino". Most of these events are rejected by the selection program. We have performed a Monte Carlo calculation to estimate the residual background. Charged kaons with $3 < p_T < 15$ GeV/c and decaying in the central detector were generated according to a parametrization of the transverse momentum distribution of charged particles³⁵⁾, assuming a ratio of kaons to all charged particles of 0.25^{36} . A full simulation of the UA1 detector was performed, and each track was subjected to the same reconstruction and selection procedures as the experimental data, including the scanning of these events. Normalizing to the integrated luminosity of 108 nb^{-1} , we found 4 events

Table 4

Selection of $W \rightarrow \mu\nu$ candidates. The number of events is indicated at each stage

Events with a $p_t > 5$ GeV/c muon selected by the fast filter program	17,326
Fully reconstructed events with muon $p_t > 15$ GeV/c or $p > 30$ GeV/c	713
Events with a good quality CD track which matches the muon chambers well	285
Events remaining after rejection of cosmic rays	247
Events remaining after a tight cut on the χ^2 of the CD track fit to remove decays	144
Events where the muon is isolated both in the CD and in the calorimeters	53
Events with no jet activity opposite the muon in the transverse plane	36
Events remaining as W candidates after scanning (see text)	18
Events with a neutrino transverse momentum > 15 GeV/c	14

in which the K decay was recognized and simulated a muon with $p_t > 15$ GeV/c. Imposing the additional requirement of $p_t > 15$ GeV/c for the accompanying neutrino leaves less than one event as an upper limit to the background to $W \rightarrow \mu\nu$ from this source.

In addition, we expect about 5 events in our data sample with muons from decays of pions or kaons with $p_t > 15$ GeV/c. These will be similarly suppressed by the reconstruction and selection procedures ; in particular such events will be characterized by jets which transversely balance the high- p_t hadrons and are therefore rejected by our topological cuts. The momentum measurements in the central detector and in the iron agree very well, (Fig. 28) as a good check of our procedure.

Eighteen events survive our selection criteria and contain a muon with $p_t > 15$ GeV/c. The muons are isolated, and there is no visible structure to compensate their transverse momenta, in contrast with what might be expected for background events from heavy-flavour decays. Including the muon in the transverse energy balance, all events exhibit a large missing transverse energy of more than 10 GeV, attributed to an emitted neutrino. For the final $W \rightarrow \mu\nu$ sample, we consider only those 14 events with a neutrino transverse momentum $p_t > 15$ GeV/c. As in the electron case, the transverse momentum of the neutrino is strongly correlated, both in magnitude and in direction, with the transverse momentum of the muon. Fig. 29a shows this correlation in the direction parallel to the muon p_t . Similarly the component of the neutrino p_t perpendicular to the muon p_t is small. The characteristic back-to-back configuration and the high momenta of both leptons, well above the threshold, are very suggestive of a two-body decay of a massive, slow particle. The large errors in the momentum determination of the muons smear the expected Jacobian peak of

Fig. 28 Two-dimensional plot of Q/p_{μ} versus Q/p_{CD} for the $W \rightarrow \mu\nu$ events, where p_{μ} and p_{CD} are the momenta measured in the muon chambers and central detector respectively, and Q is the charge of the muon. The events with tracks in the bottom chambers are not shown.

a two-body decay. However, the transverse momentum distribution agrees well with that expected from a $W^{\pm}$ decay, once it is smeared with the experimental errors (Fig. 29b).

Fig. 29a Transverse energy of the neutrino parallel to the muon versus transverse momentum of the muon. Since the two quantities are correlated, error bars are shown for the difference and the sum. The difference in the transverse energy of the W parallel to the muon which is measured in the calorimetry and is therefore not correlated with the transverse momentum of the muon. For the errors in the sum only two error bars are shown for typical events. The filled circles correspond to the final sample of 14 W events, and the open circles to the 4 events with neutrino $p_t < 15$ GeV/c.

Fig. 29b The solid curve is an ideogram of the transverse momentum distribution of the muons in the final sample of 14 $W \rightarrow \mu\nu$ events. The dashed curve is a Monte Carlo prediction, based on the W production spectra measured in $W \rightarrow e\nu$ decays and a W mass of $80.9 \text{ GeV}/c^2$ smeared with errors.

The transverse momentum $p_t^{(W)}$ of the decaying particle is well measured, because the muon momentum does not enter into its determination. In fact, $p_t^{(W)}$ is simply energy

measured in the calorimeters, after subtraction of the muon deposition. The measured distribution is given in Fig. 30a and agrees well with our previous measurement from the $W \rightarrow e\nu$ sample, shown in Fig. 30b. Each of the two events with the highest $p_t^{(W)}$ has a jet which locally balances the transverse momentum of the W .

In order to determine the mass of the muon-neutrino system, we have used in a maximum likelihood fit the eight measured quantities for each event (momentum determination of the muon in the CD and in the muon chambers, angles of the muon, four-vector of the energy for the rest of the event) and their relevant resolution functions. We have taken account of the cuts imposed on the measured muon and neutrino transverse momenta³⁷⁾. We obtain a fitted W mass of $m_W = 81_{-7}^{+6} \text{ GeV}/c^2$, in excellent agreement with the measured value from $W \rightarrow e\nu$. This result is insensitive to the assumed decay angular distribution of the W . If the mass is fixed at the electron value of $80.9 \text{ GeV}/c^2$, a fit of the decay asymmetry gives $\langle \cos \theta^* \rangle = 0.3 \pm 0.2$, fully consistent with our result from $W \rightarrow e\nu$ and with the expected V-A coupling. The asymmetry measurement is not very significant since the ambiguity due to the two possible solutions for the longitudinal momentum of the W could be resolved in only a few cases. This is due to the large momentum errors and the limited acceptance in pseudorapidity ($|\eta| < 1.3$) for the muons.

The overall acceptance for the final sample of 14 $W \rightarrow \mu\nu$ events is limited by two main factors, namely the geometrical acceptance of the muon trigger system for muons with $p_t > 15 \text{ GeV}/c$ (49%) and the influence of the track quality cuts applied to the muon. The latter has been

Fig. 30a The transverse momentum distribution of the W derived from the energy imbalance measured in the calorimetry.
b The corresponding distribution from the $W \rightarrow e\nu$ data is shown for comparison.

estimated by applying identical cuts to an equivalent sample of 46 $W \rightarrow e\nu$ events from the 1983 data sample. 21 events remain, giving an acceptance of $(46 \pm 7)\%$. A further correction of $(87 \pm 7)\%$ is included to account for the jet veto and track isolation requirement. These three factors give an overall acceptance of $(20 \pm 3.5)\%$.

The integrated luminosity for the present data sample is 108 nb^{-1} , with an estimated uncertainty of $\pm 15\%$. The cross-section is then :

$$(\sigma.B)_\mu \pm 0.67 \pm 0.17 (\pm 0.15) \text{ nb}$$

where the last error includes the systematics from both acceptance and luminosity. This value is in good agreement both with the standard model predictions³⁰⁾ and with our result for $W \rightarrow e\nu$, namely $(\sigma.B)_e = 0.53 \pm 0.08 (\pm 0.09) \text{ nb}$.

A direct comparison between the electron and muon results has been made by selecting those $W \rightarrow e\nu$ events which are within the acceptance of the muon trigger system. Twelve events remain from the 21 which pass the muon track quality cuts. After correction for the difference in integrated luminosity (118 nb^{-1} in the electron case) this gives the following cross-section ratio, in which systematic errors approximately cancel :

$$R = (\sigma.B)_\mu / (\sigma.B)_e = 1.24^{+0.6}_{-0.4}$$

4. OBSERVATION OF THE NEUTRAL BOSON Z^0

4.1. Event selection. We now extend our search to the neutral partner Z^0 , responsible for neutral currents. As in our previous work, production of intermediate vector bosons is achieved with proton-antiproton collisions at $\sqrt{s} = 540$

GeV in the UA1 detector, except that now we search for electron and muon pairs rather than for electron-neutrino coincidence. The process is then :

$$\bar{p} + p \rightarrow Z^0 + X$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad +e^+ + e^- \quad \text{or} \quad \mu^+ + \mu^-$$

The reaction is then approximately a factor of 10 less frequent than the corresponding $W^\pm$ leptonic decay channels. A few events of this type are therefore expected in our muon or electron samples. Evidence for the existence of the Z^0 in the range of masses accessible to the UA1 experiment can also be drawn from weak-electromagnetic interference experiments at the highest PETRA energies, where deviations from point-like expectations have been reported.

Events for the present paper were selected by the so-called "express line", consisting of a set of four 168E computers³⁸⁾ operated independently in real time during the data-taking. A subsample of events with $E_T \geq 12$ GeV in the electromagnetic calorimeters and dimuons are selected and written on a dedicated magnetic tape. These events have been fully processed off-line and further subdivided into four main classes : (i) single, isolated electromagnetic clusters with $E_T > 15$ GeV and missing energy events with $E_{\text{miss}} > 15$ GeV, in order to extract $W^\pm + e^\pm \nu$ events ; (ii) two or more isolated electromagnetic clusters with $E_T > 25$ GeV for $Z^0 + e^+e^-$ candidates ; (iii) muon pair selection to find $Z^0 + \mu^+\mu^-$ events ; and (iv) events with a track reconstructed in the central detector, of transverse momentum within one standard deviation, $p_t \geq 25$ GeV/c, in order to evaluate some of the background contributions. We will discuss these different categories in more detail.

4.2. Events of type $Z^0 + e^+e^-$. An electron signature is defined as a localized energy deposition in two contiguous cells of the electromagnetic detectors with $E_T > 25$ GeV, and a small (or no) energy deposition (≤ 800 MeV) in the hadron calorimeters immediately behind them. The isolation requirement is defined as the absence of charged tracks with momenta adding up to more than 3 GeV/c of transverse momentum and pointing towards the electron cluster cells. The effects of the successive cuts on the invariant electron-electron mass are shown in Fig. 31. Four e^+e^- events survive cuts, consistent with a common value of (e^+e^-) invariant mass. They have been carefully studied using the interactive event display facility MEGATEK. One of these events is shown in Figs. 32a and 32b. The main parameters of the four events are listed in table 5 and 7. As one can see from the energy deposition plots (Fig. 33), their dominant feature is two very prominent electromagnetic energy depositions. All events appear to balance the visible total transverse energy components ; namely, there is no evidence for the emission of energetic neutrinos. Except for one track of event D which travels at less than 15° parallel to the magnetic field, all tracks are shown in Fig. 34, where the momenta measured in the central detector are compared with the energy deposition in the electromagnetic calorimeters. All tracks but one have consistent energy and momentum measurements. The negative track of event C shows a value of (9 ± 1) GeV/c, much smaller than the corresponding calorimeter deposition of (48 ± 2) GeV. One can interpret this event as the likely emission of a hard "photon" accompanying the electron. Subsequent calibrations of the electromagnetic (e.m.) counters indicated that the centroid of the energy deposition in the calorimeters was significantly displaced with respect to the incident electron track, indicating an angle of $\Delta\phi = (14 \pm 4)$ degrees between the

Fig. 31 Invariant mass distribution (uncorrected) of two electromagnetic clusters : a) with $E_T > 25$ GeV ; b) as above and a track with $p_t > 7$ GeV/c and projection length > 5 cm pointing to the cluster. In addition, a small energy deposition in the hadron calorimeters immediately behind (< 0.8 GeV) ensures the electron signature. Isolation is required with $\sum p_t < 3$ GeV/c for all other tracks pointing to the cluster. c) The second cluster also has as isolated track.

Fig. 32a Event display. All reconstructed vertex associated tracks and all calorimeter hits are displayed.

charged and neutral components. This excluded the possibility of an external bremsstrahlung in the vacuum pipe and detector window. The estimated probability of an internal bremsstrahlung exceeding the angle and energy observed is, according to Berends³¹⁾, about 0.005, or 2% for the sample of four events. A rather similar event has been reported by the UA2 Collaboration. In this case the photon and electron hit separate cells, thus directly indicating a finite $e\text{-}\gamma$

Fig. 32b The same, but thresholds are raised to $p_t > 2$ GeV/c for charged tracks and $E_T > 2$ GeV for calorimeter hits. We remark that only the electron pair survives these mild cuts.

separation. More recently, an event of the type $\mu^+ \mu^- \gamma$ has been observed in the UA1 study of $Z^0 \rightarrow \mu^+ \mu^-$ decays. Also in this events, a small but finite angle ($\sim 8^\circ$) is observed between the muon and the hard photon ($E \sim 30$ GeV). Event parameters are summarized in table 8. It is certainly premature to draw any conclusion about the origin of such events. It shows however how

Fig.33 Electromagnetic energy depositions at angles $> 5^\circ$ with respect to the beam direction for the four electron pairs.

entirely new phenomena may be occurring in the collider energy range.

The average invariant mass of the pairs, combining the four consistent values, is $(95.2 \pm 2.5) \text{ GeV}/c^2$ (table 7).

Fig. 34 Magnetic deflection in $1/p$ units compared to the inverse of the energy deposited in the electromagnetic calorimeters. Ideally, all electrons should lie on the $1/E = 1/p$ line.

Table 5
Properties of the individual electrons of the pair events

Run, event	Drift chamber measurement					Shower counter measurement						
	p (GeV)	Δp a) (GeV)	Q	dE/dx b)	y c)	ϕ (deg)	E_{tot} (GeV)	Electromagnetic samples (GeV)				Had. energy H
								S_1	S_2	S_3	S_4	
A 7433 1001	33	+9	+	1.8 ± 0.3	1.01	144	44	14	27	3	0.0	0.0
	63	+23 -13	-	1.7 ± 0.2	-1.19	-31	48	6	37	4	0.2	0.0
B 7434 746	27	+19 -8	+	1.6 ± 0.3	-0.36	131	42	2	18	20	1.3	0.1
	93	+66 -28	-	1.8 ± 0.2	-1.45	-60	102	42	56	4	0.2	0.0
C 6059 1010	32	+11 -6	+	1.3 ± 0.2	0.64	67	61	1	37	22	0.6	0.0
	9	+1 -1	-	1.4 ± 0.1	0.24	-121	48	1	23	23	1.3	0.0
D 7739 1279	d)	d)	d)	d)	-0.19	169	51	1	13	34	2.4	0.0
	50	+50 -17	-	1.5 ± 0.2	-0.79	-9	55	8	38	9	0.0	0.1

- a) $\pm 1\sigma$ including systematic errors.
b) Ionization loss normalized to minimum ionizing pion.
c) The rapidity y is defined as positive in the direction of outgoing $\bar{p}$.
d) Unmeasured owing to large dip angle.

Table 6

Properties of the muons of the dimuon event 6600-222

Track parameters							p/CD matching d)	
Q	p (GeV/c)	l (cm)	y	ϕ (°)	Normalized ionization I/I ₀		λ_{abs}	Angle (mrad)
					m. calorimeter	Hadron calorimeter		
+	58.8 ⁺⁸ ₋₆							
	60.3 ± 10.8 b)							
	59.2 ^{+6.4} _{-5.2} c)	170	1.19	-27.6	0.8 $\pm$ 0.5	1.2 $\pm$ 0.5	10.2	$\Delta X_1 = -1.3 \pm 1.9$ $\Delta\phi = -2 \pm 6$ $\Delta X_2 = 11.6 \pm 10.7$ $\Delta\lambda = 11 \pm 14$
-	63.6 ⁺³⁰ ₋₁₅ a)							
	43.1 ± 6.2 b)							
	46.1 ^{+6.1} _{-5.7} c)	80	-0.28	119.1	1.2 $\pm$ 0.9	1.6 $\pm$ 0.8	11.1	$\Delta X_1 = -0.1 \pm 8.0$ $\Delta\phi = -6 \pm 3$ $\Delta X_2 = -8.0 \pm 8.5$ $\Delta\lambda = -9 \pm 14$

Momentum determination : a) Central detector and μ chamber (statistical errors only) ;
b) Transverse momentum balance ;
c) Weighted average of (a) and (b) ;
d) Difference between the extrapolated CD track and the track measured in the μ chambers (see Fig. 6).

μ -CD matching :

Remarks:

The acceptance of the single muon trigger starts at a transverse momentum of about 2.5 GeV/c and reaches its full efficiency of 97% at 5.5 GeV/c. The geometrical acceptance of the dimuon trigger used in this analysis, reduced the acceptance for 2⁰ events to about 30%.

Table 7
Mass and energy properties of lepton pair events

Run, event	Lepton pair properties			General event properties			
	Mass a) (GeV/c ²)	p _t (GeV/c)	x _F b)	E _{tot} (GeV)	Σ E _T (GeV)	Missing E _T (GeV)	Charged tracks
A 7433 1001	91 ± 5	2.9 ± 0.9	0.02 ± 0.01	274	82	2.1 ± 3.6	27
B 7434 746	97 ± 5	7.9 ± 1.2	0.39 ± 0.01	494	149	9.3 ± 5.0	67
C 6059 1010	98 ± 5	8.0 ± 1.5	0.17 ± 0.01	412	143	3.3 ± 4.8	38
D 7339 1279	95 ± 5	8.4 ± 1.4	0.17 ± 0.01	493	157	0.8 ± 5.0	54
E 6600 (μμ) ²²²	95 ± 8	24 ± 5	0.14 ± 0.02	278 ^{c)}	128 ^{c)}	3.4 ± 5.9 ^{c)}	28

- a) These errors have been scaled up arbitrarily to 5 GeV to represent the present level of uncertainty in the overall calibration of the e.m. calorimeter which will be recalibrated completely at the end of the present run. This scale factor is not included in the error bars plotted in Fig. 8.
- b) x_F is defined as the longitudinal momentum of the dilepton divided by beam energy.
- c) Includes the muon energies.

Table 8

Energy, angle, and mass properties of the $ee\gamma$ events

	UA1	UA2
E_γ (GeV)	38.8 ± 1.5	24.4 ± 1.4
E_{e_1} (GeV)	61.0 ± 1.2	68.5 ± 1.6
E_{e_2} (GeV)	9 ± 1	11.4 ± 0.9
$\Delta\phi(e_2\gamma)$ ($^\circ$)	14.4 ± 4.0	31.8
$m(e_1e_2)$ (GeV/c 2)	42.7 ± 2.4	49.8
$m(e_1e_2\gamma)$ (GeV/c 2)	98.7 ± 5.0	89.7 ± 2.8
$m(e_1\gamma)$ (GeV/c 2)	88.8 ± 2.5	74.1
$m(e_2\gamma)$ (GeV/c 2)	4.6 ± 1.0	9.1

Notes: For the UA1 event $e_1 = e^+$ and $e_2 = e^-$.

The UA2 numbers are calculated from ref. [4].

4.3. Events of type $Z^0 \rightarrow \mu^+\mu^-$. Events from the dimuon trigger flag have been submitted to the additional requirement that there is at least one muon track reconstructed off-line in the muon chambers, and with one track in the central detector of reasonable projected length (≥ 40 cm) and $p_t \geq 7$ GeV/c. Only 42 events survive these selection criteria. Careful scanning of these events has led to only one clean dimuon event, with two "isolated" tracks (Fig. 35). Most of the events are due to cosmics. Parameters are given in table 6 and 7. Energy losses in the calorimeters traversed by the two muon tracks are well within expectations of ionization losses of high-energy muons (Fig. 36a). The position in the coordinate and the angles at the exit of the iron absorber (Fig. 36b) are in agreement with the

EVENT 6600. 222.

EVENT 6600. 222.

Fig. 35 Display for the high-invariant-mass muon pair event :
a) without cuts and b) with $p_t > 1$ GeV thresholds
for tracks and $E_T > 0.5$ GeV for calorimeter hits.

Fig. 36a Normalized energy losses in calorimeter cells transversed by the two muon tracks.

Fig. 36b Arrows show residuals in angle and position for muon track. Distribution come from cosmic-ray calibration with $p > 50$ GeV/c.

extrapolated track from the central detector, once multiple scattering and other instrumental effects have been calibrated with $p > 50$ GeV cosmic-ray muons traversing the same area of the apparatus. There are two ways of measuring momenta, either in the central detector or using the muon detector. Both measurements give consistent results. Furthermore, if no neutrino is emitted (as suggested by the electron events which exhibit no missing energy), the recoil of the hadronic debris, which is significant for this event, must be equal to the transverse momentum of the $(\mu^+\mu^-)$ pair by momentum conservation. The directions of the two muons then suffice to calculate the momenta of the two tracks. Uncertainties of muon parameters are then dominated by the errors of calorimetry. As shown in table 6 this determination is in agreement with magnetic deflection measurements. The invariant mass of the $(\mu^+\mu^-)$ pair is found to be $m_{\mu\mu} = 95.5 \pm 7.3$ GeV/c², in excellent agreement with that of the four electron pairs (see table 7).

4.4. Backgrounds. The most striking feature of the events is their common value of the invariant mass (Fig. 37) ; values agree within a few percent and with expectations from experimental resolution. Detection efficiency is determined by the energy thresholds in the track selection, 15 GeV/c for $e^\pm$ and 7 GeV/c for $\mu^\pm$. Most "trivial" sources of background are not expected to exhibit such a clustering at high masses. Also, most backgrounds would have an equal probability for $(e\mu)$ pairs, which are not observed. Nevertheless, we have considered several possible spurious sources of events :

i) Ordinary large transverse momentum jets which fragment into two apparently isolated, high-momentum tracks, both simulating either muons or electrons. To evaluate this effect, events with (hadronic) tracks of momenta compatible with $p_t > 25$ GeV/c were also selected in the express

Fig. 37 Invariant masses of lepton pairs.

line. After requiring that the track is isolated, one finds one surviving event with transverse energy ~ 25 GeV in a sample corresponding to 30 nb^{-1} . Including the probability that this track simulates either a muon ($\sim 2 \times 10^{-3}$) or an electron ($\sim 6 \times 10^{-3}$), we conclude that this effect is negligible³⁹⁾. Note that two tracks (rather than one) are needed to simulate our events (probabilities must be squared!) and that the invariant mass of the events is much higher than the background. The background is expected to fall approximately like m^{-5} according to the observed jet-jet mass distributions¹⁴⁾.

ii) Heavy-flavoured jets with subsequent decay into leading muons or electrons. In the 1982 event sample (11 nb^{-1}), two events have been observed with a single isolated muon of $p_t > 15 \text{ GeV}$ and one electron event with $p_t > 25 \text{ GeV/c}$. Some jet activity in the opposite hemisphere is required. One event exhibits also a significant missing energy. Once this is taken into account they all have a total (jet+jet+lepton+neutrino) transverse mass of around 80 GeV/c^2 , which indicates that they are most likely due to heavy-flavour decay of W particles. This background will be kinematically suppressed at the mass of our five events. Nevertheless, if the fragmentation of the other jet is also required to give a leading lepton and no other visible debris, this background contributes at most to 10^{-4} events. Monte Carlo calculations using ISAJET lead to essentially the same conclusion³⁰⁾.

iii) Drell-Yan continuum. The estimated number and the invariant mass distribution make it negligible⁴⁰⁾.

iv) W^+W^- pair production is expected to be entirely negligible at our energy⁴¹⁾.

v) Onium decay from a new quark, of mass compatible with the observation ($\sim 95 \text{ GeV/c}^2$). Cross-sections for this process have been estimated by different authors⁴²⁾, and they appear much too small to account for the desired effect.

In conclusion, none of the effects listed above can produce either the number or the features of the observed events.

4.5. Mass determination. All the observations are in agreement with the hypothesis that events are due to the production and decay of the neutral intermediate vector boson Z^0 according to reaction (1). The transverse momentum distribution is shown in Fig. 38, compared with the observed distributions for the $W^\pm \rightarrow e\nu$ events and with QCD

calculations. The muon events and one of the electron events (event B) have visible jet structure. Other events are instead apparently structureless.

From our observation, we deduce a mass value for the Z^0 particle.

$$m_{Z^0} = (95.2 \pm 2.5) \text{ GeV}/c^2$$

The half width based on the four electron events is $3.1 \text{ GeV}/c^2$ ($< 5.1 \text{ GeV}/c^2$ at 90% c.l.), consistent with expectation from the experimental resolution and the natural Z^0 width, $\Gamma_{Z^0} = 3.0 \text{ GeV}$. At this point it is important to stress that the final calibration of the electromagnetic calorimeters is still in progress and that small scale shifts are still possible, most likely affecting both the $W^\pm$ and Z^0 mass values. No e.m. radiative corrections have been applied to the masses.

Fig. 38 Transverse momentum spectra : a) for $W \rightarrow e \nu$ events, and b) $Z^0 \rightarrow l^+ l^-$ candidates. The lines represent QCD predictions.

5. COMPARING THEORY WITH EXPERIMENT

The experiments discussed in the previous paragraph have shown that the W-particle has most of the properties required in order to be the carrier of weak interactions. The presence of a narrow di-lepton peak has been observed around 95 GeV/c². Rates and features of the events are consistent with the hypothesis that one has indeed observed the neutral partner of the W[±]. Statistics at present is not sufficient to test experimentally the form of the interaction, neither has parity violation been detected. The precise values of the masses of Z⁰ and W[±] now available constitute however a crucial test of the idea of unification between weak and electromagnetic forces and in particular of the predictions of SU(2) x U(1) theory of Glashow, Weinberg and Salam. Careful account of systematic errors is needed in order to evaluate an average between the UA1 and UA2 mass determination.

The charged vector boson mass given in the present work is

$$m_{W^\pm} = (80.9 \pm 1.5) \text{ GeV/c}^2 \quad (\text{statistical errors only})$$

to which a 3% energy scale uncertainty must be added. In the present report a value for the Z⁰ mass, $m_{Z^0} = (95.1 \pm 2.5) \text{ GeV/c}^2$ has been given. Neglecting systematic errors, a mass value is found with somewhat smaller errors :

$$m_{Z^0} = (95.6 \pm 1.4) \text{ GeV/c}^2 \quad (\text{statistical errors only})$$

to which the same scale uncertainty as for the W[±] applies. The quoted errors includes : i) the neutral width of the Z₀ peak, which is found to be $\Gamma < 8.5 \text{ GeV/c}^2$ (90% confidence level), ii) the experimental resolution of counters, and iii) the r.m.s. spread between calibration

Fig. 39a m_Z plotted against m_W determined by the UA1 experiment. The elliptical error curves reflect the uncertainty in the energy scale at the 68% and 90% confidence levels. The heavy curve shows the Standard Model prediction for $\rho = 1$ as a function of the Intermediate Vector Boson (IVB) masses.

constants of individual elements. In Fig. 39a we have plotted m_Z against m_W . The elliptical shape of the errors reflects the uncertainty in the energy scale. One can see that there is excellent agreement with the expectations of the $SU(2) \times U(1)$ Standard Model. One can also determine the

Fig. 39b ρ plotted against $\sin^2 \theta_W$ as determined from the measurement of the IVB masses. The 68% and 90% confidence level limits are shown.

classic parameters :

$$\sin^2 \theta_W = \frac{38.5 \text{ GeV}/c^2}{m_W} = 0.226 \pm 0.008 (\pm 0.014) ,$$

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 0.925 \pm 0.05 ,$$

where the number in parenthesis is due to systematic errors. The result is shown in Fig. 39b again in good agreement with expectations and published results⁴³⁾.

ACKNOWLEDGEMENTS

These lectures are based on the work of the UAl Collaboration team, to which I want to express all my appreciation for the remarkable work which has led to so many results. At present the following individuals are members of the collaboration :

G. Arnison, A. Astbury, B. Aubert, C. Bacci, A. Bezaguet,
R.K. Bock, T.J.V. Bowcock, M. Calvetti, P. Catz,
P. Cennini, S. Centro, F. Ceradini, S. Cittolin, D. Cline,
C. Cochet, J. Colas, M. Corden, D. Dallman, D. Dau,
M. DeBeer, M. Della Negra, M. Demoulin, D. Denegri,
A. Diciaccio, D. DiBitonto, L. Dobrzynski, J.D. Dowell,

K. Eggert, E. Eisenhandler, N. Ellis, P. Erhard, H. Faissner,
M. Fincke, G. Fontaine, R. Frey, R. Frühwirth, J. Garvey,
S. Geer, C. Ghesquiere, P. Ghez, K.L. Giboni, W.R. Gibson,
Y. Giraud-Heraud, A. Givernaud, A. Gonidec, G. Grayer,
T. Hansl-Kozanecka, W.J. Haynes, L.O. Hertzberger,
C. Hodges, D. Hoffmann, H. Hoffmann, D.J. Holthuizen,
R.J. Homer, A. Honma, W. Jank, G. Jorat, P.I.P. Kalmus,
V. Karimaki, R. Keeler, I. Kenyon, A. Kernan,
R. Kinnunen, W. Kozanecki, D. Kryn, F. Lacava, J.P. Laugier,
J.P. Lees, H. Lehmann, R. Leuchs, A. Leveque, D. Linglin,
E. Locci, J.J. Malosse, T. Markiewicz, G. Maurin,
T. McMahon, J.P. Mendiburu, M.N. Minard, M. Mohammadi,
M. Moricca, K. Morgan, H. Muirhead, F. Muller, A.K. Nandi,
L. Naumann, A. Norton, A. Orkin-Lecourtois, L. Paoluzi,
F. Pauss, G. Piano Mortari, E. Pietarinen, M. Pimiä,
J.P. Porte, E. Radermacher, J. Ransdell, H. Reithler,
J.P. Revol, J. Rich, M. Rijssenbeek, C. Roberts,
J. Rohlf, P. Rossi, C. Rubbia, B. Sadoulet, G. Sajot,
G. Salvi, G. Salvini, J. Sass, J. Saudraix, A. Savoy-Navarro,
D. Schinzel, W. Scott, T.P. Shah, D. Smith, M. Spiro,
J. Strauss, J. Streets, K. Sumorok, F. Szoncsó, C. Tao,
G. Thompson, J. Timmer, E. Tscheslog, J. Tuominiemi,
B. Van Eijk, J.P. Vialle, J. Vrana, V. Vuillemin, H.D. Wahl,
P. Watkins, J. Wilson, R. Wilson, C.E. Wulz,
Y.G. Xie, M. Yvert, E. Zurfluh

REFERENCES

- [1] C. Rubbia, P. McIntyre and D. Cline, Study Group, Design study of a Proton-Antiproton Colliding Beam Facility, CERN/PS/AA 78-3 (1978), reprinted in Proc. Workshop on Producing High-Luminosity, High Energy Proton-Antiproton Collisions (Berkely, 1978), report LBL-7574, UC34, p 189.
Proc. Inter. Neutrino Conf. (Aachen, 1976) (Vieweg, Braunschweig, 1977) p. 683.
- [2] The Staff of the CERN Proton-Antiproton Project", Phys. Lett. 107B, (1981) 306.
- [3] UA1 Proposal: A 4π solid-angle detector for the SPS used as a proton-antiproton collider at a centre-of-mass energy of 540 GeV, CERN/SPSC 78-06 (1978).
M. Barranco Luque et al., Nucl. Instrum. Methods 176 (1980) 175.
M. Calvetti et al., Nucl. Instrum. Methods 176 (1980) 255.
K. Eggert et al., Nucl. Instrum. Methods 176 (1980) 217 and 233.
A. Astbury, Phys. Scr. 23 (1981) 397.
UA1 Collaboration, The UA1 detector (presented by J. Timmer) in Proc. 18th Rencontre de Moriond, Antiproton-Proton Physics and the W discovery, 1983, ed by J. Tran Thanh Van, page 593.

- [4] UA1 Collaboration, G. Arnison et al., Phys. Lett. 123B (1983) 115.

- [5] UA1 Collaboration, Transverse Energy Distributions in the Central Calorimeters, preprint CERN EP/82-122 (1982).

- [6] M.J. Corden et al., Physica Scripta 25 (1982) 468.
C. Cochet et al., UA1 Tech. Note TN 82-40.

- [7] G. Arnison et al., Phys. Lett. 107B (1981) 320.
G. Arnison et al., Phys. Lett. 123B (1983) 108.

- [8] G. Wolf, DESY Report EP/82-122 (1982).

- [9] F.E. Paige and S.D. Protopopescu, ISAJET, BNL 31987.

- [10] M. Della Negra, Physica Scripta 25 (1982) 468.
R.K. Bock et al., Nucl. Inst. Meth. 186 (1981) 533.

- [11] Z. Kunszt and E. Pietarinen, CERN preprint TH 3584 (1983).

- [12] K. Kunszt and E. Pietarinen, Nucl. Phys. B164 (1980) 45.
T. Gottschalk and D. Sivers, Phys. Rev. D21 (1980) 102.
F. Berends et al., Phys. Lett. 103B (1981) 124.

- [13] R. Brandelik et al., Phys. Lett. 114B (1982) 65.[16]

- [14] UA1 Collaboration, Jet fragmentation at the SPS pp collider - UA1 experiment (presented by V. Vuillemin), in Proc. 18th Rencontre de Moriond, Antiproton-Proton Physics and the W discovery 1983, (ed. J. Tran Thanh Van), p. 309.

- [15] G. Arnison et al., Phys. Lett. 118B (1982) 173.

- [16] B. Combridge et al., Phys. Lett. 70B (1977) 234.

- [17] B. Combridge and C. Maxwell, preprint RL-83-095 (1983).

- [18] UA1 Collaboration, G. Arnison et al., Phys. Lett. 132B (1983) 214.

- [19] F. Berends et al., Phys. Lett. 103B (1981) 124.

- [20] J.C. Collins and D.E. Soper, Phys. Rev. D16 (1977) 2219.

- [21] D. Drijard et al., Phys. Lett. 121B (1983) 433.

- [22] R.K. Ellis et al., Nucl. Phys. B173 (1980) 397.

- [23] N.G. Antoniou et al., Phys. Lett. 128B (1983) 257.

- [24] H. Abramowicz et al., Z. Phys. C12 (1982) 289.

- [25] G. Arnison et al., Phys. Lett. 122B, 103 (1983).

- [26] G. Arnison et al., Phys. Lett. 129B (1983) 273.

- [27] UA2 Collaboration in Proceeding of the International Europhysics Conference , Brighton, July 1983, page 472.

- [28] A. Nakamura, G. Pancheri and Y. Srivastava, Frascati preprint LFN-83/43 (R) (June 1983).

- [29] P. Aurenche and J. Lindfors, Nucl. Phys. B185 (1981) 274.

- [30] F.E. Paige and S.D. Protopopescu, ISAJET program, BNL 29777 (1981). All cross-sections are calculated in the leading log approximation assuming $SU(2) \times U(1)$.

- [31] F. Berends et al., Nucl. Phys. B202 (1982) 63, and private communications.

- [32] M. Jacob, to be published. We thank Professor M. Jacob for very helpful comments on the subject.

- [33] K. Eggert et al., Nucl. Instrum. Methods 176 (1980) 217 and 233.

- [34] For more detailed information, see for example : UA1 Collaboration, Search for Isolated Large Transverse Energy muons at $\sqrt{s}=540$ GeV, in Proc. 18th Rencontre de Moriond on Antiproton-Proton Physics, La Plagne, 1983 (Editions Frontières, Gif-sur-Yvette, 1983), p.431.

- [35] G. Arnison et al., Phys. Lett. 118B (1982) 167.

- [36] Calculation based on : M. Banner et al., Phys. Lett. 122B (1983) 322.

- [37] In the maximum likelihood fit, the measured quantities of each event are compared with computed distribution functions, smeared with experimental errors. A Breit-Wigner form is assumed for the W mass [with a width (FWHM) of $3 \text{ GeV}/c^2$], and Gaussian distributions are used for the transverse and longitudinal momenta of the W (with r.m.s. widths of $7.5 \text{ GeV}/c$ and $67.5 \text{ GeV}/c$, respectively). In the W centre of mass, the angle θ^* of the emitted positive (negative) lepton with respect to the outgoing antiproton (proton) direction is generated according to a distribution in $\cos \theta^*$ of $(1+\cos \theta^*)^2$ as expected for $V(\pm A)$ coupling.

- [38] J.T. Carrol, S. Cittolin, M. Demoulin, A. Fucci, B. Martin, A. Norton, J.P. Porte, P. Ross and K.M. Storr, Data Acquisition using the 168E, Paper presented at the Three-Day In-Depth Review on the Impact of Specialized Processors in Elementary Particle Physics, Padua 1983, ed. Istituto Nazionale di Fisica Nucleare, Padova, (1983) p. 47.
- [39] Electron-pion discrimination has been measured in a test beam in the full energy range and angles of interest. The muon tracks have the following probabilities : i) no interaction : 2×10^{-5} (4×10^{-5}) ; ii) interaction but undetected by the calorimeter and geometrical cuts : 10^{-4} (4×10^{-4}) ; iii) decay : 10^{-3} (0.7×10^{-3}).
- [40] S.D. Drell and T.M. Yan, Phys. Rev. Lett. 25 (1970) 316.
F. Halzen and D.H. Scott, Phys. Rev. D18 (1978) 3378.
See also ref. 6.
S. Pakvasa, M. Dechantsreiter, F. Halzen and D.M. Scott, Phys. Rev. D20 (1979) 2862.
- [41] R. Kinnunen, Proc. Proton-Antiproton Collider Physics Workshop, Madison, 1981 (univ. Wisconsin, Madison, 1982):
R.W. Brown and K.O. Mikaelian, Phys. Rev. D19 (1979) 922.

- [42] T.G. Gaisser, F. Halzen and E.A. Paschos, Phys. Rev. D15 (1977) 2572.
R. Baier and R. Rückl, Phys. Lett. 102B (1981) 364.
F. Halzen, Proc. 21st Int. Conf. on High Energy Physics, Paris, 1982 [J. Phys. (France), No. 12 t 43 (1982)], p, C3-381.
F.D. Jackson, S. Olsen and S.H.H. Tye, Proc. AIP Dept. of Particles and Fields Summer Study on Elementary Particle Physics and Future Facilities, Snowmass, Colorado, 1982 (AIP, New York, 1983), p. 175.
- [43] J.E. Kim et al., Rev. Mod. Phys. 53 (1981) 211.