Measurement of direct electron-positron pair production from hadronic bremsstrahlung

A. T. Goshaw, L. E. Evans, L. R. Fortney, J. S. Loos,* W. J. Robertson, and W. D. Walker
Duke University, Durham, North Carolina 27706

R. C. Field and V. Chaloupka
Stanford Linear Accelerator Center, Stanford, California 94305

P. J. Dornan, G. Hall, and A. P. White
Imperial College, London, England
(Received 6 July 1981)

We have made a measurement of very-low-energy e^+e^- pair production from $\pi^\pm p$ collisions at 18 GeV/c. Using the SLAC 1-m bubble chamber to study a sample of 178×10^3 interactions, we find a signal of centrally produced direct e^+e^- pairs which accounts for $(48\pm 13)\%$ of all e^+e^- pairs detected with $|x| < 0.02$ and $P_T < 10$ MeV/c. This measurement agrees with a calculation of e^+e^- pair production from the internal conversion of hadronic bremsstrahlung.

I. INTRODUCTION

One of the most basic direct electron production mechanisms in hadronic collisions is the internal conversion of bremsstrahlung photons arising from the acceleration of charged hadrons. This process is expected to be the dominant source of direct electron production near threshold and several theoretical papers have been devoted to calculations of its cross section.[1] The interest in this process stems partly from its basic character and partly because it must be removed from the total direct electron production spectrum before any anomalous low-energy electron signals can be isolated for analysis. It is rather remarkable that, despite the fundamental nature of this process, it has never been measured experimentally.

We report here results from a measurement we have made of the production of low-energy electrons and positrons from $\pi^\pm$-proton collisions at 18 GeV/c. These data are used to isolate a signal of very-low-energy, directly produced e^+e^- pairs which are identified as coming from the internal conversion of hadronic bremsstrahlung. In this introduction, we first review the theoretically expected sources of direct electron production from hadronic collisions and summarize the expected production characteristics of low-energy e^+e^- pairs. We then briefly review the experimental data that are available on low-energy direct e^- and e^+ production. With this background established, we discuss our experimental procedure (Sec. II), the e^+e^- pair data (Sec. III), and finally a comparison of our data to theory (Sec. IV).

A. Theory of electron-positron pair production by hadronic bremsstrahlung

In this discussion electrons and positrons coming from the secondary electromagnetic or weak decays of produced hadrons will be excluded. This leads us to consider the dynamics of e^+e^- pair production only, which can be conveniently divided into external hadronic-bremsstrahlung processes [Fig.

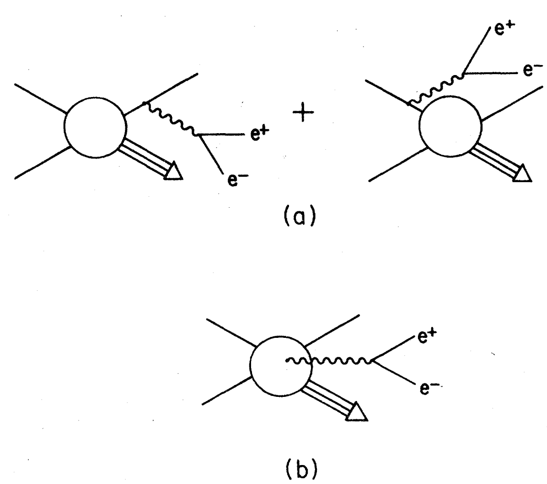

FIG. 1. Direct e^+e^- pair production from hadronic collisions: (a) hadronic bremsstrahlung; (b) other direct-emission sources (see the text).

1(a)] and direct-emission processes [Fig. 1(b)]. The contribution of hadronic bremsstrahlung to low-energy e^+e^- pair production is calculable from a knowledge of the hadronic-production cross section (see below). However, the direct-emission process is not calculable without a detailed knowledge of the hadronic-production matrix element, and therefore can only be estimated in a model-dependent manner. This has been done by numerous authors[2] using vector-meson dominance, hard quark-antiquark annihilation (the Drell-Yan mechanism), soft sea quark-antiquark interactions, and perturbative quantum chromodynamics. These processes make important contributions to $\mu^+\mu^-$ pair production and high-mass e^+e^- pairs. However, e^+e^- pair production near threshold is expected to be dominated by the simple hadronic-bremsstrahlung process, and the rest of our discussion will be limited to this source of direct electrons and positrons.

The cross section for the production of e^+e^- pairs from hadronic bremsstrahlung has been calculated by a number of authors with various assumptions about the detailed knowledge of the hadronic-production cross section.[1] The basic procedure is to start with the soft-photon theorem originally introduced by Low[3] and to demand an internal conversion of the bremsstrahlung photon. This leads to the following expression[4] for the production cross section for e^+e^- pairs from the hadronic interaction $1+2\rightarrow 3+4+\ldots+n$:

$$\frac{d\sigma}{d\mu\, d\omega\, d\Omega\, d\Omega^*}=\frac{\alpha^2}{(2\pi)^4}\left[\frac{[\mu^2-(2m)^2]^{1/2}(\omega^2-\mu^2)^{1/2}}{\mu^2\omega^2}\right]\times\int d^3P_3 d^3P_4\ldots d^3P_n\left[\frac{(J\cdot l)^2}{\mu^2}-J\cdot J\right]\frac{d\sigma^h}{d^3P_3 d^3P_4\ldots d^3P_n}\,. \tag{1}$$

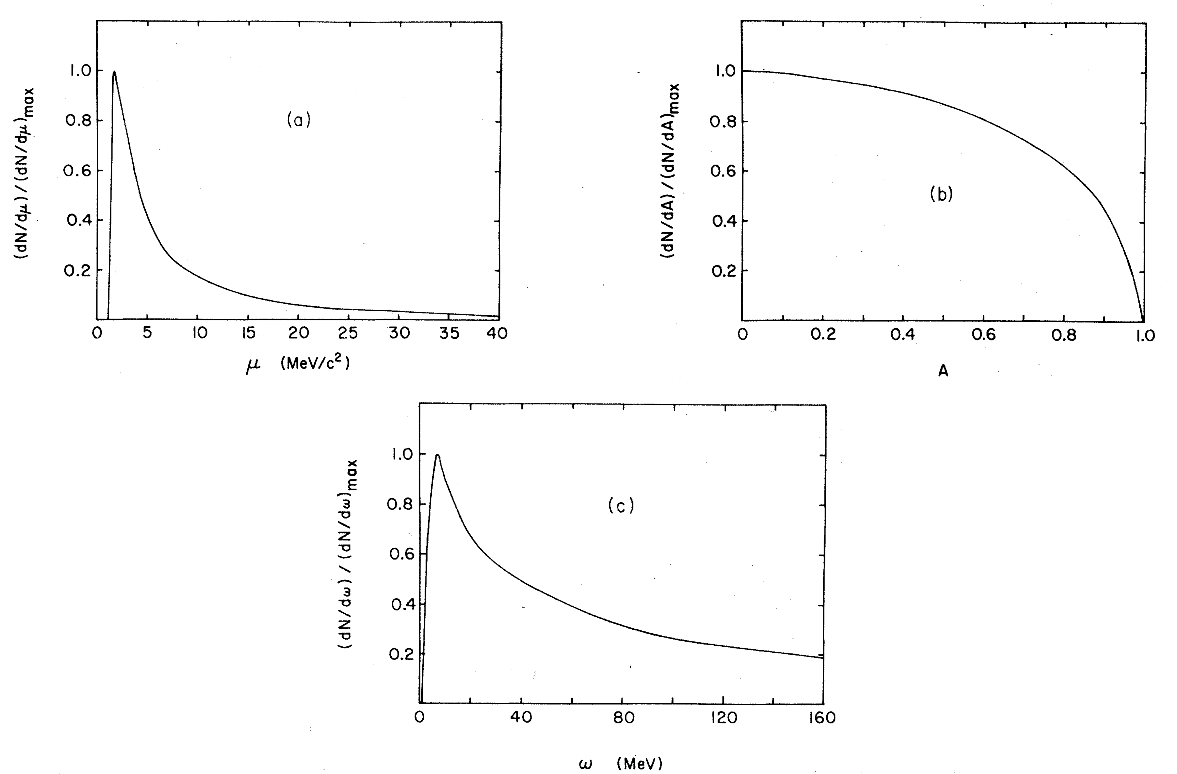

FIG. 2. Properties of e^+e^- pairs produced from hadronic inner bremsstrahlung: (a) the e^+e^- invariant-mass distribution; (b) the distribution of the energy partition between the e^+ and e^- $[A=|E_+-E_-|/(E_++E_-)]$; (c) the e^+e^-

In this expression $d\sigma^h/d^3P_3 \ldots d^3P_n$ is the center-of-mass hadronic-production cross section, μ the e^+e^- invariant mass, ω the e^+e^- energy in the center of mass, $d\Omega$ the e^+e^- production solid angle, and $d\Omega^*$ the solid angle of the e^+ in the e^+e^- rest system. J and l are the following four-vectors:

$$l = P_+ - P_- ,$$

$$J = \omega \sum_{i=1}^{n} \frac{Q_i}{(P_+ + P_-)\cdot P_i} P_i ,$$

where $P_\pm$ = the $e^\pm$ four-momentum and P_i = the four-momentum of the hadron with charge Q_i (see Ref. 5).

We have calculated the e^+e^- production properties from Eq. (1) using Monte Carlo techniques which use as input fully measured $\pi^\pm p$ interactions at 18 GeV/c. Therefore, there are no approximations in our theoretical predictions other than those inherent in the derivation of Eq. (1). We present here some results of these calculations in order to establish the characteristics of e^+e^- pair production due to hadronic inner bremsstrahlung. Some general properties of the produced e^+e^- pairs that are rather independent of production processes are shown in Fig. 2. The pair-production rate and angular distribution depend strongly on the number of charged particles produced in the event, the rapidity charge structure, and whether or not high-P_T charged particles are produced. Some typical production characteristics are shown in Fig. 3 where we have plotted the Feynman-x and P_T distributions of the bremsstrahlung e^+e^- pairs produced from 18-GeV/c π^-p four-prong events. These show that the e^+e^- pairs coming from this source are produced with very low x and P_T values. This is to be expected since the center-of-mass production spectrum is dominated by a $1/\omega$ energy dependence [see Eq. (1)] which restricts the pairs to have small values of longitudinal and tranverse momentum. The tranverse-momentum spectrum is further enhanced at low P_T because the e^+e^- pairs are emitted preferentially along the direction of the incident and produced charged hadrons.

Although the production characteristics shown in Fig. 3 are typical, we emphasize that the bremsstrahlung e^+e^- pairs from some hadronic final states will be quantitatively different. For example, if interactions with high-P_T charged hadrons are selected, the average e^+e^- transverse momentum will be appreciably increased due to the fact that there will be a bremsstrahlung component along the direction of the large-angle hadrons.

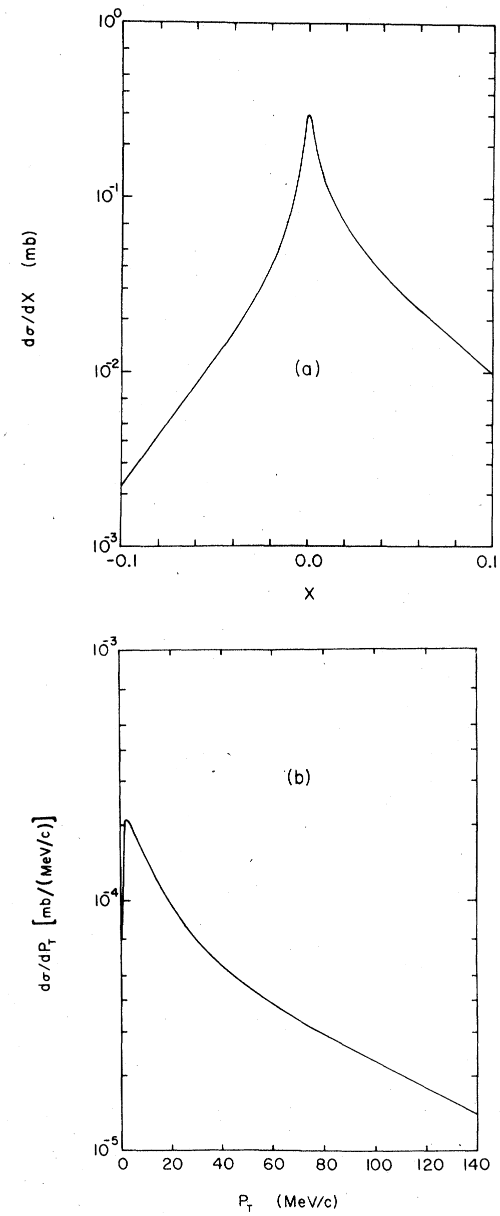

FIG. 3. Production characteristics of bremsstrahlung produced e^+e^- pairs coming from 18-GeV/c π^-p interactions with four charged particles in the final state. The data presented here are for pairs with center-of-mass energies less than 300 MeV: (a) the Feynman-x distribution; (b) the transverse-momentum distribution.

B. Previous measurements of low-mass e^+e^- pairs

We will limit this review of previous experiments to those studying the hadronic production of e^+e^-

pairs having masses less than that of the ρ^0 meson. To begin with, we note that no experimental evidence has been reported for the production of direct e^+e^- pairs with masses less than that of the π^0. However, several experiments have found direct e^+e^- pairs with masses between those of the π^0 and ρ^0 mesons. The data come from three π^-p experiments using π^- beams with energies of 16,[6] 17,[7] and 18 GeV/c.[8] All three experiments find an excess of e^+e^- pairs which cannot be explained from the Dalitz decay of mesons. The pairs are centrally produced with a rapidly falling P_T spectrum. In addition to these three π^-p experiments, two pp experiments[9] with proton beams of about 10 GeV/c have shown some evidence for direct e^+e^- pairs with masses just above the mass of the π^0 meson. Two CERN ISR experiments[10] have looked for direct e^+e^- production with $P_T > 2$ GeV/c and find none.

In summary, data from π^-p and pp interactions at intermediate energies show evidence for the production of direct e^+e^- pairs with masses between those of the π^0 and ρ^0 mesons. No satisfactory explanation of this low-mass e^+e^- continuum has been found. In the present experiment, we search for the hadronic production of direct e^+e^- pairs with masses less than that of the π^0 meson and compare the data to that expected from the pair conversion of hadronic inner bremsstrahlung.

II. EXPERIMENTAL PROCEDURE

Our experiment was designed to make an unbaised study of e^+e^- pair production from $\pi^{\pm}p$ interactions at 18 Gev/c. The data were taken in the SLAC 1-m bubble chamber which was fitted with three tantalum plates, each one radiation length thick, for the purpose of $e^{\pm}$ identification. The plate configuration within the bubble chamber is shown in Fig. 4; details of the $e^{\pm}$ identification are discussed below. These data have been used previously to search for the hadronic production of direct single $e^{\pm}$ (Ref. 11) and for anomalous e^+e^- pairs with mass greater than that of the π^0.[8] Here we are interested in low-mass e^+e^- pairs and will emphasize those aspects of the experimental procedure relevant to this measurement.

Each $\pi^{\pm}p$ interaction was examined for secondary particles that identified themselves as electrons or positrons by means of one of the following signatures: (1) Spiraling in the magnetic field ($e^{\pm}$ identifiable down $\sim$1 MeV /c), (2) bremsstrahlung

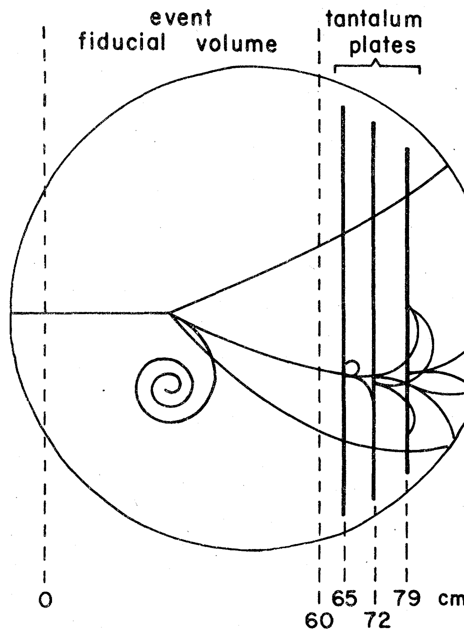

FIG. 4. A drawing of the SLAC 1-m bubble chamber showing the tantalum plates used for electron and positron identification. An e^+e^- pair is shown in which the e^- is identified by spiraling and the e^+ by an electromagnetic shower in the plates.

in the hydrogen, (3) high-energy secondary electrons, (4) ionization (useful up to $\sim$200 MeV/c), and (5) electromagnetic showers initiated in the tantalum plates. These combined identification techniques make the experiment sensitive to electrons of all momenta down to $\sim$1 MeV/c. The actual detection efficiency of the $e^{\pm}$ was measured by making use of e^+e^- pairs produced from the conversion of photons in the hydrogen. The criteria described above were applied to this source of known $e^{\pm}$ and a detection-efficiency function was evaluated. Figure 5 shows the energy dependence

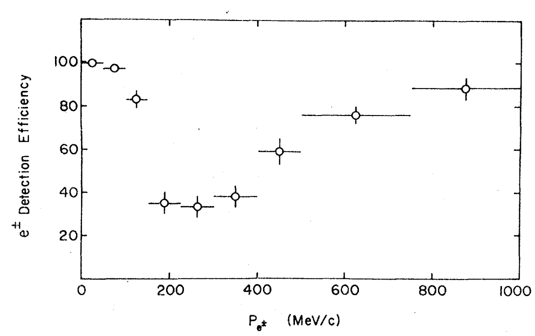

FIG. 5. The detection efficiency (in percent) of electrons and positrons as a function of momentum (averaged over the event fiducial volume).

of this efficiency averaged over e^+e^- pairs produced upstream of the tantalum plates.

Misidentification of hadrons as electrons has been carefully studied and measured[11] to be less than 1 in $10.^4$ For the results presented here, we accept only those e^+e^- pairs in which *both* the e^+ and e^- have been identified, and therfore the hadron contamination is completely negligible.

The $\pi^{\pm}p$ interactions were scanned initially with loose electron identification criteria that were designed to safely include all $e^{\pm}$ having the signatures described above. All candidate $e^{\pm}$ were measured and then reexamined by physicists who strictly applied the criteria (1) to (5). The average scanning efficiency for finding identifiable e^+e^- pairs was $(95\pm1)\%$. This efficiency was studied as a function of the longitudinal and transverse momenta of the pairs; no significant variation was found.

The data consist of 3057 e^+e^- pairs produced from 74 800 π^+p and 103 450 π^-p interactions. The background caused by photons converting to e^+e^- pairs in the hydrogen near the vertex is estimated to be 170 ± 50 events. All data are corrected for the scanning loss described above (average event weight $=1.05$). When comparisons of the data are made to theory, the predicted e^+e^- spectrum is modified by the experimental $e^{\pm}$ detection efficiency.

III. THE e^+e^- PAIR DATA

We have chosen for analysis all those e^+e^- pairs having masses less than one-half of the π^0's mass. This cut reduces the total number of 3057 pairs down to 2924. All of the e^+e^- pair spectra presented below are taken from these 2924 pairs with no distinction between π^+p and π^-p production.

The major contributor of e^+e^- pairs to this data is the Dalitz decay of π^0 mesons produced in the $\pi^{\pm}p$ interactions: $\pi^{\pm}p\rightarrow X\pi^0$, $\pi^0\rightarrow\gamma e^+e^-$. Therefore, a simulation of this process is essential if a relatively small direct e^+e^- pair signal is to be extracted from the data. Fortunately, the π^0 Dalitz pairs result from essentially a tertiary process and consequently have longitudinal- and traverse-momentum spectra which depend relatively weakly on the production dynamics of the π^0 as compared to the well known decay dynamics. These spectra can therefore be calculated very reliably. Two independent simulation programs were used at different institutions and were found to produce compatible results. A brief description of one of these simulations is given below.

The analysis begins by assuming that all of the e^+e^- pairs are Dalitz pairs from the decay of π^0 mesons, and proceeds to search for signals in the data that are incompatible with this assumption. The π^0 production spectrum from $\pi^{\pm}p$ interactions at 18 GeV/c was generated using a Monte Carlo technique that has been shown to be successful in predicting measured photon spectra from πp collisions.[12,13] The starting point of this prediction is the measured π^- production spectrum from π^+p collisions (π^+ from π^-p collisions could equally well be used). A Monte Carlo calculation was made to simulate the Dalitz decay "π^-"$\rightarrow\gamma e^+e^-$. At this stage the mass cut on the e^+e^- pairs was applied and each e^+ and e^- was weighted by the experimental detection efficiency. The Feynman-x distribution of the π^- was then weighted by a smooth function of the x variable of the π^- until the simulated x distribution of the e^+e^- pairs fitted that of the measured data.

Figure 6 shows the x distribution of the e^+e^- pair data. The solid curve is the result of our fit to the data from the expected contribution of detected Dalitz pairs from π^0 decays. The fit is excellent and requires no additional source of e^+e^- pairs. Consequently, at this point in our analysis we have determined the e^+e^- pair spectrum from π^0 Dalitz decays under the assumption that the π^- and π^0 production at the same x value has the same P_T distribution. Our final direct e^+e^- pair signal is very insensitive to this assumption.

Figure 7 shows the $P_T{}^2$ distribution of the e^+e^- pairs produced in the central x region. Once again, the solid curves are the $P_T{}^2$ spectra expected

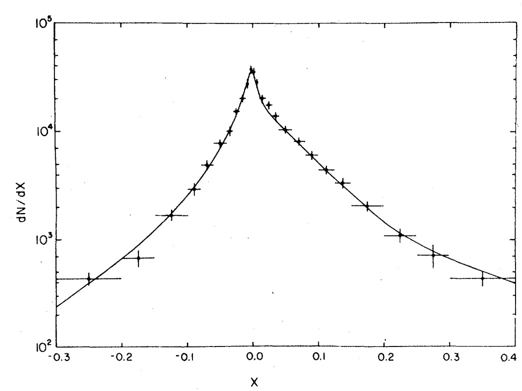

FIG. 6. The Feynman-x distribution of measured e^+e^- pairs. The solid curve is a fit to these data using Monte Carlo-simulated π^0 Dalitz decays.

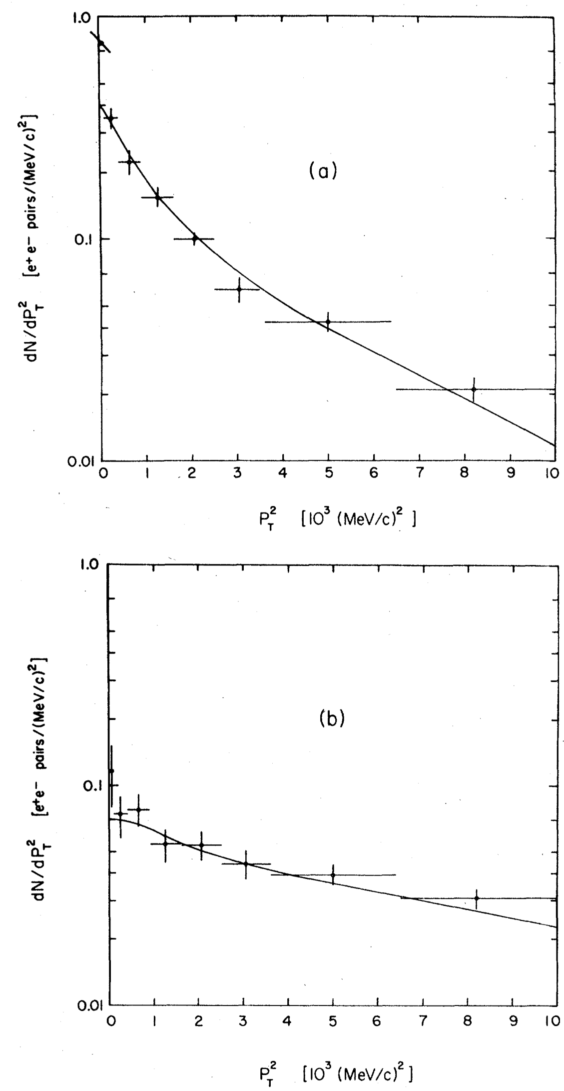

FIG. 7. The $P_T{}^2$ distribution of measured e^+e^- pairs. The solid curves are estimates of the contribution of e^+e^- pairs from the Dalitz decay of π^0's; (a) pairs with $|x| < 0.02$; (b) pairs with $0.02 < |x| < 0.06$.

from detected Dalitz-pair decays of π^0's. Figure 7(a) includes all pairs with $|x| < 0.02$ and shows an excess of e^+e^- pairs produced with $P_T{}^2 < (10$ Mev/$c)$.[2] The statistical significance of this effect is 5 standard deviations (39 events expected and 76 events observed). The pair spectrum at higher values of $P_T{}^2$ is well fitted by the predicted π^0 Dalitz pairs and cannot be modified to explain the low-$P_T{}^2$ excess.[14]

A cut selecting e^+e^- pairs with smaller $|x|$ values increases the statistical significance of the low-$P_T{}^2$ excess but loses some of the direct-pair signal. It is found, for example, that the e^+e^- data within the range $|x| < 0.0075$ and $P_T{}^2 < (5$ Mev/$c)^2$ disagrees with the π^0 Dalitz-pair prediction by over 10 standard deviations (5 events expected and 33 observed). Figure 7(b) shows the $P_T{}^2$ spectrum for pairs with $0.02 < |x| < 0.06$. This can be fitted acceptably over the entire range by π^0 Dalitz pairs.

We have also studied the spectrum of Dalitz pairs from other hadron decays ($\eta \to \gamma e^+e^-$, $\omega \to \pi^0 e^+e^-$, $\Sigma^0 \to \Lambda e^+e^-$, etc.). None of these decays make any appreciable contribution of e^+e^- pairs in the signal region. Externally converted photons also make a negligible contribution to the signal.

We therefore conclude that we have found a direct e^+e^- pair signal with $|x| < 0.02$ ($|P_L| < 60$ MeV/c) and $P_T < 10$ MeV/c. This signal consists of 37 ± 10 events or $(48 \pm 13)\%$ of all e^+e^- pairs detected in this kinematic range. Figure 8 presents the $P_T{}^2$ distribution of the direct e^+e^- pairs obtained by subtracting the π^0 Dalitz pairs from the data shown in Fig. 7(a).[14]

IV. COMPARISON OF THE DATA TO THEORY

We are able to account for the observed direct e^+e^- pair signal on the basis of the internal conversion of bremsstrahlung photons produced from the charged hadrons accelerated in the collisions

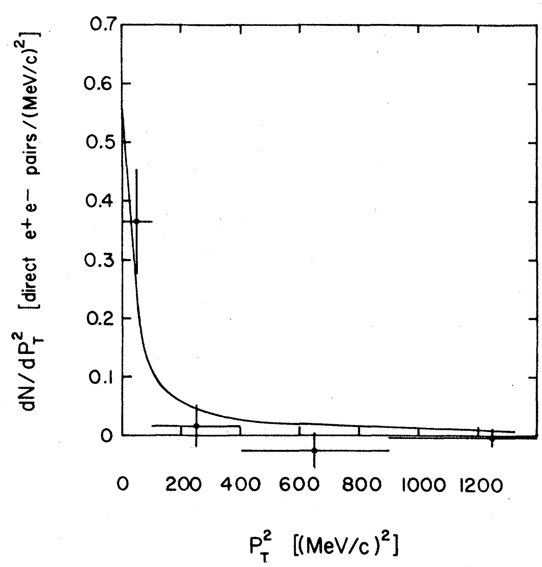

FIG. 8. The measured signal of direct e^+e^- pairs. The solid curve is the theoretical prediction of e^+e^- pairs produced from the internal conversion of hadronic inner bremsstrahlung.

[see Fig. 1(a)]. The cross section for this process, given by Eq. (1), can be evaluated using the Monte Carlo procedure discussed in Sec. I A. The charged-hadron-production cross section, $d\sigma^h/d^3P_3 \ldots d^3P_n$, was obtained from measurements of all the charged tracks, on an event-by-event basis, in a sample of $\pi^{\pm}p$ interactions at 18 GeV/c. Using this data as input to Eq. (1), the absolute number and production spectrum of bremsstrahlung-induced e^+e^- pairs was calculated for the total sample of 74 880 π^+p and 103 450 π^-p collisions. Each e^+e^- pair was subjected to the detection efficiency of our experiment so that the theoretical prediction could be compared directly to our data.

The solid curve in Fig. 8 is the resulting prediction for the $P_T{}^2$ spectrum of e^+e^- pairs with $|x| < 0.02$. Good agreement is found, both in the rate and the $P_T{}^2$ dependence, between our observed direct e^+e^- pair signal and the pairs expected from the internal conversion of hadronic inner bremsstrahlung. The prediction corresponds to a yield of 3.4×10^{-5} pairs produced with $P_T < 10$ MeV/c per charged hadron.

V. SUMMARY

We have measured for the first time the production of low-mass (<20 MeV/c^2), direct e^+e^- pairs from hadronic collisions. The measured signal drops off rapidly as a function of x and P_T of the e^+e^- pair and is observable only if very-low-energy $e^{\pm}$ are detected (most of the direct e^+e^- pairs observed have $e^{\pm}$ laboratory momenta in the range 1 to 150 MeV/c). In the kinematic range $|x| < 0.02$ and $P_T < 10$ MeV/c, we find that direct e^+e^- pair production from $\pi^{\pm}p$ collisions at 18 GeV/c is about equal to the production of e^+e^- pairs from the Dalitz decay of hadrons [$(48\pm13)\%$ of all detected pairs are directly produced]. These data agree well with the prediction of e^+e^- pair production from the internal conversion of hadronic inner bremsstrahlung. We conclude that our measurement is the first observation of this basic source of direct e^+e^- pairs.

The same QED mechanism, hadronic inner bremsstrahlung, predicts that soft direct photons should be emitted from hadronic collisions at a rate approximately $1/\alpha = 137$ times that of the direct e^+e^- pairs. Some of us have recently reported the results of a study of direct photon production from collisions at 10.5 GeV/c,[13] and find that the production characteristics of these direct photons are also in agreement with the predictions of hadronic inner bremsstrahlung.

ACKNOWLEDGMENTS

We would like to thank the University of Notre Dame, especially J. M. Bishop, for providing us with their 18.5-GeV/c $\pi^{\pm}p$ data. We also wish to thank the SLAC accelerator and bubble-chamber staff for their efficient operation of the equipment. This work was supported in part by the U. S. Department of Energy.

---

*Now at Argonne National Laboratory, Argonne, IL 60439.

[1]R. Ruckl, Phys. Lett. 64B, 39 (1976); N. S. Craigie and H. N. Thompson, Nucl. Phys. B141, 121 (1978); N. S. Craigie, Phys. Rep. 47, 1 (1978).

[2]A complete survey of these theoretical studies is beyond the scope and peripheral to the intent of our research. We give here a few relevant review papers which contain extensive references: L. M. Lederman, Phys. Rep. 26C, 149 (1976); J. W. Cronin, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1977,* edited by F. Gutbrod (DESY, Hamburg, 1977); L. M. Lederman, in *Proceedings of the 19th International Conference on High Energy Physics, Tokyo, 1978,* edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Phys. Soc. of Japan, Tokyo, 1979); S. Mikamo, INS Symposium on Particle Physics in the GeV Region, Tokyo, 1979 (unpublished).

[3]F. E. Low, Phys. Rev. 110, 974 (1958); T. H. Burnett and M. Kroll, Phys. Rev. Lett. 20, 86 (1968).

[4]Equation (1) is a QED calculation done to lowest order in α and does not include hadron off-mass-shell effects or form factors. These approximations are expected to be valid for the low-mass, low-energy direct e^+e^- pairs studied in this experiment. A more complete theoretical study of hadronic inner bremsstrahlung is being undertaken by one of us (A. T. G.) and the results, including the derivation of Eq. (1), will be published separately.

[5]Q and P of the incident hadrons are the negative of their physical values. The metric chosen has $P\cdot P = +m^2$.

[6]R. Stroynowski *et al.*, in *High Energy Physics — 1980,* proceedings of the XXth International Conference, Madison, Wisconsin, edited by L. Durand and L. G. Pondrom (AIP, New York, 1981), p. 161.

[7]G. Abshire *et al.*, in *High Energy Physics — 1980*

(Ref.6), p. 158.
[8]J. Ballam et al., Phys. Rev. Lett. 41, 1207 (1978).
[9]E. W. Beier et al., Phys. Rev. Lett. 37, 1117 (1976); S. Naito et al., submitted to INS Symposium on Particle Physics in the GeV Region, Tokyo, 1979 (unpublished).
[10]J. H. Cobb et al., Phys. Lett. 78B, (1978); A. Chilingarov et al., Nucl. Phys. B151, 29 (1979).
[11]J. Ballam et al., Phys. Rev. Lett. 40, 741 (1978).
[12]J. R. Elliott et al., Phys. Rev. D 17, 83 (1978).
[13]A. T. Goshaw et al., Phys. Rev. Lett. 43, 1065 (1979).
[14]An idependent simulation of the $\pi^0 \to e^+e^-\gamma$ background had a shallower P_T dependence and resulted in a somewhat higher value of the excess e^+e^- pairs. This would increase the significance of our observed signal, without changing the quoted yield outside the assigned errors.