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OBSERVATION OF MUONIC Z^0-DECAY AT THE $\bar{p}p$ COLLIDER

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Abstract

We report the observation of five muonic Z^0 decays. The mass and cross-section times branching ratio is consistent with the previous measurements of $Z^0 \rightarrow e^+e^-$. Three of the muonic decays have unexpected features. One event is of the type $Z^0 \rightarrow \mu^+\mu^-\gamma$. Two of the $Z^0 \rightarrow \mu^+\mu^-$ decays are accompanied by several (> 4) energetic (E_T > 10 GeV) jets which are difficult to explain within the framework of standard QCD corrections.

1. INTRODUCTION

We have recently observed the muonic decay of the charged intermediate Vector Bosons (IVBs) $W^{\pm}$.[1]. In an earlier analysis we have also reported on the observation of one event consistent with the muonic decay of the neutral IVB, Z^0 [2],

$$p\bar{p} \to Z^0 X \; ; \; Z^0 \to \mu^+\mu^- \qquad (1)$$

The present paper reports on five events of type (1) that were recorded during the 1983 run, corresponding to an integrated luminosity of 108 nb^{-1}. All these events are described in detail but special emphasis is given to three of them ; one event consistent with the hypothesis $Z^0 \to \mu^+\mu^-\gamma$ and two events where the $\mu^+\mu^-$ pair is accompanied by several energetic jets. These three events do not fit easily in the standard picture of Z^0 production.

Since the dimuon background contamination is negligible, the search has been extended to events where both muons have transverse momentum $p_T > 5$ GeV/c. In addition to the five Z^0 events, ten events were found with much lower dimuon masses, which will be reported in a separate paper.

2. DETECTION AND MEASUREMENT OF MUONS AND JETS

2.1) Muon identification

The UA1 apparatus has already been described[3]. The components relevant to the identification and measurement of muons were discussed in detail in Ref. 1. In brief, a muon emerging from the $p\bar{p}$ interaction region traverses the Central Detector (CD), the electromagnetic calorimeter and the magnetized hadron calorimeter. After 60 cm of additional iron shielding (except in the forward region) it enters the muon chambers which cover about 75% of the full solid angle.

The momenta of muons are determined in the CD by their deflection in the central dipole field of 0.7 T. The momentum uncertainty due to the measurement error on each point is $\Delta p/p \sim 0.5\% \times p$ (p in GeV/c).

The track position and angle measurements in the muon chambers permit a second, essentially independent, measurement of momentum. For high momentum ($p \geq 20$ GeV/c) muons, the precision of this momentum measurement is comparable to the measurement in the CD[1].

Finally the muon momenta can be constrained by relying on overall transverse momentum conservation. For $Z^0 \to \mu^+\mu^-$ events, where no neutrino is emitted, the transverse momentum of the recoil hadronic debris must be equal to the transverse momentum of the $(\mu^+\mu^-)$ system. The muon momenta and the transverse energy flow are adjusted in a fit to obtain an over-all balanced event.

Jets are defined using the UA1 jet algorithm[4)] applied to energy vectors defined from calorimeter cells. A correction is applied to the measured energy ($\sim$ +25%) and momentum ($\sim$ +20%) of each jet, as a function of the pseudorapidity η, azimuth ϕ and transverse energy E_T of the jet, on the basis of test beam data and Monte Carlo studies. The jet momentum resolution is typically 18% for a calorimeter jet of E_T = 15 GeV, and improves with increasing jet transverse energy. In this paper we consider all jets with $E_T \geq 7.5$ GeV and pseudorapidity less than 2.5, keeping in mind, however, that the jet finding procedure and jet energy measurement become less reliable when the E_T is smaller than 15 GeV.

3. EVENT SELECTION AND ACCEPTANCE

3.1) Event selection

During the 1983 data-taking period about 2.5×10^6 events were recorded on tape for an integrated luminosity of 108 nb^{-1}. Of these about 1.0×10^6 events were muon triggers. All the events were passed through a fast filter program which selected muon candidates with $p_T > 3$ GeV/c or p > 6 GeV/c[1)]. This filter program selected 7.2×10^4 events.

The 17326 events from the fast filter program which contained a muon candidate with $p_T > 5$ GeV/c were fully reconstructed, and then passed through an automatic selection program which applied stricter CD track quality and CD-muon chamber matching requirements than were used at the filter stage. This yielded a reduced sample of 6781 events.

A dimuon selection was made requiring two $p_T > 5$ GeV/c muon tracks in the event, each satisfying the criteria used in the inclusive muon selection. This gave 26 candidate dimuon events which were scanned on a high resolution graphics display facility. Of these events, 7 were identified as cosmic rays and 6 as leakage of hadron showers through cracks in the calorimeters, leaving 13 candidates after scanning.

In addition to the dimuon selection described above, all events with a dimuon trigger and at least one reconstructed CD track with $p_T > 7$ GeV/c were examined. Two extra dimuon events were found in this way. In one event both CD tracks were very short and failed the track length requirements of the filter. In the other event one muon passed very close to the edge of the chamber and was seen in only one projection. Hence the final dimuon sample (both muons $p_T > 5$ GeV/c) contains 15 events. Their mass distribution $m_{\mu\mu}$ is shown in fig. 1. The 5 events with dimuon masses exceeding 70 GeV/c^2 are interpreted as Z^0 decays.

3.2) Acceptance for muon pairs

We have estimated the acceptance for detecting dimuons from Drell-Yan and Z^0 decays by Monte Carlo calculation[5]. Both muons are required to have $p_T > 5$ GeV/c and to hit the sensitive area of the muon chambers ($|\eta| \leq 2$), and at least one muon is required to hit the area that was active in the muon trigger ($|\eta| \leq 1.3$).

Due to the 5 GeV/c p_T cut-off, the acceptance for Drell-Yan pairs is small for masses below 10 GeV/c^2 and rises to 32% at 25 GeV/c^2. It then continues to rise slowly, mainly due to the increasingly central production of high-mass pairs. At the Z^0-mass the acceptance reaches 44%, determined by the limited rapidity range of the muon trigger and the ($\sim$ 75%) azimuth coverage. This acceptance is reduced to 37% when we require a CD track length of at least 40 cm in the bending plane.

4. BACKGROUND

We have considered a number of possible backgrounds to the muon sample. High p_T charged hadrons can fake muons either by penetrating the calorimeters and additional iron shielding without interaction, or by leakage of the hadronic shower. These backgrounds have been measured in a test beam and are found to be $\leq 10^{-4}$ per incident hadron after requiring matching between CD and muon chamber tracks. The leakage-induced background is then negligible. The dominant background process is pion and kaon decay. The probability for a pion (kaon) to decay before reaching the calorimeter is $\sim 0.02/p_T$ ($\sim 0.11/p_T$), where p_T is in GeV/c. This background has been evaluated from events with a single high p_T muon candidate by calculating the probability for decays of other high p_T particles (pion or kaon) in each event. The background is found to be $< 10^{-3}$ events.

The background contribution due to heavy flavour jets, with semileptonic decays has been estimated from events with a large-p_T lepton accompanied by a recoil jet (< 10^{-3}). The Drell-Yan continuum[5] yields a background of 0.1 events for masses greater than 60 GeV/c^2. Production of W^+W^- pairs was found to be completely negligible.

5. RESULTS

The masses of the 15 events which survive our selection criteria are shown in fig. 1. Two clear classes are identified. Ten events cluster at low masses, and will be discussed in a separate paper. The other five events, which have high masses, are reported here. Their parameters are listed in Table 1.

Including the muons in the calculation of the vector energy, all events are consistent with having no missing transverse energy. It is therefore justifiable to apply the method of transverse momentum balance, as described in section 2. It also means that the transverse momentum, $p_T^{\mu\mu}$, of the dimuon system is balanced by the transverse energy flow of the "rest of the event". This quantity has smaller measurement errors than the $p_T^{\mu\mu}$ determined from the momenta of the muons. We therefore show $p_T^{\mu\mu}$ as determined from the total energy flow in fig. 4a and table 1.

Three events show a topology different from what was naively expected for Z^0-production. Only two events, D and E show small $p_T^{\mu\mu}$ and have no jet activity.

In event C a single neutral electromagnetic deposition of E=28.3 GeV, consistent in shower development with one or several γ (π^0) was found near to one of the muons. Otherwise the event is very "quiet", the scalar E_T of the "rest of the event" is 15.6 GeV, smaller than the average activity in minimum bias events. This $\mu\mu\gamma$ event C should be considered in the context of two similar events found in the electron decay channel by the UA1 and UA2 Collaborations [6,7]. These events were interpreted as $Z^0 \rightarrow e^+e^-\gamma$. For both electron events it is necessary to include the γ to reconstruct a mass that is consistent with the Z^0-mass. In addition, the p_T of the $e^+e^-\gamma$ system is significantly smaller than the p_T of the

e^+e^- system. The same tendency is seen in the $\mu^+\mu^-\gamma$-event, but the measurement errors are much larger. The mass values and transverse momenta are listed in table 2. As for the electron events, the γ is close to one of the leptons. Both the angle $\alpha_0(\mu^+\gamma) = 7.9^0 \pm 0.1$ and the fraction $k_0 = 0.35 \pm 0.04$ of the energy carried by the γ are too large to be accounted for by bremsstrahlung. For muons the probability of external bremsstrahlung is negligible. The calculated probability for internal bremsstrahlung is

$$P \quad (\alpha > \alpha_0, \ k > k_0) = 0.007.$$

Hence less than 0.04 $Z^0 \to \mu\mu$ events are expected to show a bremsstrahlung as observed in event C. In what follows the γ will always be included in the $\mu\mu$ system.

The events A and B show large jet activity of a similar configuration, fig. 2 and 3. In both events the jet activity is shared by four jets (table 3), one of them forward and the other three in the central rapidity region $|\eta| < 1.2$. The masses and transverse momenta of the muon jet system are given in table 4. The multijet masses alone are in the IVB mass range. The masses of the muons and the central jets exceeds 120 GeV/c^2. Similar high masses were found in one $Z^0 \to e^+e^-$ event[2)], that also shows large jet activity, and in the events with mono jets and missing energy[8)]. These events contain considerably more jet activity than expected from QCD. A high statistics experiment is planned in order to conclusively assess the existence of such a phenomena.

The measured transverse momentum of the Z^0, p_T^Z, is given in fig. 4a together with the distributions for $Z^0 \to e^+e^-$ and $W^\pm \to \mu\nu$, $e\nu$. They are all consistent with a common distribution. Figure 4b shows the longitudinal motion of the IVBs, which is determined mainly by the structure functions for the valence quarks. The Z^0 decay angular distribution, shown in fig. 4c, shows no significant structure with present statistics.

Averaging the observed mass values of the four $\mu^+\mu^-$ events and the $\mu^+\mu^-\gamma$ event we find

$$<m_{\mu\mu}> = 85.8^{+7.0}_{-5.4} \text{ GeV/c}^2$$

consistent with the value measured for $Z^0 \to e^+e^-$[2,7],

$$<m_{ee}> = 95.6 \pm 1.4(\pm 2.9) \text{ GeV/c}^2, \qquad \text{(UA1)}$$

where the first error accounts for the statistical error and the second for the uncertainty of the overall energy scale of the electromagnetic calorimeters. The average value from all 9 Z^0 events found in the UA1 experiment is $m_{Z^0} = 93.9 \pm 2.9$ GeV/c^2. The error includes the systematic uncertainty.

The integrated luminosity for the present data sample is 108 nb^{-1}, with an estimated uncertainty of 15%. With the geometrical acceptance of 0.37 the cross-section, calculated using the 4 events with both tracks longer than 40 cm, is

$$(\sigma.B)_{\mu\mu} = 100 \pm 50 \ (\pm 15) \text{ pb},$$

where the last error includes the systematics both from acceptance and luminosity. This value is in good agreement both with Standard Model predictions[9] and with our results for $Z^0 \to e^+e^-$, namely $(\sigma.B)_{ee} = 41 \pm 21(\pm 7)$ pb. From the electron and the muon channels we get the average cross-section of

$$(\sigma.B)_{\ell\ell} = 58 \pm 21(\pm 9) \text{pb}.$$

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FIGURE CAPTIONS

Fig. 1. Invariant mass distribution of the $\mu\mu$ system for events where both muons have transverse momenta larger than 5 GeV/c. The bottom part of the figure shows the mass values with their errors for the 5 Z^0 candidates A to E as determined by using the method of E_T-balance (events A,B,D,E). For event C the topology of which is unusual, we chose to relax our assumption about missing energy and therefore used muon momenta determined without the balance constraint. The errors on the masses for the events below $M_{\mu\mu}$ = 30 GeV/c^2 are small.

Fig. 2. Configuration of the $Z^0 \rightarrow \mu^+\mu^-$ event A with jets :

a) in the plane transverse to the beam axis,

b) in pseudorapidity η.

c) "Lego"-plot of the energy deposition in the calorimeters as function of η and azimuth ϕ.

Fig. 3. Same as fig. 2, but for the $Z^0 \rightarrow \mu^+\mu^-$ event B. The CD jet (No.4) is indicated with a dotted line; it does not appear on the Lego plot of the calorimeter cells.

Fig.4. a) Transverse momentum distributions of the lepton pairs originating from $W \rightarrow \ell^+\nu$ and $Z^0 \rightarrow \ell^+\ell^-$ decays.

b) Fractional beam momentum (x_F) distributions of these lepton pairs. (In the case of $W \rightarrow \ell^\pm\nu$ the smaller of the two solutions for X_F is plotted when the ambiguity could not be resolved.)

c) Angular distributions of the leptons in the Z^0 rest frame. We define θ^* as the angle between the positive lepton and the outgoing antiproton direction.

Table 1. Properties of the UA1 High Mass Dimuon Events.

	Properties of the individual muons		Lepton-pair properties			General event properties excluding $\mu^+\mu^-$		
Run Event	Q	$p^{a)}$ (GeV/c)	Mass (GeV/c^2)	p_T (GeV/c)	x_F	E_{tot} (GeV)	$\Sigma\|E_T\|$ (GeV)	Charged tracks
A 6219 947	+	34.4^{+6}_{-5}	80.1^{+13}_{-10}	11.4±3.9	0.01	383	83.1	50
	−	47.8^{+11}_{-7}						
B 6600 222	+	55.8^{+8}_{-6}	86.5^{+9}_{-8}	16.6±3.4	0.15	167	47.3	26
	−	40.1^{+5}_{-4}						
C 6636 509	+	50.6^{+6}_{-5} b)	88.4^{+46}_{-15} c)	5.7±2.0 c)	0.33 c)	219	26.1	30
	−	42.2^{+44}_{-14} b)						
D 8523 831	+	61.8^{+16}_{-11}	95.8^{+24}_{-16}	$1.3^{+2.6}_{-1.3}$	0.20	270	27.7	22
	−	45.7^{+12}_{-8}						
E 7428 1110	+	40.6^{+36}_{-13}	87.5^{+61}_{-28}	5.6±2.5	0.03	303	34.0	32
	−	47.5^{+34}_{-14}						

a) Average momentum obtained from the three methods, see text.

b) Momenta obtained without E_T balance.

c) Parameters for $(\mu^+\mu^-\gamma)$ − System

Table 2. Mass values for the $Z^0 \to \mu\mu\gamma$ event C. The parameters of the γ/π^0 are $E_T = 10.5 \pm 0.9$ GeV, $\eta = -1.7$, $\phi = -152^0$.

Combination	Mass GeV/c^2	p_T GeV/c
$\mu^+\mu^-\gamma$	88.4^{+46}_{-15}	5.7 ± 2.0 1)
$\mu^+\mu^-$	70.9^{+37}_{-12}	10.4 ± 2.4 1)
$\mu^+\gamma$	5.0 ± 0.4	30^{+3}_{-2}
$\mu^-\gamma$	52.5^{+28}_{-9}	31^{+43}_{-14}

1) From calorimetry only.

TABLE 3. Jet Parameters of the $Z^0 \rightarrow \mu^+\mu^-$ Events A, B, see fig. 2 and 3.

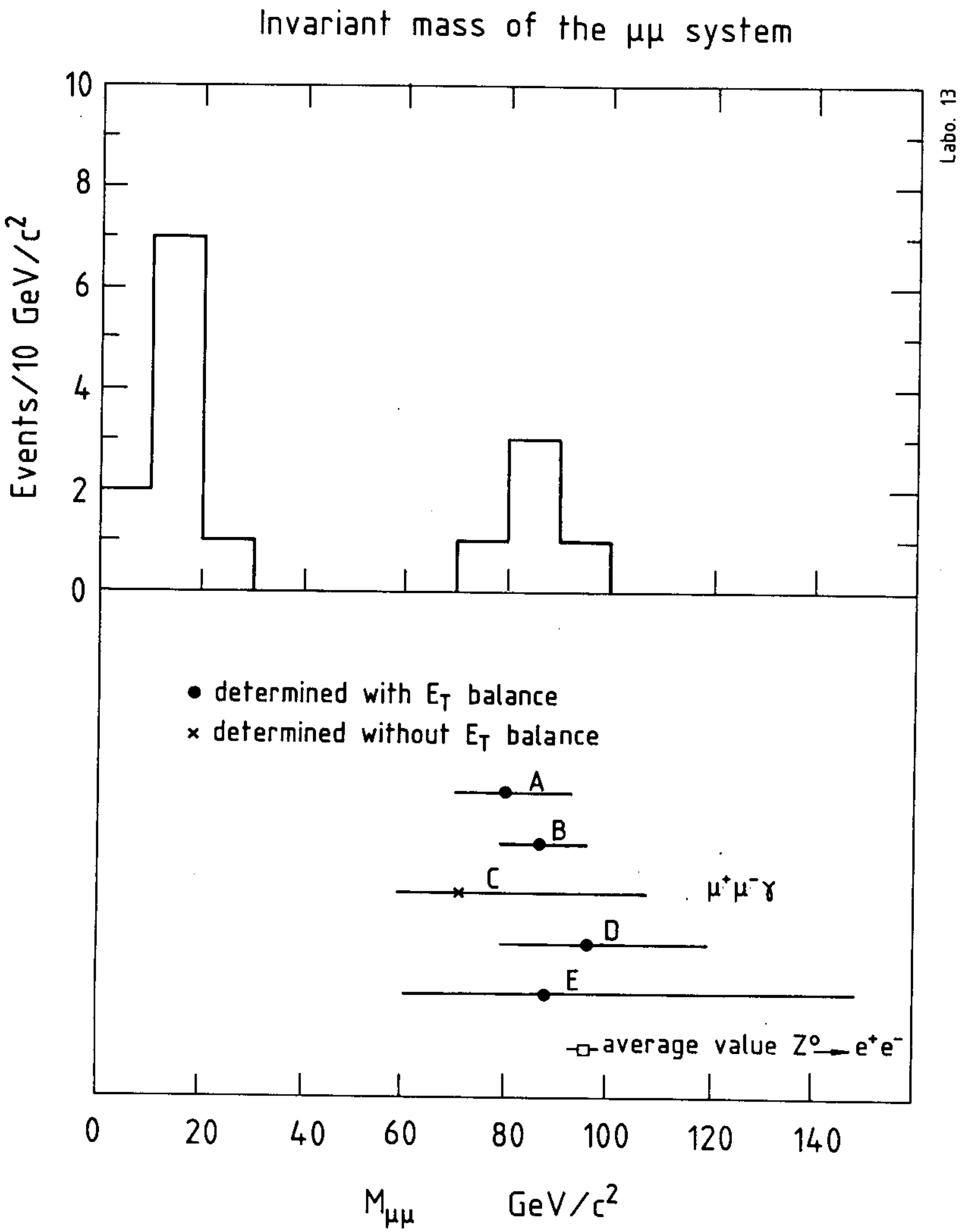
Run Event	Jet No.	E_T GeV GeV	η	ϕ deg
A 6219 947	1	22.8 ± 3.3	0.1	177
	2	13.0 ± 2.2	-0.7	-7
	3	11.5 ± 4.4	-1.1	-162
	4	16.9 ± 3.0	-2.3	32
B 6600 222	1	11.2 ± 4.1	0.6	6
	2	20.6 ± 3.5	2.1	-115
	3	10.1 ± 3.8	-0.5	-156
	4	> 7.1 ± 0.1 [1)]	1.2	-88

1) Only the charged component of the jet is given (CD jet), since the jet points towards an insensitive region of the calorimeter.

Table 4. The $Z^0 \to \mu^+\mu^-$ Events with Jets : Mass, p_T, X_F.

Run Evt	Combination	Mass GeV/c²	p_T GeV/c	X_F
A 6219 947	$\mu^+\mu^-$	80.1^{+13}_{-10}	18^{+9}_{-7}	0.01±0.03
	$\mu^+\mu^-$ central jets	149 ± 17	24 ± 10	-0.08±0.04
	$\mu^+\mu^-$ all jets $\lvert\eta\rvert<2.5$	214 ± 21	24 ± 12	-0.39±0.07
	central jets	62 ± 9	21 ± 6	-0.08±0.02
	all jets $\lvert\eta\rvert<2.5$	114 ± 14	8 ± 7	-0.40±0.06
B 6600 222	$\mu^+\mu^-$	$86.5^{+9.4}_{-8.4}$	21^{+6}_{-5}	0.13±0.02
	$\mu^+\mu^-$ central jets[1)]	129 ± 16	15 ± 6	0.18±0.03
	$\mu^+\mu^-$ all jets[1)] $\lvert\eta\rvert<2.5$	183 ± 22	10^{+13}_{-10}	0.50±0.06
	central jets[1)]	39 ± 8	10 ± 5	0.05±0.01
	all jets[1)] $\lvert\eta\rvert<2.5$	81 ± 16	29 ± 6	0.37±0.05

1) CD Jet included.



Invariant mass of the μμ system
Labo. 13
Events/10 GeV/c²
0
2
4
6
8
10
● determined with E_T balance
× determined without E_T balance
A
B
C
D
E
μ⁺μ⁻γ
average value Z° → e⁺e⁻
0
20
40
60
80
100
120
140
M_μμ GeV/c²

Fig. 1

EVENT A 6219. 947.
GRID INTERVAL = 10.0 GEV/C

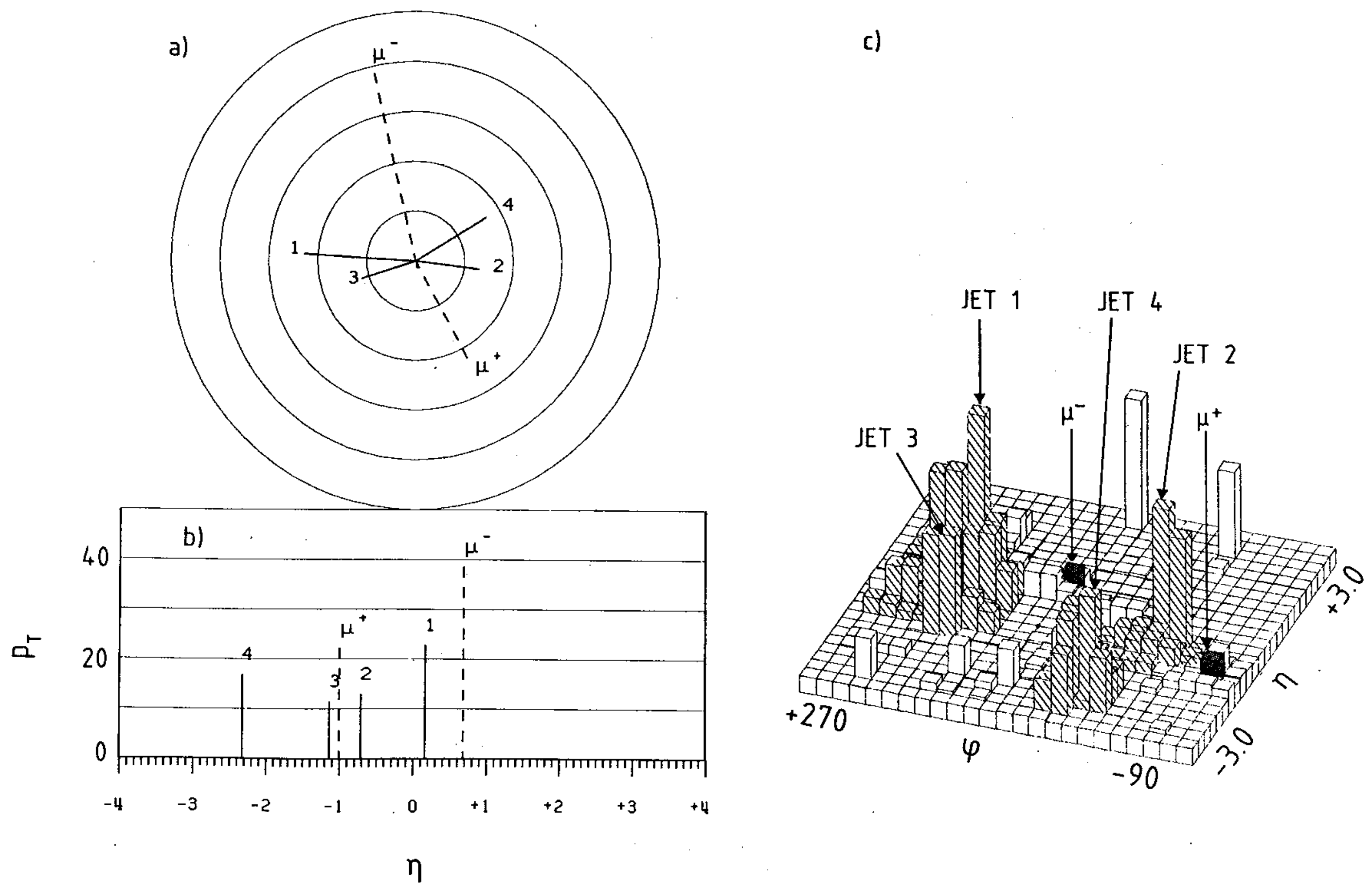


FIG. 2

EVENT B 6600. 222.
GRID INTERVAL = 10.0 GEV/C

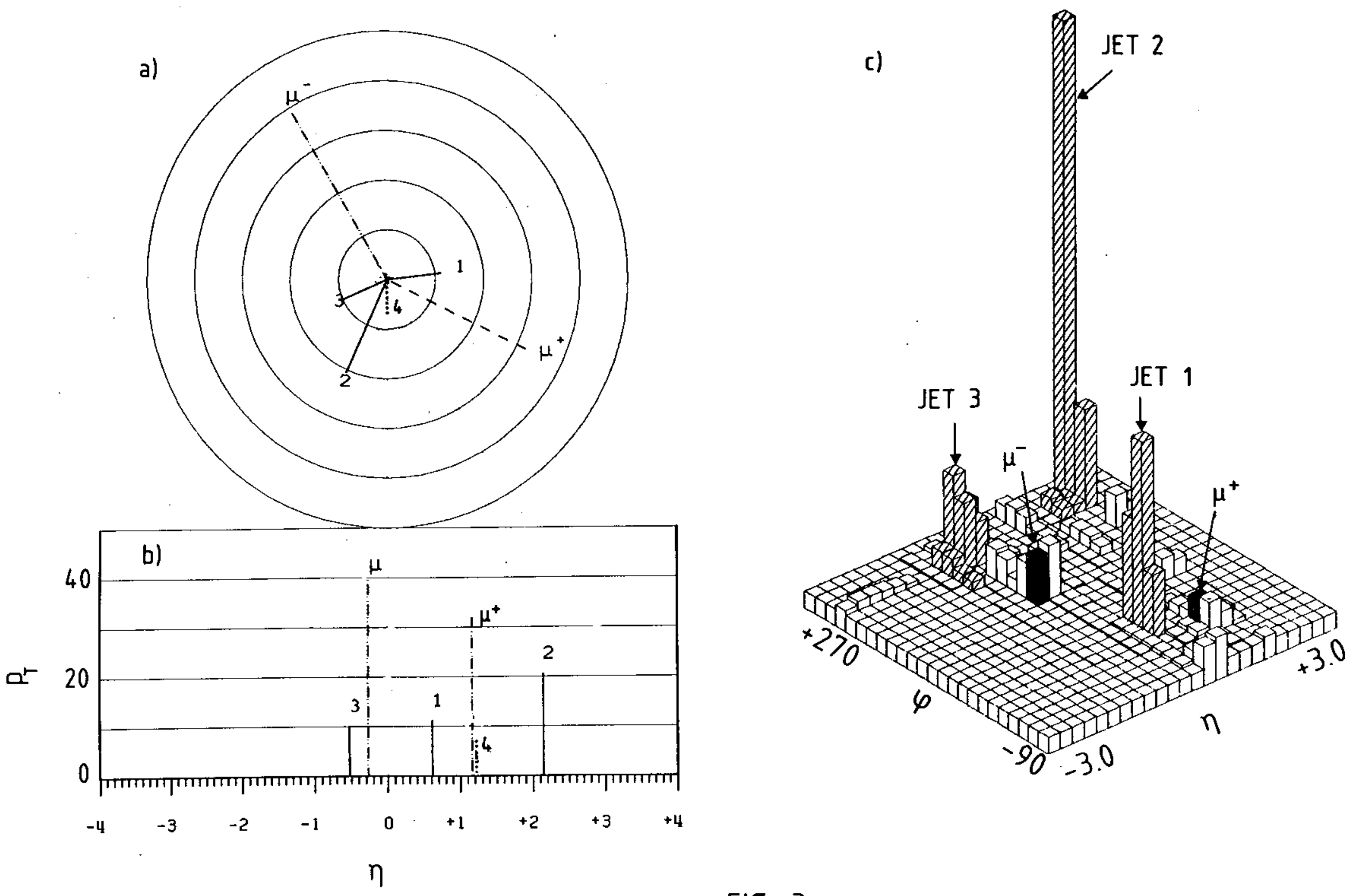
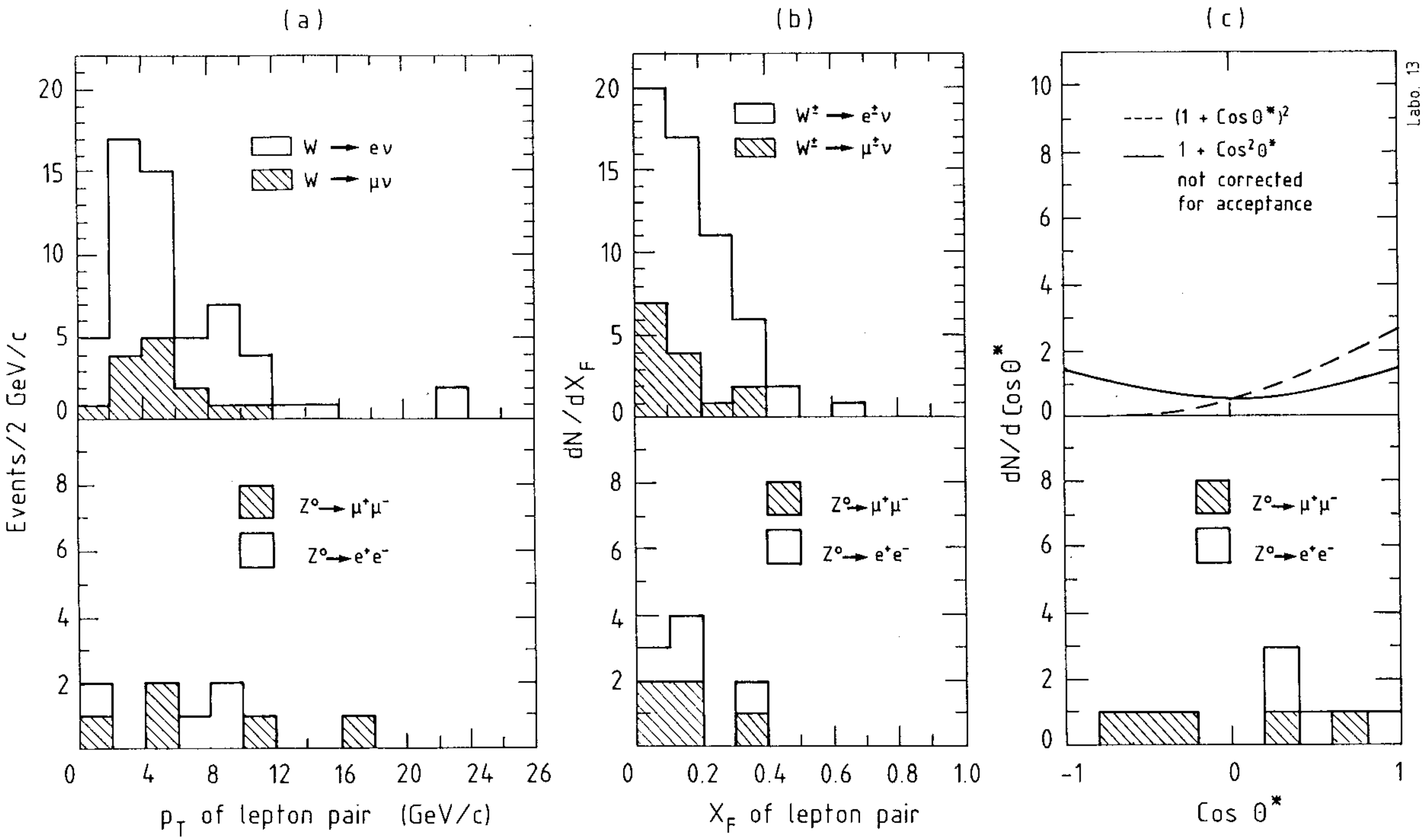


FIG. 3



(a)
(b)
(c)
Labo. 13
W → eν
W → μν
W± → e±ν
W± → μ±ν
Z° → μ+μ-
Z° → e+e-
--- (1 + Cos θ*)²
— 1 + Cos²θ*
not corrected
for acceptance
Events/2 GeV/c
dN/dX_F
dN/d Cos θ*
p_T of lepton pair (GeV/c)
X_F of lepton pair
Cos θ*

Fig.4