Hadron Production at Large Transverse Momentum

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We have studied production of π^0 with transverse momentum between 2.0 and 4.4 GeV/c at 65 and 93° in the c.m. system in 300-GeV proton-nucleon collisions, by inserting foils of various thicknesses into a secondary beam and measuring the electron and positron spectra produced by γ conversion. The π^0 invariant cross sections are given at 93 and 65°. We also report invariant cross sections for negatively charged hadrons as a function of transverse momentum.

The discovery of a copious yield of hadrons[1] produced at high transverse momentum provides a new tool for short-range hadrodynamics. We have performed a high-luminosity, large-acceptance search for "direct" leptons at the Fermi National Accelerator Laboratory (FNAL), observing particles produced at wide angles in 300-GeV proton-nuclear collisions. In the course of this search,[2] we measure the spectra of electrons and positrons produced by γ conversion in thin foils. The conversion-electron spectra allow us to deduce the π^0 spectra under the assumption that all of the γ's come from π^0 decays.[1] Charged hadrons are also recorded simultaneously in this experiment.

The extracted proton beam is transported ~1.6 km to the proton area at FNAL. The last stage of the transport system forms a parallel beam which drifts ~700 m before being brought to a $0.4\times3\text{-mm}^2$ focus. The optics permit stable operation with a 40% targeting efficiency on a Be target, 0.22 mm wide and 100 mm long. The small transverse dimension of the target and the small residual matter between the target and our apparatus represent $\leq 0.9\%$ of a radiation length for conversion of γ's in the direction of our detector.

Our apparatus is shown schematically in Fig. 1. A 9-mrad×9-mrad aperture is defined by a tungsten-lined steel collimator 8.2 m long, tapered to minimize wall illumination. The production angle is measured horizontally with data taken at 50 and 83 mrad, corresponding to 65 and 93° in the proton-nucleon c.m. system.

In order to work at high luminosity, we choose to detect particles only after magnetic deflection in the vertical plane. The "point-source" target and trajectory in the vertical plane after the magnet define the momentum. The horizontal-plane trajectory is used to verify the target source. The scintillation hodoscopes (210 elements), see Fig. 1, have a spatial resolution of 6 mm corresponding to a momentum resolution of 4% at 30 GeV/c. Two magnet settings cover the entire kinematic range ($P_\perp = 2$ to 11 GeV/c) with good efficiency and large overlap.

Particle identification is obtained by using two calorimeters which follow the hodoscopes: a

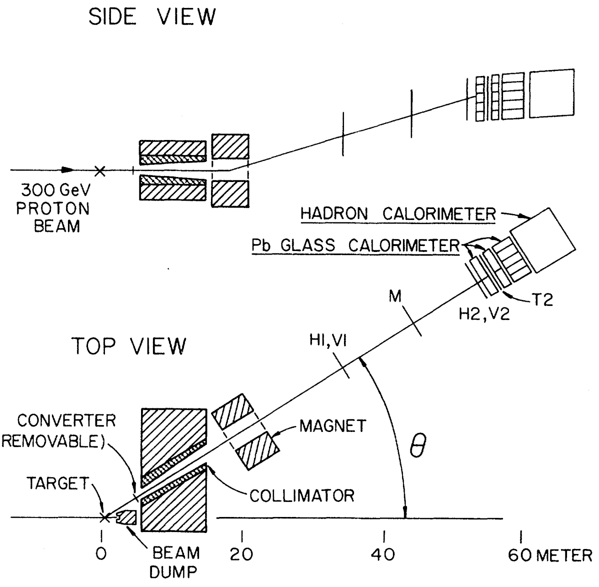

FIG. 1. Experimental apparatus for electron and γ-ray study. H_1, M, and H_2 are horizontal hodoscopes. V_1 and V_2 have vertical scintillator strips. A set of diagonal strips near V_1 is not shown.

total-absorption lead-glass electromagnetic shower detector[3] to identify electrons, and a steel-scintillator hadron detector to separate muons from hadrons.[4]

The electromagnetic shower detector consists of 2 radiation lengths of lead followed by an array of 45 identical SF-5 lead-glass blocks. Scintillation counters are placed just before and immediately behind the lead. The glass blocks are arranged in three layers (6, 6, and 15 radiation lengths, respectively) along the particle trajectory. The hadron calorimeter contains four additional scintillation counters for analog information and steel which, when added to the lead-glass, totals 1 kg/cm^2 of iron equivalent.

An event trigger is generated by a series of scintillation counters near the hodoscopes and loss requirements in each hodoscope plane. To reduce hadrons in the electron-trigger sample, a large pulse height is required in a scintillation-counter array ($T2$) placed after the first layer of lead-glass. In addition, the total energy in the first two layers of glass is required to pass certain preset threshold levels. The lowest-threshold triggers are prescaled so that a very large dynamic range in counting rate is sampled more uniformly. This trigger technique also serves to measure the trigger efficiencies for the higher-threshold events.

Each block of glass and each scintillation shower counter has its signal integrated by a 1024 channel analog-to-digital converter.[5] Calibration and stability monitoring details are described elsewhere.[3] All the event information is passed to a PDP-15 computer for later analysis. The resulting electron-energy resolution at 40 GeV is better than 4% full width at half-maximum with gain shifts (after corrections) of less than $\frac{1}{2}$% due to time or entry location.

A typical plot of energy deposited in the glass (E) divided by the momentum (P) of the particle (i.e., the fraction of its energy that a particle leaves in the lead-glass) for all triggers is shown as distribution a in Fig. 2. Electrons, which begin to cascade in the lead and leave all their energy in the glass, appear at $E/P = 1$, while most hadrons leave only a fraction of their energy and thus appear at $E/P < 1$. However, because of charge exchange and other processes, a significant number of hadrons (~1 in 2000) leave more than 90% of their energy in the glass and thus appear as a background under the electron peak at $E/P > 0.9$. Hadron rejection is improved by applying cuts on the longitudinal shower development in the array and cuts on the signals from the scintillation counters sandwiching the 2 radiation lengths of lead. These cuts, about 80% efficient for electrons, result in the E/P distribution b shown in Fig. 2, where a clear electron peak is visible.

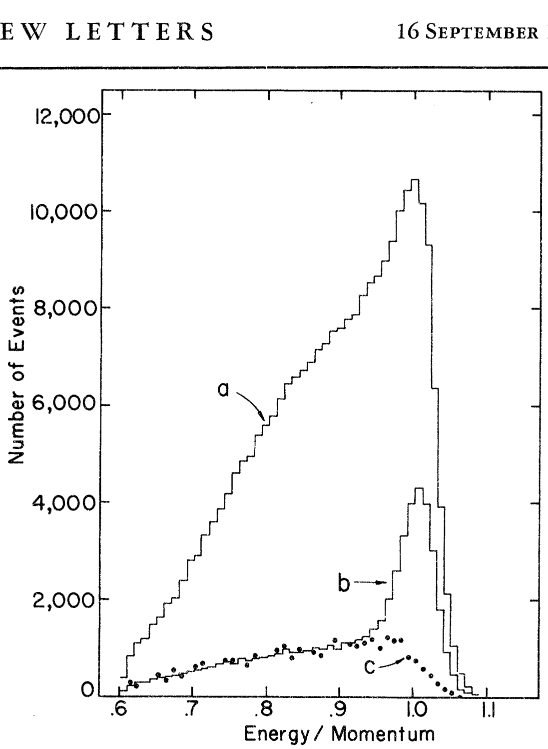

FIG. 2. Distribution a: E/P distribution with no cuts; distribution b: E/P with shower cuts; distribution c: E/P with shower cuts and with 5-cm Pb which removes all electrons.

The cuts, the requirement of showering in the lead, and the requirement that $0.95 < E/P < 1.05$ combine to give a hadron rejection of better than 10^4. We also study the E/P distributions with 5 cm of lead inserted in the secondary beam producing an effectively pure hadron beam (distribution c, Fig. 2). No artificial peak appears in the cut distribution and the shape agrees with the background below the electron signal. Subtraction of this background (less than the signal even in the worst case) leaves a very clean electron peak and gives a hadron rejection of better than 10^5.

In the π^0 experiment, we take data with foils of 2, 4, and 6% of a radiation length inserted in the secondary beam upstream of the magnets to measure the spectra of electrons and positrons produced by γ conversions. A plot of the electron yield as a function of thickness is shown in Fig. 3(a). The uncorrected points are from the raw data. Corrections are then applied to take ac-

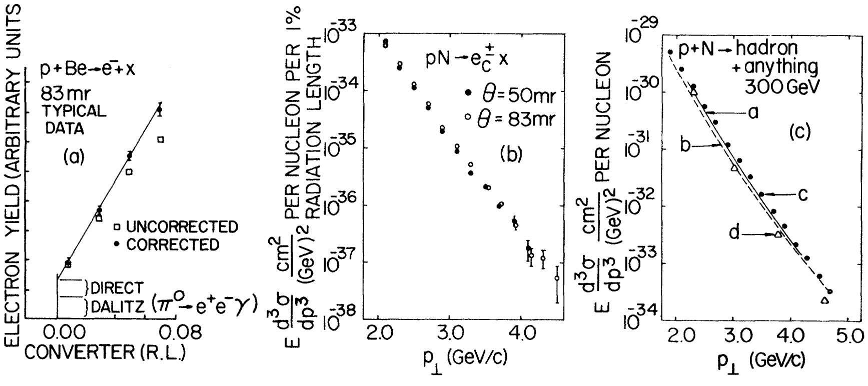

FIG. 3. (a) Yield of electrons versus foil thickness. (b) Invariant cross section for conversion electrons. The errors shown are statistical only. (c) Invariant cross sections near 90°: *a*, π^0's (this experiment); *b*, CCR modified fit; *c*, h^- this experiment ($h^- \equiv \pi^- + K^- + \bar{p}$); *d*, $(\pi^+ + \pi^-)/2$ (Ref. 6).

count of the energy loss due to bremsstrahlung by the electrons as they pass through the foils. The slope of the resulting line gives the number of electrons from γ conversions per 1% radiation length.

This slope is determined as a function of transverse momentum at both 50 and 83 mrad to obtain the spectra shown in Fig. 3(b), where the invariant cross section for electrons from γ-ray conversions in 1% radiation length is plotted. These data are taken on a Be target, and are normalized to a cross section per nucleon by dividing by 9, the ratio $A(\mathrm{Be})/A(\mathrm{H})$.[6] Data are taken at different magnet currents which make different sections of our spectrometer sensitive to the same transverse momentum. The yields are in excellent agreement, providing a sensitive check of our understanding of the acceptance of our detector. The data are averaged over polarity since, as expected for electrons from conversions, there is no difference observed between electrons and positrons.

Figure 3(c) shows an invariant cross section for π^0 production at 90° which would give rise to the electron data of Fig. 3(b). Systematic uncertainties in the absolute normalizations are believed to be smaller than 30%. A potentially larger error in the π^0 cross section could come from other sources of γ's. For instance, if the η^0 is produced with the same cross section as the π^0, its decay mode into two γ's would mean we have overestimated the π^0 cross section by about 35%.

We have at the same time measured charged-hadron spectra with a trigger that complemented the electron trigger and also used the information from the hadron calorimeter to reject muons and backgrounds.

The resulting $P_\perp$ distribution for negative hadrons (expected to be about 80% π^-)[7] is given in Fig. 3(c). Also shown is a fit to the π^0 spectrum of the CERN–Columbia University–Rockefeller University collaboration (CCR)[1] modified to fit smoothly at moderate $P_\perp$,

$$E\frac{d^3\sigma}{dp^3}=\frac{15\text{ mb}}{(P_\perp^{\,2}+1)^4}\exp(-13x_\perp),\quad x_\perp=\frac{2P_\perp}{\sqrt{s}}, \qquad (1)$$

and the average of the charged-pion spectra measured at FNAL by the University of Chicago–Princeton University group reduced from p-Be to p-N collisions by using the same factor of A.[6]

The π^0 data at 90° are in excellent agreement with the modified CCR fit. Furthermore, the invariant cross sections at 65 and 93° are very similar, indicating that any angle dependence beyond that given in Eq. (1) is not large.

Finally, charged-hadron spectra have a slope indistinquishable from that of the π^0. These data also agree very well with the FNAL work of Cronin *et al.* for $x_\perp < 0.5$.[7]

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[1] F. W. Büsser *et al.*, Phys. Lett. 46B, 471 (1973). See also B. Alper *et al.*, Phys. Lett. 44B, 521 (1973); M. Banner *et al.*, Phys. Lett. 44B, 537 (1973).

[2] J. A. Appel *et al.*, following Letter [Phys. Rev. Lett. 33, 722 (1974)].

[3] The calibration, stability, resolution, and hadron rejection of the lead-glass is discussed more fully by J. A. Appel *et al.*, "Performance of a Lead-Glass Electromagnetic Shower Detector at FermiLab" (to be published).

[4] M. H. Bourquin and D. H. Saxon, Nucl. Instrum. Methods 108, 461 (1973).

[5] F. W. Sippach, to be published.

[6] J. W. Cronin *et al.*, in Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1–10 July 1974 (to be published).

[7] J. W. Cronin *et al.*, Phys. Rev. Lett. 31, 1426 (1973).

Observation of Direct Production of Leptons in p-Be Collisions at 300 GeV

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Direct production of electrons and muons is observed in 300-GeV p-Be collisions. The yields are much higher than predicted from current models. Data are consistent with charge symmetry and universality.

We describe here the observation of high-transverse-momentum electrons and muons produced directly in proton-beryllium collisions at 300 GeV.[1] The primary motivation for this measurement is the search for the parents of "direct" leptons.[2] Candidates for the parents include (i) virtual massive photons, (ii) vector mesons (ρ, ω, φ, . . .) produced with large transverse momentum, (iii) intermediate bosons ($W^{\pm}$, Z^0, . . .), (iv) charmed particles, and (v) heavy leptons.

Electron detection has the virtue of high resolution in energy and angle. This is important in maintaining sensitivity to "bumps" which would be generated by the two-body decay of one of the above parents with discrete mass M produced with small transverse momentum. A peak would appear in the lepton transverse-momentum spectrum at a value of $P_{\perp}=M/2$. Muon detection has the complementary advantage of having backgrounds (π and K decay) which are lower by a factor of ~ 4.

The electron experiment is performed with the apparatus already described.[3] A magnetic momentum analysis followed by shower detection in a lead-glass spectrometer provides hadron rejection of a factor of ~ 10^5. Efficiencies for electron detection are determined by studying the effect of cuts on an electron-enriched sample of events. A ready source of calibration electrons is obtained by inserting a 1-radiation-length converter into the intense γ flux from the target.

Two important backgrounds are the γ conversion in the minimum of material in the secondary beam and the π^0 Dalitz decays. Both of these can be subtracted with high precision by the following method. A series of foils of known thicknesses are inserted into the secondary beam and the electron yield is plotted as a function of foil thickness [Fig. 3(a) of the previous Letter]. This permits

TABLE I. Electron yield, normalized to π^0 yield.[a] $1.9 < P_{\perp} < 4$ GeV/c.

$\left.\begin{matrix}\pi^0\\ \eta^0\end{matrix}\right\} \rightarrow \gamma + e^+ + e^-$	$\dfrac{[1.6+0.8\eta^0/\pi^0]\times 10^{-4}}{1+0.38\eta^0/\pi^0}$[b]
$\mu^- \rightarrow e\nu\bar{\nu}$	10^{-8}
$\bar{\pi} \rightarrow e\nu$	10^{-7}
$K^- \rightarrow \pi^0 e^- \bar{\nu}$	3×10^{-6}
$K_L{}^0 \rightarrow \pi^+ e^- \bar{\nu}$	2×10^{-6}
Hyperons	$3\times 10^{-6}\times(\text{hyperon}/\pi^0)$[b]
Signal	$\sim 1\times 10^{-4}$

[a] We assume in the paper that γ's arise from π^0's. If η^0 production were to equal π^0 production there would result a 7% increase in the Dalitz subtraction.

[b] η^0/π^0 and hyperon/π^0 refer to the ratio of production cross sections for these particles.