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OBSERVATION OF THE MUONIC DECAY OF THE CHARGED INTERMEDIATE VECTOR BOSON

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ABSTRACT

Muons of high transverse momentum p_T^μ have been observed in the large drift chambers surrounding the UA1 detector at the CERN 540 GeV $p\bar{p}$ collider. For an integrated luminosity of 108 nb^{-1} , 14 isolated muons have been found with $p_T^\mu > 15 \text{ GeV}/c$. They are correlated with a large imbalance in total transverse energy, and show a kinematic behaviour consistent with the muonic decay of the Intermediate Vector Boson $W^\pm$ of weak interactions. The partial cross-section is in agreement with previous measurements for electronic decays and with muon-electron universality. The W mass is determined to be $m_W = 81_{-7}^{+6} \text{ GeV}/c^2$.

1. INTRODUCTION

We have recently observed large transverse momentum electrons, in coincidence with missing transverse energy, in 540 GeV proton-antiproton interactions at the CERN $p\bar{p}$ collider [1]. The topology and rate of these events agrees well with the hypothesis that they result from the production and subsequent electronic decay of Intermediate Vector Bosons (IVBs) $W^\pm$:

$$p\bar{p} \rightarrow W^\pm X ; \quad W^\pm \rightarrow e^\pm (\bar{\nu}_e) . \quad (1)$$

Using a sample of 52 selected events, the weak origin was confirmed by observing the forward-backward charge asymmetry of the electrons, typical of left-handed currents [2]. From the measured transverse mass distribution, a mass of $(80.9 \pm 1.5) \text{ GeV}/c^2$, with 3% systematic error, was determined for $W^\pm$, in excellent agreement with the expectation of the Glashow-Salam-Weinberg model of electroweak interactions [3].

Muon-electron universality predicts an equal number of events of type (1), in which the electron is replaced by its heavy counterpart, the muon:

$$p\bar{p} \rightarrow W^\pm X ; \quad W^\pm \rightarrow \mu^\pm (\bar{\nu}_\mu) . \quad (2)$$

Although almost identical with process (1) in theory, the muonic decay [process (2)] 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 (1) and (2) 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 [1,2].

The present paper reports the first observation of the muonic decay of the charged IVBs with corresponding measurements of the W mass, the decay charge asymmetry and the partial cross-section.

2. DETECTION AND MEASUREMENT OF MUONS AND NEUTRINOS

The UA1 apparatus has already been described [4-6]. Here we limit our discussion to those components which are relevant to the identification and measurement of muons. In brief, a fast muon, emerging from the $p\bar{p}$ 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 [5], which is a cylindrical drift chamber

array, 5.8 m in length and 2.3 m in diameter, surrounding the interaction region. 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 $7.0 \times 3.5 \times 3.5 \text{ m}^3$. The momentum accuracy for high-momentum tracks is limited by the localization error inherent in the system ($\leq 100 \mu\text{m}$) and by the diffusion of electrons drifting in the gas, which is proportional to $\sqrt{\ell}$ and amounts to about $350 \mu\text{m}$ after the maximum drift length of $\ell = 19.2 \text{ cm}$ [4,5]. 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 chambers [6], nearly $4 \text{ m} \times 6 \text{ m}$ in size, surround the whole detector, covering an area of almost 500 m^2 . A graphical display of a $W \rightarrow \mu\nu$ event is shown in fig. 1, 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 $45 \text{ mm} \times 150 \text{ mm}$, giving a maximum drift length of 70 mm. An average spatial resolution of $300 \mu\text{m}$ has been achieved throughout the sensitive volume of the tubes [7]. 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 alignment of the muon chambers and the match in angle and position of muon tracks with extrapolations of the central detector tracks were extensively studied with high-momentum ($p > 10 \text{ GeV/c}$) cosmic-ray muons. The fitted track parameters and errors from the central detector were extrapolated through the calorimeters and extra iron, taking into account the additional correlated errors in position and angle due to multiple scattering. Selection criteria were then defined, based on the agreement of extrapolated track position and direction with measurements from the muon chambers alone.

The track position and angle measurements in the muon chambers permit a second, essentially independent, measurement of momentum. The statistical and systematic errors in this second momentum determination were carefully checked with high-momentum cosmic-ray muons; fig. 2 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. The accuracy in each component of the missing transverse energy is $0.4 \sqrt{E_t}$, where E_t is the scalar transverse energy sum ($\sum E_i \sin \theta_i$) and units are in GeV. 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.

3. HARDWARE TRIGGER AND DATA-TAKING

The muon chamber geometry (fig. 1) permits a quick definition of a track, pointing to the interaction vertex within a specified cone of aperture ± 150 mrad. This is accomplished by a dedicated set of hardware processors, which analyse the pattern of hit tubes after the “minimum bias” trigger [1,2,4] has signalled an event. This operation is carried out in less than $1 \mu\text{s}$ after the maximum drift-time in the muon chambers ($1.4 \mu\text{s}$), and introduces no additional dead-time, since it is completed before the next beam-crossing. Only about 10^{-4} of “minimum bias” events have one or more track candidates in the muon chambers and are thus retained. The forward chambers were only partially used in the trigger, because their trigger rate was too high. This limited the acceptance in pseudorapidity to $|\eta| < 1.3$, with typically 2/3 of the full azimuthal acceptance. The muon trigger rate was approximately 1 Hz at the peak luminosity $L = 1.5 \times 10^{29} \text{ cm}^{-2} \cdot \text{s}^{-1}$. The integrated luminosity for the data reported here was 108 nb^{-1} , after subtraction of dead-time. Out of 2.5×10^6 events recorded on tape, 1×10^6 events were muon triggers.

4. EVENT SELECTION

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 $p_T > 3 \text{ GeV}/c$ or $p > 6 \text{ GeV}/c$. 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 $p_T > 5 \text{ GeV}/c$ were passed through the standard UA1 processing chain. Of these, 713 events had a muon candidate with $p_T > 15 \text{ GeV}/c$ or $p > 30 \text{ GeV}/c$. 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. A muon was considered to be in a jet if the sum

of the transverse momenta of other tracks in a surrounding cone of half width $\Delta r = (\Delta\phi^2 + \Delta\eta^2)^{1/2} < 0.7$ (ϕ : azimuthal angle, η : pseudorapidity) exceeded 3 GeV/c or if a standard jet algorithm [8] found a calorimeter jet with $E_T > 10$ GeV and with its axis within the above cone. 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 1.

5. MUON IDENTIFICATION AND BACKGROUND

The muon identification is based on the calorimeter information and the agreement of the extrapolated central detector track with the track in the muon chamber. A muon traverses the calorimeters and the additional absorbers without deviations beyond those of multiple scattering, and with minimum ionization losses in the four e.m. and two hadronic calorimeter segments. The ionization losses of the muons from the W sample, normalized to perpendicular incidence, are in good agreement with results from a 45 GeV muon test beam. Furthermore the two muon momentum measurements agree well, as shown in fig. 3.

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 particles [9], assuming a ratio of kaons to all charged particles of 0.25 [10]. 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 in which the K decay was not 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.

6. RESULTS

Eighteen events survive our selection criteria, as defined in Section 4, 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 [1,2], the transverse momentum of the neutrino is strongly correlated, both in magnitude and in direction, with the transverse momentum of the muon. Figure 4a 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 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. 4b).

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 the missing energy measured in the calorimeters, after subtraction of the muon deposition. The measured distribution is given in fig. 5a and agrees well with our previous measurement from the $W \rightarrow e\nu$ sample, shown in fig. 5b. 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 momenta [11]. We obtain a fitted W mass of $m_W = 81^{+6}_{-7}$ GeV/c², in excellent agreement with the measured value from $W \rightarrow e\nu$ [2]. 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 GeV/c², 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 movement 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 $p_T > 15$ GeV/c (49%) and the influence of the track quality cuts applied to the muon. The latter has been 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 requirements. 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

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

where the last error includes the systematics from both acceptance and luminosity. This value is in good agreement both with the standard model predictions [12] and with our published result for $W \rightarrow e\nu$ [2], namely $(\sigma \cdot B)_e = 0.53 \pm 0.08 (\pm 0.09) \text{ nb}$.

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:

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

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Table 1

Selection of $W \rightarrow \mu\nu$ candidates. The numbers 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

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- 11) 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 GeV/c²], and Gaussian distributions are used for the transverse and longitudinal momenta of the W (with r.m.s. widths of 7.5 GeV/c and 67.5 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.
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Figure captions

- Fig. 1 A graphical display of a $W^+ \rightarrow \mu^+ \nu$ event. The vertical arrow shows 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. 2 Distribution of $1/p_\mu - 1/p_{CD}$ for vertical cosmic-ray muons with $p_{CD} > 10$ GeV/c, where p_μ and p_{CD} are the momenta measured in the muon chambers and central detector respectively.
- Fig. 3 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. Two events with tracks in the bottom chambers are not shown.
- Fig. 4a 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 is 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. 4b 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 GeV/c² smeared with errors.
- Fig. 5 The transverse momentum distribution of the W derived from the energy imbalance measured in the calorimetry. The corresponding distribution from the $W \rightarrow e \nu$ data is shown for comparison.

Fig. 1

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

Fig. 5