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OBSERVATION OF μe EVENTS IN $\bar{\nu}$ AND ν INTERACTIONS IN THE FERMILAB 15' NEON-H BUBBLE CHAMBER*

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ABSTRACT. In an exposure of the Fermilab 15' neon (64 atomic %) - H_2 bubble chamber to a broad band $\overset{(-)}{\nu}$ beam, 3 μ^+e^-X and 6 μ^-e^+X events (with estimated backgrounds 1.1 and 0.6 events, respectively) were found with the $\mu^\pm$ identified in the EMI. The fractions of μ^+e^- and μ^-e^+ production relative to $\bar{\nu}_\mu$ and ν_μ charged current interactions are respectively $\bar{f} = (0.10 \pm ^{0.13}_{0.07})\%$ and $f = (0.34 \pm ^{0.23}_{0.13})\%$, giving $\bar{f}/f = 0.3 \pm ^{0.5}_{0.2}$.

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Considerable attention has been given to the recently reported reaction $\nu_\mu N \rightarrow \mu^- e^+ X$ ... which occurs at a fractional rate f of $\sim 1/2\%$ of all ν_μ-charged current (CC) interactions.[1] The most popular interpretation of this phenomenon, and of the events with $\mu^+\mu^-$ in the final state, reported in both ν_μ and $\bar{\nu}_\mu$ interactions,[2] is that they are due to the production of charmed particles which subsequently decay (semi)leptonically. The existence of the $\bar{\nu}_\mu$ reaction $\bar{\nu}_\mu N \rightarrow \mu^+ e^- X$ ... has not previously been reported, but a 90% confidence upper limit of (1/2)% has been set[3] on its fractional rate $\bar{f}$. The ratio of rates $\bar{f}/f$ is a quantity that is expected to be sensitive to the fraction of the nucleon momentum carried by the strange quarks of the sea.[4] We report here a simultaneous measurement of $\bar{f}$ and f, and, therefore, a determination of $\bar{f}/f$ which is relatively free of systematic effects.

The data come from ∿45K pictures produced by an exposure of the Fermilab 15' bubble chamber (BC) plus External Muon Identifier[5] (EMI) to a wide band antineutrino beam. The BC has a 30KG field and was filled with a heavy mixture of hydrogen and neon (64% Ne atomic fraction). This liquid's short radiation length (39 cm) yields high electron identification and γ-ray conversion efficiencies, and its short interaction length (∿1.3 m for pions), together with the EMI, permits good separation of muons and hadrons. The primary proton beam energy was 400 GeV and the average intensity on the 12" long aluminum oxide target was 1.0×10^{13} protons/pulse. Of the two horns normally used at Fermilab as a focusing device for wide band beams, only the one downstream was available here. Because of this and the fact that no plug was inserted into the beam, the flux was such that the $\bar{\nu}_\mu$ - and ν_μ-induced charged current (CC) event rates were similar: the relative numbers of CC events, which satisfy our cuts,[6] are $\bar{\nu}_\mu:\nu_\mu:\bar{\nu}_e:\nu_e$ = 2.8K:2.3K:36:71; the median event energies are (in GeV) 30:47:32:32, and the rms widths of the event energy distributions are (in GeV) 25:46:29:24. This experiment is thus in a unique position to compare the CC events induced by $\bar{\nu}$ with those by ν interactions.

The film was double scanned (15% third scanned) for all neutral-induced events (except those below ∿ one GeV and those with only one non-$e^\pm$, non-interacting track[7]). Events with one or more possibly-primary $e^\pm$ among the outgoing tracks were reviewed by physicists, who eliminated identifiable

Dalitz and close e^+e^- pairs, Compton electrons, δ-rays, π, K decays, etc. For those events whose $e^\pm$ showed at least two independent signatures[8] all charged tracks and associated V^0's, neutral stars and energetic γ's were measured and reconstructed with TVGP or HYDRA. The $e^\pm$ track momenta were corrected for bremsstrahlung losses by a Behr-Mittner method,[9] and for early catastrophic bremsstrahlung by adding the energy of the corresponding converted pairs.

We thus obtain 74 e^- events and 42 e^+ events (with $p_e > 0.8$ GeV and $E_{vis} > 10$ GeV and satisying other cuts[6]), which we interpret as resulting mostly from ν_e and $\bar{\nu}_e$ interactions, respectively. The 3 μ^+e^- and 6 μ^-e^+ candidates among them, whose characteristics are given in Table I, all have $y_e = 1-p_e/\Sigma p_x$ above ~ 0.8. The y_e distributions (Fig. 1) of the other $e^\pm$ events are approximately uniform for e^-, and peaked at low y_e for e^+, and thus resemble those observed for $\mu^\pm$ events.[2,3,10] The four e^+ events with $y_{e^+} > 0.8$ and no μ^- can be accounted for by i) $\bar{\nu}_e$ events (1.9 event, assuming a 10% fraction of antiquarks in the nucleon[2,3,10]); ii) μ^-e^+ events where the μ^- misses the EMI or fails to register in it acceptably[6] (1.0 event); and iii) asymmetric Dalitz or close converted e^+e^- pairs on neutral current events (0.2 event). Thus our y distribution for $\bar{\nu}_e$ interactions is not significantly different from that observed for $\bar{\nu}_\mu$ interactions[2,10] at similar energies.

The μe event sample was obtained from the sample of primary $e^\pm$ events as follows. All the leaving tracks were extrapolated to the EMI. For those which did not geometrically miss it, the extrapolated position was compared to the closest actual hit and C_μ, the probability that a muon would have given a worse match, was calculated, along with C_h, the probability that a hadron would have given a better match.[5] To be identified as a muon, a leaving track was required to have a momentum $p > 4$ GeV/c, and to hit the EMI in a way such that the "likelihood"[5] $\mathcal{L} \equiv -\partial C_\mu/\partial C_h$ be greater than 5. Six μ^-e^+ and three μ^+e^- candidate events were thus identified. Their characteristics are given in Table 1. A tracing of one of the μ^+e^- events (event #1) is shown on Fig. 2, along with a picture of the vertex under high magnification.

For normalization purposes, we measured all the neutral-induced events in ∿6K pictures, and obtained 182 $\bar{\nu}_\mu$ and 188 ν_μ CC events with $\Sigma p_x > 10$ GeV and a leaving track satisfying the muon identification criteria discussed above. After corrections for scanning losses and, in the $\bar{\nu}$ case, for the 15% loss due to the one-prong events,[7] these correspond to 2846 $\bar{\nu}$ and 2261 ν CC events with an identified muon in our complete sample of film.

The backgrounds and losses to the μe events are summarized in Table II. The important backgrounds are of two types: first, a false μ due to "punchthru", i.e., a leaving hadron ($L^\pm$) from a $\overset{(-)}{\nu}_e$ event falsely registers as a μ in the EMI. An estimate of this background was obtained from the number of $L^\pm$ of $p > 4$ GeV/c from $\overset{(-)}{\nu}_e$ events which register as hadrons in the EMI, by using a punchthru probability of 7.7 ± 2.3% per $L^\pm$. The latter was determined from a study of 343 μ^+ and 324 μ^- events some 23% of which had $\geqslant 1$ $L^\pm$ in addition to the μ. (The punchthru probability is compatible with momentum independence above ∿4 GeV/c.) The estimated punchthru backgrounds to $e^\pm\mu^\mp$ and $e^\mp\mu^\mp$ are reduced by factors of 2 or more by requiring $p_{L^\pm} > p_e$. All of our μe events have $p_\mu > p_e$. Second, a false lone primary $e^\pm$ on a $\overset{(-)}{\nu}_\mu$ event, resulting either from an asymmetric Dalitz pair ("ADP") asymmetric close e^+e^- pair ("ACP"), close Compton electron ("CCE"), π charge exchange interaction ("CEX") yielding an ADP or ACP, or $K^\pm_{e3}$ decay in flight ("Ke3"). We have assumed that an $e^\pm$ above 5 MeV (on an ADP or ACP), a gap > 5 mm between vertex and ACP or CCE and a kink of 6° in projection is detectable on the average μe event (see Fig. 2); that 9% of the $\overset{(-)}{\nu}$ CC have a K^+ and 5% a K^-. Other backgrounds are negligible within our cuts.[6] For example, colinear K^+_{e3} and $\pi \to \mu \to e$ decays at rest are eliminated by ionization information and by the requirement that the $e^\pm$ have $\geqslant 2$ signatures, $\geqslant 1$ of which must occur before the $e^\pm$ momentum falls below ∿100 MeV/c. For none of the surviving μ^+e^- events does the e^- lie within 3σ of being in the kinematic region for a δ-ray.

The total estimated false e^- background to the μ^+e^- sample is thus 0.53 ± 0.3 event for $p_{e^-} \geqslant 0.8$ GeV/c. (For $p_{e^-} \geqslant 0.3$, 1.6, 3.0 GeV/c, it would be 1.60, 0.20 and 0.07 events, respectively.) For $0.3 < p_e <$ 0.8 GeV/c, we have one additional μ^+e^- candidate and one μ^-e^+. The false

e^- background to μ^-e^- is roughly equal to that for μ^+e^-. We have no μ^+e^+ and one μ^-e^- candidate event; this is compatible with the expected false $e^\mp$ + false $\mu^\mp$ background.

The efficiencies and the losses due to our $e^\pm$ defining cuts are also summarized in Table II. By false Dalitz pairs we mean single primary $e^\pm$ which are mistaken as part of showers caused by Dalitz (or close) pairs or close triplets because of the chance superposition of a real Dalitz pair, etc. The ($\sim$1%) probability of a close δ-ray on an e^+ is included in this. By false Compton we mean a lone primary e^- rejected because of a gap caused by a fluctuation of the bubble density near the vertex.

Taking these backgrounds, losses and efficiencies into account, the 3 μ^+e^- and 6 μ^-e^+ correspond to $\bar{f} = (0.10 \pm {}^{0.13}_{0.07})\%$ and $f = (0.34 \pm {}^{0.23}_{0.13})\%$ relative to all $\overset{(-)}{\nu}_\mu$ CC events satisfying our cuts.[6] Thus $\bar{f}/f = 0.3 \pm {}^{0.5}_{0.2}$. (Here systematic errors cancel approximately.) It is worth emphasising that the total false e^- background expected for $p_e > 3.0$ GeV/c is < 0.1 event. Therefore the probability that both events with $p_{e^-} > 3$ GeV/c (events #1 and 2) arise from any of the sources of false single primary e^- is $\ll 1\%$. The probability that all three (or more) μ^+e^- events are due to a fluctuation in the expected 0.6 event punchthru background is $< 3\%$. The sum of the probabilities that all three (or more) μ^+e^- events arise from the various possible combinations of punchthru and false e^- background is about 7%.

The median ν_μ ($\bar{\nu}_\mu$) CC event energy is $\sim$ 47 (30) GeV in our experiment compared with 65 GeV for the 6 μ^-e^+ and 26 GeV for the 3 μ^+e^-. We have therefore no evidence that the μ^+e^- events are produced by higher energy $\bar{\nu}$ than are typical $\bar{\nu}$ CC events, contrary to what might be expected[4] if they came from a very heavy particle carrying a new quantum number beyond charm.

In the standard (GIM[4]) model context, $\bar{f}/f$ provides a constraint on the fraction of the nucleon momentum carried by the nonstrange and strange antiquarks of the sea. For example, if there were no sea, $\bar{f}/f$ would be zero; in the limit that the strange sea dominated both μe production reactions, $\bar{f}/f$ would approach $\sigma(\nu_\mu \rightarrow \mu^-)/\sigma(\bar{\nu}_\mu \rightarrow \mu^+)$ which is experimentally[2] ≈ 2.5. If the x distributions[11] of the valence and sea quarks are approximately as assumed by Field and Feynman[12] (with 1/4 of the sea strange) and if the charmed quark mass is of order 2 GeV, a value of $\bar{f}/f \approx 0.6$ is predicted,[4] quite compatible with our result. If the contribution of the strange sea to this calculation is removed, $\bar{f}/f < 0.1$ is predicted; in this case, if f = 0.5% two or more μ^+e^- events would represent a fluctuation with < 12% probability.

We conclude that our results for the rate and characteristics of $\nu_\mu \rightarrow \mu^-e^+\underline{X}$ production are compatible with other recent experiments',[1] and that our $\overset{(-)}{\nu}_\mu \rightarrow \mu^\pm e^\mp X$ rates and characteristics are understandable in the framework of the GIM model.[4,12]

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6. We require: i) $E_{vis} \approx \Sigma p_x > 10$ GeV where the sum is over all measured particles (including γ-rays, V^0's and neutral stars) and x is the beam direction; for $e^\pm$ we require also each of ii) $p_e > 0.8$ GeV/c, iii) $\geqslant$ 2 independent signatures,[8] $\geqslant$ 1 of which occurs before p_e falls below ∿0.1 GeV/c, iv) $M_{e^\pm x^\mp} > m_{\pi^0}$, where $x^\mp$ is any track which could be the companion of the $e^\pm$ in a Dalitz pair, v) the angle between this e^- and any other track, x, be inconsistent ($\geqslant 2\sigma$) with the angle this e^- would have if it were a δ-ray on x; for $\mu^\mp$ we require vi) $p_\mu > 4$ GeV/c and

vii) that this leaving track register in the EMI as a μ with likelihood[5] $\mathcal{L} > 5$. Within our $\sim$14 m^3 fiducial volume (which provides $\geqslant$ 90 cm of potential path length for forward tracks), the muon identification efficiency is $\sim$97% (geometric) * 93% (electronics) * 95% ($\mathcal{L} > 5$) $\approx$ 86% for $p > 4$ GeV/c; an $e^{\pm}$ of $p_e > 0.8$ GeV/c has a (95 ± 3)% probability to show $\geqslant$ 2 of the required signatures; the effective $e^{\pm}$ event scanning efficiency is (85 ± 5)%.

7. The number of one prong events,(15 ± 5)% of $\bar{\nu}_{\mu}$ CC, was estimated by multiplying the number of events with only a μ^+ and evaporation prongs by the ratio (events with only a μ^- and a proton)/(events with only a μ^-, proton and evaporation prongs). We assume that the proportions of events without visible evaporation prongs are the same in the reactions $\bar{\nu}p \rightarrow \mu^+ n$ and $\nu n \rightarrow \mu^- p$.
8. To be considered an $e^{\pm}$, a track had to show a least one (two after analysis) of the following identifying characteristics ("signatures"): i) spiralization to a point in the chamber; ii) visible sign of bremsstrahlung (sudden change of curvature and/or materialization in the chamber of the radiated quantum);iii) δ-ray or trident of an energy such that only an $e^{\pm}$ could have yielded it; or, iv) for positrons, annihilation in flight yielding a tangent γ-ray.
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11. We define $x = Q^2/(2M_p E_h)$, $y = E_h/E_{\nu}$, $y_e = 1-p_e/\Sigma p_x$, where Q^2 is the square of the four-momentum transferred from the $\overset{(-)}{\nu}$ to the μ, $E_h = E_{\nu}-E_{\mu}$, $E_{\nu} \approx E_{vis} \approx \Sigma p_x$.
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TABLE I

Characteristics of the μe Events[6]

		$n_{ch}^{\$}$	ΣQ	Σp_x	p_μ	p_e	Visible[11]		Str. Part.
							x	y	
μ^+e^-	1	7	+3	26	20.5*	3.6	0.17	0.22	
	2	4	0	17	4.9	3.4	0.02	0.7	
	3	5	+1	28	4.9*	2.0	0.10	0.83	Λ
μ^-e^+	4	9	+1	82	31.5*	1.1	0.18	0.62	
	5	7	+1	42	23.2*	0.9	0.24	0.45	
	6	5	+1	70	59.0*	5.1	0.66	0.16	K^+(?)
	7	5	+1	33	25.1*	0.9	0.13	0.25	K^+
	8	11	+1	60	28.9*	7.6	0.31	0.55	
	9	6	0	73	49.1*	10.9	0.23	0.33	K^o

[\$] n_{ch} is the number of outgoing prongs (not counting protons of range $\lesssim$ 4 cm) and ΣQ their net charge. The momenta are in GeV/c. $\Sigma p_x \approx E_\nu$.

[*] This track has highest transverse momentum, relative to the incident ν direction, of any outgoing track of the event.

TABLE II

SUMMARY OF DATA[6]

Total Frames:	48.5K,	with EMI 45K
Events with e^+, no μ	36	e^-, no μ 71
CC events	2.3K μ^-	2.8K μ^+[7]
μe events	6 $\mu^- e^+$	3 $\mu^+ e^-$
Backgrounds	to $\mu^- e^+$	to $\mu^+ e^-$
1. $\bar{\nu}_\mu$ plus false e		
Asym. Dalitz pairs	0.04	0.04
Close Asym. pairs	0.13	0.12
Close Compton e^-	-	0.16
Charge exchange	-	0.12
$K^\pm_{e3}$	0.17	0.09
Subtotal	0.34±0.2	0.53±0.3
2. $\overset{(-)}{\nu}_e$ + false μ	0.23±0.2	0.54±0.3
Total background	0.57±0.3	1.1 ±0.4
Losses		
Dalitz pair cut	1%	3%
δ-ray cut	-	3%
False Dalitz pairs, etc.	11%	5%
False Compton e^-	-	4%
Tot. loss from $e^\pm$ cuts	(12±8)%	(15±8)%
Efficiencies		
Scanning	(85±5)%	(85±5)%
$e^\pm$ 2 sig.	(95±3)%	(95±3)%
Corr. no. μe events	7.61 $\mu^- e^+$	2.81 $\mu^+ e^-$
$\mu e/CC = \overset{(-)}{f}$	$(0.34^{+0.23}_{-0.13})\%$	$(0.10^{+0.13}_{-0.07})\%$

FIGURE CAPTIONS

1. Distribution of $y_e = 1-p_e/\Sigma p_x \simeq 1-E_e/E_\nu$ for the events[6] with
   a) a primary e^-
   b) a primary e^+
   The events with an identified[6] $\mu^\pm$ are shown hatched.
2. a) Event #1 (see Table I).
   b) A diagram labelling the tracks of event #1.
   c) The vertex region of event #1. The invariant mass of the proton and the π^- is compatible with the Λ^0 mass. The kinking track may be a K^+. The other tracks are protons (or nuclear debris).

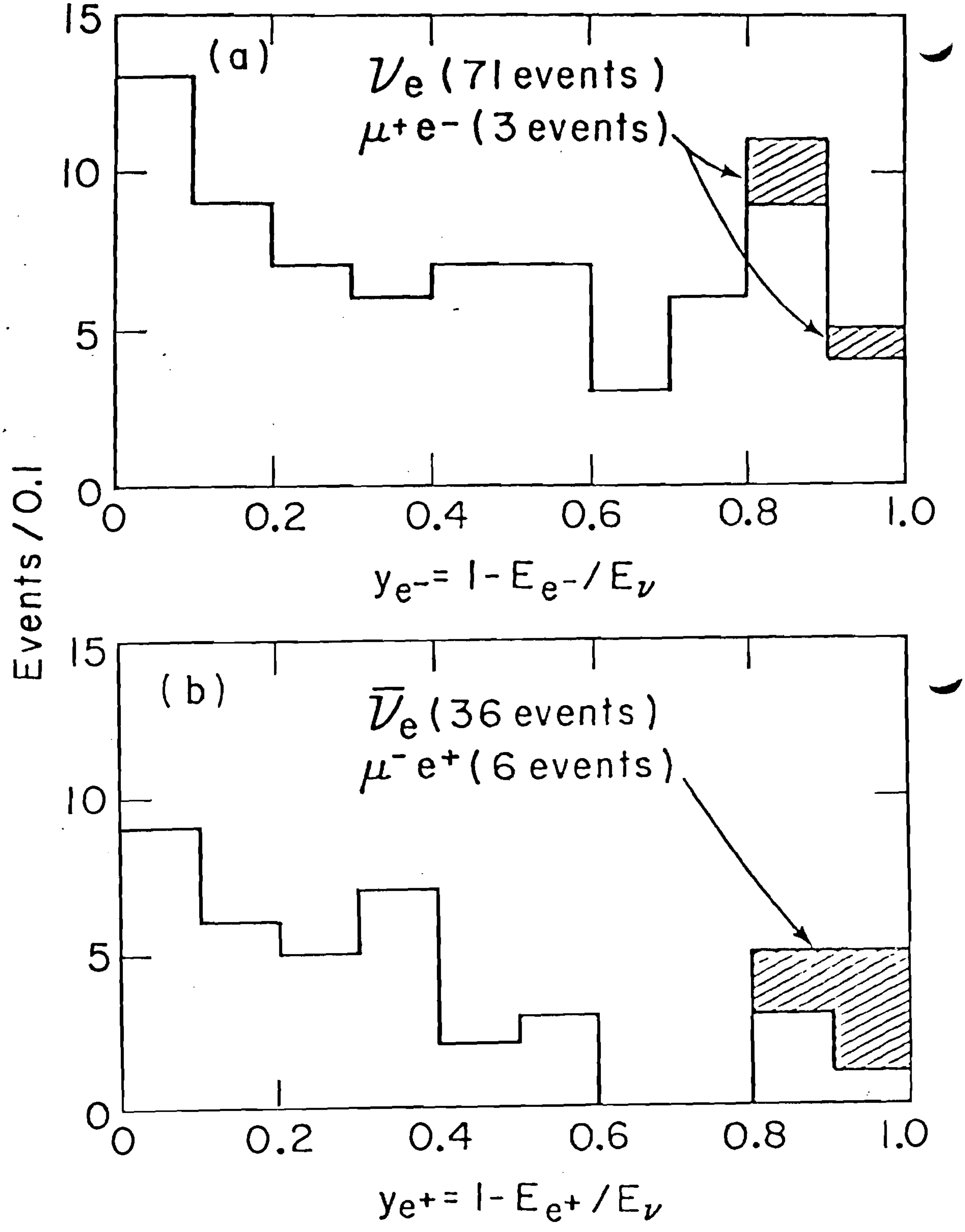

Fig 1

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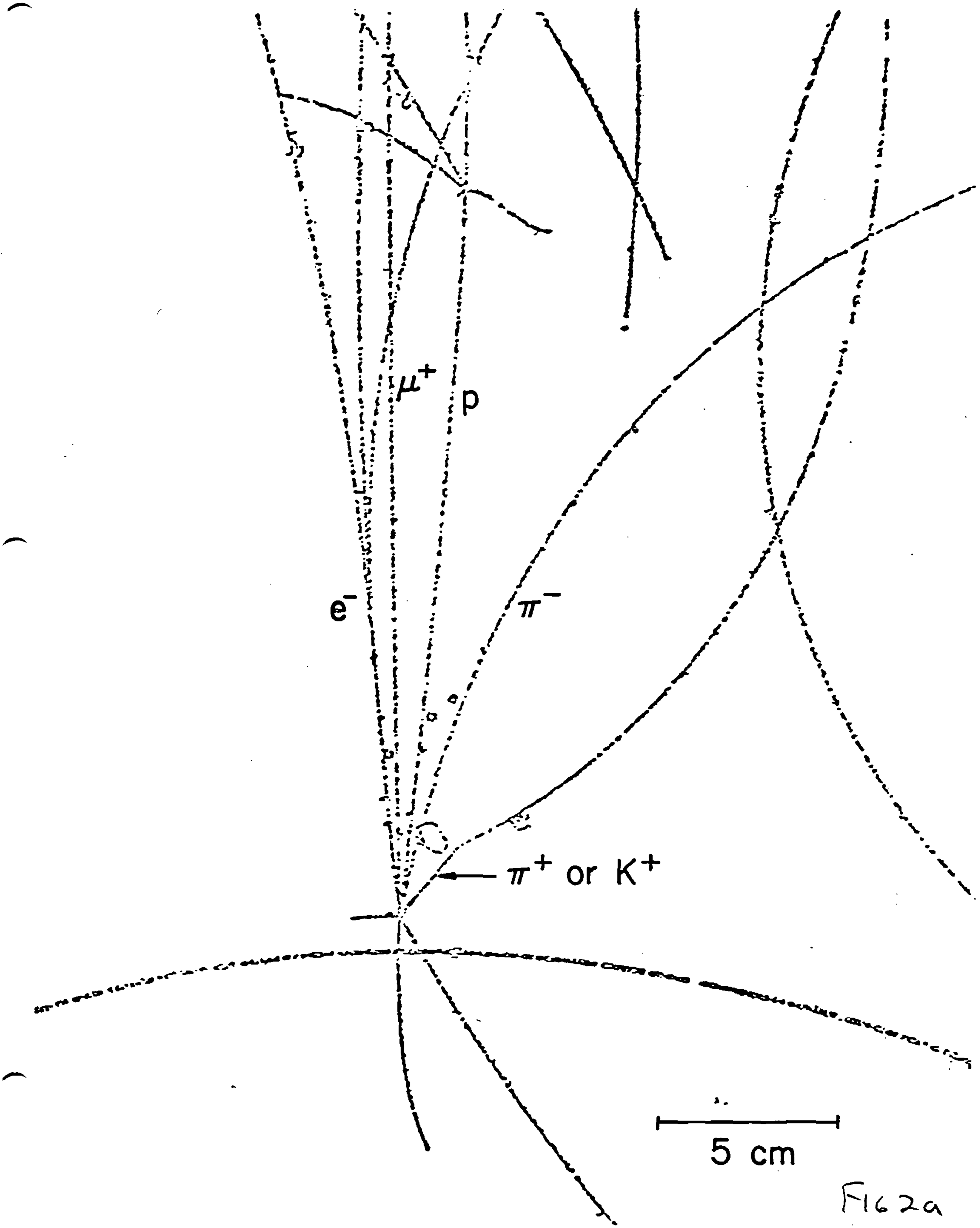


FIG 2a

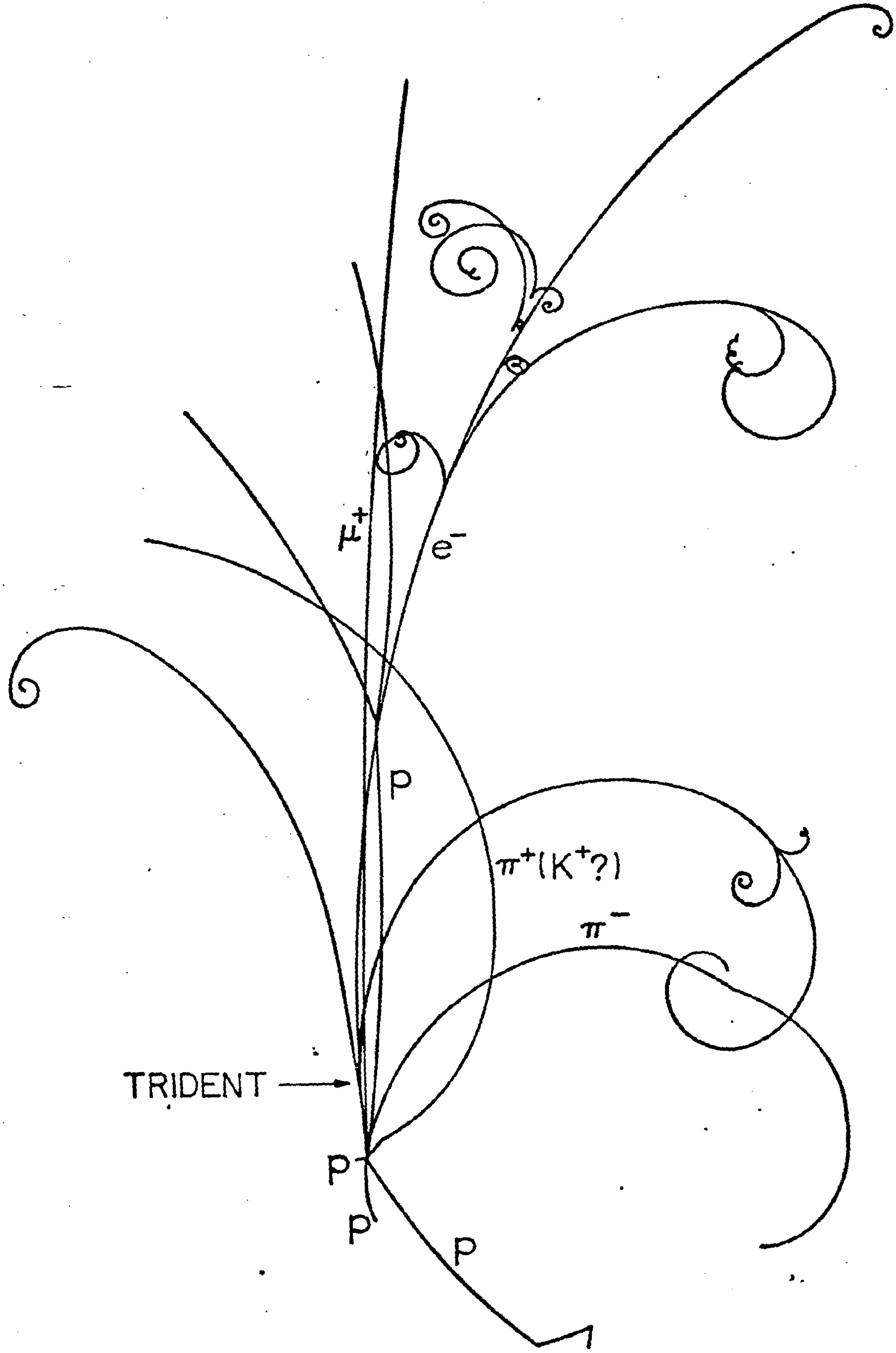
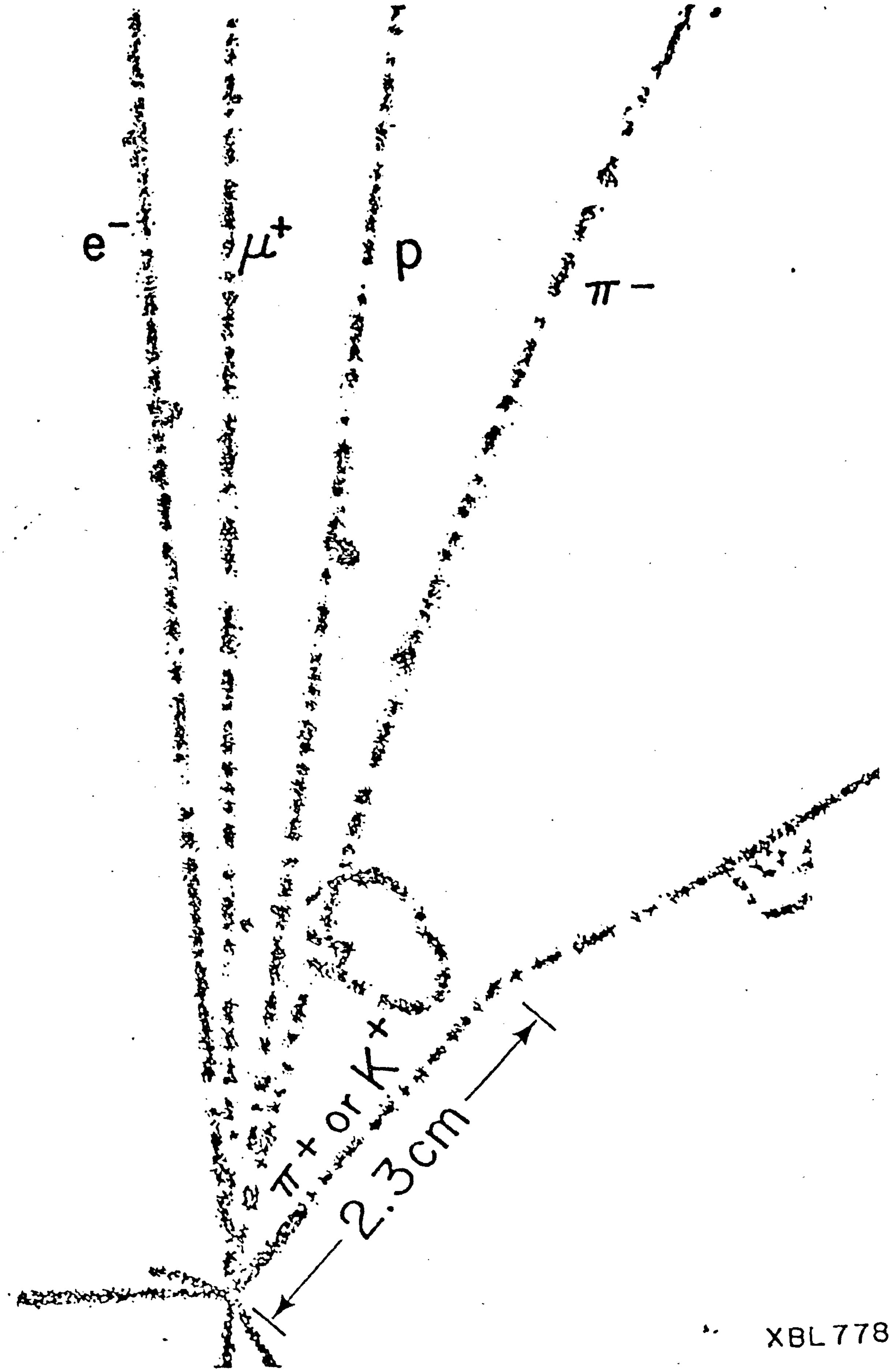


Fig 2b



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