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UPPER LIMITS FOR CHARM PRODUCTION IN 150 GeV p-Be INTERACTIONS

The ACCMOR Collaboration

Amsterdam[1]-Bristol[2]-CERN[3]-Cracow[4]-Munich[5]-Rutherford[6] Collaboration

R. Bailey[6)], H. Becker[5)], E. Belau[5)], T. Böhringer[3)], M. Bosman[3)], M. Cerrada[3)], V. Chabaud[3)], C. Damerell[6)], C. Daum[1)], H. Dijkstra[1)], A. Dwurazny[4)], A. Gillman[6)], R. Gilmore[2)], L. Görlich[4)], Z. Hajduk[4)], C. Hardwick[1)], W. Hoogland[1)], B.D. Hyams[3)], R. Klanner[5)], G. Lütjens[5)], G. Lutz[5)], J. Malos[2)], W. Männer[5)], G. Polok[4)], M. Rozanska[4)], K. Rybicki[4)], H.J. Seebrunner[5)], W. Spierenburg[1)], U. Stierlin[5)], R.J. Tapper[2)], H.G. Tiecke[1)], M. Turala[4)], J. Vermeulen[3)], G. Waltermann[5)], P. Weilhammer[3)], F. Wickens[6)], L. Wiggers[1)], A. Wylie[3)] and T. Zeludziewicz[5*)]

ABSTRACT

A search has been made for the hadronic production of charmed baryons and mesons with a large aperture forward magnetic spectrometer using 150 GeV protons originating from the CERN-SPS. A prompt electron trigger was used as a signature for charm. Upper limits at 90% Confidence Level have been obtained for the production of Λ_c^+, D^0, $\bar{D}^0$, D^+ and D^-:
$\sigma(\Lambda_c) \leq 8$ μb, $\sigma(D^0) \leq 64$ μb, $\sigma(\bar{D}^0) \leq 37$ μb, $\sigma(D^+) \leq 51$ μb and $\sigma(D^-) \leq 49$ μb per nucleon, assuming linear A-dependence.

1) NIKHEF-H, Amsterdam, The Netherlands
2) University of Bristol, Bristol, UK
3) CERN, Geneva, Switzerland
4) Institute of Nuclear Physics, Cracow, Poland
5) Werner Heisenberg Institut für Physik, Munich, W.-Germany
6) Rutherford Laboratory, Chilton, Didcot, UK
*) Visitor from the Institute of Nuclear Physics, Cracow, Poland

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1. Introduction

The production of charmed mesons has been observed in experiment NA11 [1] in a negative pion beam of 120, 175 and 200 GeV at the CERN-SPS. With the same set-up we have also made a search for production of charmed baryons and mesons with 150 GeV protons. Hadroproduction of Λ_c^+ and D with incident protons has been observed at SPS/Fermilab energies and at ISR energies, but there are large inconsistencies in the measurements.

The results, reported in this letter, put further limits on the production of charm in proton beams at $\sqrt{s}$ = 17 GeV. They will be compared with other data in this energy range.

2. The experiment

A schematic lay-out of the experiment is shown in Fig. 1. The unseparated positive hadron beam, H6, derived from the CERN-SPS, is focused onto four 8 mm long Be targets with a height of 2 mm, which are positioned with 60 mm spacing along the beam line. The target cell in which the interaction takes place is identified by a 0.5 mm scintillation counter (I) behind each target segment. The identity of beam particles is tagged with differential Cherenkov counters (CEDAR's). The proton content of the beam is 63% at 150 GeV.

The fast trigger uses the signals of the multicellular Cherenkov counter Q (π-threshold of 12 GeV) and the lead-scintillator calorimeter E-CAL ($E_{e,min}$ = 2.8 GeV) to select interactions containing an electron from the reactions:

$$p\ Be \rightarrow \Lambda_c^+ + \bar{D}(\rightarrow eX) + X', \text{ and}$$
$$p\ Be \rightarrow D + \bar{D}(\rightarrow eX) + X' \text{ or c.c.}$$

It rejects background due to pair electrons from γ-conversion and Dalitz decay of π^0 and η^0 using the cell structure of E-CAL and its geometric extension with scintillator-lead-scintillator sandwich counters H. Further reduction of background from hadrons, photons and conversion pairs is achieved with a second stage trigger using the information from the multiwire proportional chambers P2 and the calorimeter E-CAL [1,2].

Hadronic decays of Λ_c^+, D^0, $\bar{D}^0$, D^+ and D^- into charged hadrons are reconstructed off-line using the data of the following components of the spectrometer:

- Fourty-eight planes of large area drift chambers (DC) and two spectrometer magnets (M1 with 0.90 T·m, M2 with 2.06 T·m) to measure momentum vectors of the charged particles,
- Three multicellular Cherenkov counters C1, C2 and C3 (π-threshold 3.6, 6.4 and 12.2 GeV, respectively) to assign particle identity in the momentum range 4-80 GeV based on pulse height information.

Results are presented on the analysis of 3.1×10^6 triggers obtained in a beam of 3.2×10^6 incoming positive particles (63% protons) per burst (1.5 s) yielding 1.5×10^5 inelastic proton interactions per burst. The first stage trigger accepts 0.5% of the inelastic interactions with a measured efficiency[1] of 37% for prompt electrons. The second stage trigger reduces the trigger rate by a factor of 4 and has an efficiency of 70% for single electrons. The dead-time of the data acquisition system is 50%, and 65 triggers per burst are recorded onto tape.

3. Data analysis

The off-line analysis removes background from the electron sample due to hadron-photon overlap, to asymmetric γ-conversions and Dalitz decays of π^0 and η^0 for which the low-energy pair electron is detected by the MWPC system P1,P8,P9 in the first spectrometer magnet. This rejects 90% of all events and keeps 70% of the single electron triggers. A study of ρ, ω and ϕ signals in an e^+e^--trigger and a study of conversion pairs in calibration data yields a combined efficiency of (18±6)% for all stages of electron selection, from the fast trigger through to the off-line filtering.

Charged particles are reconstructed with an efficiency of 95% per track. The mass resolution and mass scale have been checked[1,2] with known particles: $K_s^0(\pi^+\pi^-)$, $K^{*\pm}(K_s^0\pi^\pm)$, $\phi(K^+K^-)$, $\Lambda(p\pi^-)$, $\Sigma^+_{1385}(\Lambda\pi^+)$, and $\Lambda_{1520}(pK^-)$. Predicted mass resolutions are: $\sigma(\Lambda_c \to K^-\pi^+)$ = 8 MeV, $\sigma(D^0 \to K\pi)$ = 10 MeV, and $\sigma(D^\pm \to K\pi\pi)$ = 12 MeV, and the mass scale is known within a few MeV at the mass of the particles.

The pulse height information of C1, C2 and C3 is used to assign a particle identity to each track passing these counters. For the Λ_c search in the decay channel $pK^-\pi^+$ all positive particles which are either a proton or an ambiguous proton/kaon, and all negative particles which are either a kaon or an ambiguous kaon/proton are used, but for each pK^- pair at least one particle must be unambiguously identified. All identified positive pions and unidentified positive particles which passed through M2 are candidates for the π^+ in this Λ_c-decay mode. For the D-search in the decay channels $K\pi$ and $K\pi\pi$ the same conditions are used for K and π, respectively. The average efficiency of the particle identification was determined to be 88% by comparing the particle assignment of the Cherenkov counters with that of an independent reconstruction of K_S^0's, Λ's and $\bar{\Lambda}$'s with finite decay length[2]. The main source of inefficiency is due to particles with nearby trajectories passing through the same or neighbouring cells of the Cherenkov counters.

V^0's decaying at a finite distance from the target are reconstructed from pairs of particle trajectories after the first spectrometer magnet - with or without momentum assignment - which do not originate from the primary interaction vertex. The algorithm developed for this search is described in ref. [2].

The final single electron selected sample contains 2.24×10^5 events which have at least one proton, one kaon or one V^0. The average multiplicity of these events is 9.6, and table 1 shows the distribution of particle assignments.

4. Experimental results

For the charmed baryon search we have reconstructed invariant mass spectra of $pK^-\pi^+$, pK_S^0, $pK_S^0\pi^+\pi^-$, $\Lambda\pi^+$, $\Lambda\pi^+\pi^+\pi^-$ separately for events with an e^- and an e^+ trigger. A charm signal for Cabibbo favoured decays is expected in the case of an e^--trigger. No statistically significant enhancement is observed at the Λ_c-mass (2.282 GeV). Fig. 2 shows the $pK^-\pi^+$ spectra corresponding to the e^- and e^+ trigger. Further reduction of combinatorial background can be obtained by searching for the cascade decay $\Sigma_c^{++} \to \Lambda_c^+\pi^+$. Again, no enhancement is observed. The Feynman x_F-range of the events around the Λ_c-mass is $0.1 < x_F < 1.0$ with $\bar{x}_F = 0.4$, and $\overline{p_T^2} = 0.5$ GeV^2.

We searched for D^0 and $\bar{D}^0$ mesons in $K^\mp\pi^\pm$ spectra, and for $D^\pm$ mesons in $K^\mp\pi^\pm\pi^\pm$ spectra for trigger electron and K-meson of the same charge, "like sign Ke", which are candidates for Cabibbo favoured hadronic decay involving a K in the decay products. Fig. 3 shows no significant difference between $K\pi$-spectra with "like sign Ke", and the control sample with "unlike sign Ke". No enhancements are observed at the $\overset{(-)}{D}{}^0$-mass (1.865 GeV), and the $D^\pm$-mass (1.869 GeV). The Feynman x_F-range of the events around the D-mass is $-0.1 < x_F < 0.7$ with $\bar{x}_F = 0.3$, and $\overline{p_T^2} = 0.5$ GeV^2. No enhancement is observed in a search for the cascade decay $D^* \to D\pi$.

5. Upper limits for cross-sections

We calculate 90% C.L. upper limits for the production of Λ_c, using the branching ratio of (2.2±1.0)% [3] for the decay channel $\Lambda_c \to pK^-\pi^+$, the branching ratio of (2.40±0.4)% [3] for the decay channel $\overset{(-)}{D}{}^0 \to K^\mp\pi^\pm$, and the branching ratio of (4.6±1.1)% [3] for the decay channel $D^\pm \to K^\mp\pi^\pm\pi^\pm$.

We assume that Λ_c is produced in association with $\bar{D}$ and $\bar{D}^*$, and we neglect $\Lambda_c\bar{\Lambda}_c$ production. The latter production process involves additional baryons for baryon number conservation and should therefore have a considerably smaller cross section. Further, we assume that $\Lambda_c\bar{D}$ and $\bar{\Lambda}_c\bar{D}^*$ are produced in equal amounts and with equal population of the charge states of $\bar{D}$ and $\bar{D}^*$. Finally, we take equal semi-lepton decay rates via K and K^* for the charmed mesons. We then obtain an average semi-leptonic branching ratio for the associated meson of 10%, using the branching ratios for D and D^* of ref. [3]. This value is also used for the semi-leptonically decaying charmed meson in $D\bar{D}$-production.

For the first process we adopt the empirical relations for inclusive Λ and K_s^0 production[4], assuming that the only difference is the replacement of a strange quark by a charmed quark. Hence, we have:

$$\frac{d^2\sigma}{dxdp_T^2}(\Lambda_c^+) \propto (1 - |x_F|)\, e^{-2.9\, p_T^2}, \text{ and}$$

$$\frac{d^2\sigma}{dxdp_T^2}(\bar{D}) \propto (1 - |x_F|)^8 e^{-4.0\, p_T^2}.$$

For $D\bar{D}$ production we take equal distributions for D and $\bar{D}$, as in the D-search in a π^- beam[1], where we obtained:

$$\frac{d^2\sigma}{dxdp_T^2}(D \text{ or } \bar{D}) \propto (1 - |x_F|)^{0.8}\, e^{-1.1 p_T^2} .$$

For the acceptance calculation, we assume uncorrelated production of Λ_c and $\bar{D}$, and of D and $\bar{D}$. The acceptance calculation includes the track reconstruction efficiency, the Cherenkov efficiency and the electron identification efficiency.

Table 2 lists all numbers which enter the calculation of the upper limits. Assuming linear A-dependence we obtain with 90% confidence level:

$\sigma(\Lambda_c) \leq 8$ μb/nucleon,
$\sigma(D^0) \leq 64$ μb/nucleon,
$\sigma(\bar{D}^0) \leq 37$ μb/nucleon,
$\sigma(D^+) \leq 51$ μb/nucleon,
$\sigma(D^-) \leq 49$ μb/nucleon.

These values are subject to uncertainties in branching ratios and model-dependence of the acceptance calculations. The hadronic branching ratios introduce an uncertainty of 45% for $\Lambda_c^+ \to pK^-\pi^+$, of 17% for $\overset{(-)}{D}{}^0 \to K^{\mp}\pi^{\pm}$, and of 24% for $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$. The semi-leptonic branching ratio of the associated meson has an uncertainty of 28%.

Table 3 shows the dependence of the upper limits of the cross section on the power n in $(1 - |x_F|)^n$ and on the slope parameter b in $e^{-bp_T^2}$.

The absence of signals in the other investigated Λ_c^+ decay channels is in agreement with present knowledge of branching ratios[3].

In the $K^-\pi^+$- and the $K^-\pi^+\pi^-$-mass spectra small enhancements are visible at the D-mass. Interpreting these peaks as an indication for D^0- and D^+-production, a fit is made with a Gaussian resonance peak superimposed on a polynomial background to the combined mass distribution. This results in a small signal at a mass of (1868±10) MeV, and a width of (10±7) MeV, close to the expected values. Assuming equal amounts of D^0- and D^+-production, this signal would correspond to a cross-section for $D\bar{D}$-production of 15 μb/nucleon for linear A-dependence.

6. Discussion

Beam dump experiments, in which either a neutrino[5] or a lepton[6] attributed to semi-leptonic decay of charm has been observed, have set the scale for the charm cross-section at SPS/Fermilab energies. Neutrino beam dump experiments[5] have established a level of 20 to 30 μb/nucleon for the central hadroproduction of $D\bar{D}$, assuming linear A-dependence, at a proton energy of 400 GeV. Evidence for a value of the $\nu/\bar{\nu}$ ratio deviating from one, which could be interpreted as being due to $\Lambda_c\bar{D}$ production, is conflicting. It would support only a small value (a few μb) for $\sigma(\Lambda_c\bar{D})$.

The Fermilab beam dump experiment[6] on Fe (A=55.85) only studies the forward production of charmed particles and determines that diffractive charm production is less than a few μb in 350 GeV proton interactions. Fitting the data with a model for uncorrelated $\Lambda_c\bar{D}$ production an integrated cross-section of 29 μb/nucleon is obtained, assuming $A^{2/3}$ dependence.

An emulsion experiment[7] with protons at 400 GeV attributes three prong events without black track or recoil to Λ_c-production and obtains a cross-section of (106±39) μb/nucleon for linear A-dependence, in contradiction with the beam dump experiments.

The LEBC-EHS collaboration[8] estimates that $\sigma(\Lambda_c\bar{D}) = (18^{+15}_{-10})$ μb from the asymmetry in c and $\bar{c}$ production in 360 GeV pp interactions.

Direct observation of Λ_c^+ with neutrons of mean energy of 58 GeV on a carbon target is reported by the BIS-2 collaboration[9], yielding $\sigma(\Lambda_c) \geq (70\pm20)$ μb per C nucleus for $x_F > 0$. This translates into $\sigma(\Lambda_c) \geq (12\pm3.5)$ μb/nucleon over the entire x_F-range for linear A-dependence.

Biagi, et al.,[10] have observed a narrow state at 2.46 GeV, which is a candidate for the charmed strange baryon A^+, with a Σ^- beam of 135 GeV. They obtain $\sigma(A^+)B(A^+ \rightarrow \Lambda K^-\pi^+\pi^+) = (5.3\pm2.0)$ μb/Be nucleus for $x_F > 0.6$. This reaction differs only in the exchange of an s-quark for a d-quark from the Λ_c^+-production with protons. The authors estimate σB for x > 0 to be between 4.7 and 24.9 μb/nucleon, assuming linear A-dependence, for various models. The branching ratio is not known. However, usual branching ratios for hadronic charm decay vary from 1 to 10% which would yield $\sigma(A^+) > 50$ μb/nucleon for $x_F > 0$, and then $\sigma(\Lambda_c^+) > 100$ μb/nucleon over the entire x_F-range.

The NA11 experiment obtained an earlier[2] upper limit for $\sigma(\Lambda_c\bar{D})$ of (57±5) μb with a previous data sample. This earlier result and the present limit are in agreement and are both in line with the values obtained in the beam dump experiments[5,6], the LEBC-estimate[8] and the direct observation of Λ_c^+ [9], but cannot be reconciled with the emulsion data[7] and the direct observation of A^+ [10].

Our upper limits on $\sigma(D^0)$, $\sigma(\bar{D}^0)$, $\sigma(D^+)$ and $\sigma(D^-)$ are of the level of the results of the beam dump experiments[5,6], LEBC[8], which has $\sigma(D/\bar{D}) = (56^{+25}_{-12})$ μb, and the Yale streamer chamber experiment[11], which quotes a cross section of 20 to 50 μb/nucleon with 350 GeV protons.

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R E F E R E N C E S

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Figure captions

Fig. 1: (a) ACCMOR forward spectrometer (top view).

(b) Lay-out of the electron trigger system (top view).

M1/2	spectrometer magnets
Arm 2,3a,3b,3c	sets of drift chambers
C1,2,3	multicellular Cherenkov counters
γ-cal	gamma calorimeter
P1,2,8,9	multiwire proportional chambers
Q	electron Cherenkov counter
e-cal	electron calorimeter
I	interaction counters for tagging of hit target cells
H	scintillator-lead-scintillator sandwich counters for electron pair rejection

Fig. 2: Inclusive spectrum of the $pK^-\pi^+$ mass for events from e^- and e^+ triggers.

Fig. 3: Inclusive spectra of the $K^-\pi^+$- and the $K^+\pi^-$-mass for "like sign Ke" and "unlike sign Ke".

Fig. 4: Inclusive spectra of the $K^-\pi^+\pi^+$- and the $K^+\pi^-\pi^-$-mass for "like sign Ke" and "unlike sign Ke".

* * *

Table 1

Particle assignment of final electron selected event sample with at least one proton, one kaon or one V^0.

Number of events: 2.24×10^5.

Mean multiplicity: 9.6.

Particle charge	-	+	0
Type			
e	111,283	113,527	
π	186,364	213,228	
K	10,862	20,424	
p	3,921	97,633	
ambiguous π/K*)	4,702	7,780	
ambiguous K/p	28,492	77,812	
not identified arm 2 track**)	515,588	596,901	
not identified arm 3 track***)	25,797	32,918	
ambiguous π/K/p****)	42,452	66,922	
K_S^0			12,418
Λ^0			4,832
$\bar{\Lambda}^0$			1,666

*) used in K-sample.

**) particles not passing second spectrometer magnet.

***) particles passing second spectrometer magnet with momentum <3.6 GeV, used in π-sample.

****) particles which cannot be distinguished by C_1, C_2 and C_3, either by pulse height at very high momentum or due to geometry of nearby trajectories, used in π-sample.

<u>Table 2</u>

<u>Numbers used for the calculation of the upper limits of the cross-sections</u>

	$\Lambda_c^+ \to pK^-\pi^+$	$D^0 \to K^-\pi^+$	$\bar{D}^0 \to K^+\pi^-$	$D^+ \to K^+\pi^+\pi^+$	$D^- \to K^+\pi^-\pi^-$	
σ_m,expected	8	10		12		MeV
$n/\bar{b}/\bar{s}$ *) resp.,	365 384.5 5.3	74 63.2 22.0	148 151.1 12.7	377 368.2 34	644 644.9 32.1	events
in Δm	2260-2300	1840-1880		1840-1900		MeV
N(p, incoming)	3.04	3.04		3.04		$\times 10^{10}$
(Luminosity)$^{-1}$	13.35	13.35		13.35		pb/(nucleon.event)
B(hadronic decay)	2.2±1.0	2.4±0.4		4.6±1.1		%
B($D^*/D \to e+X$) **)	10.0±2.8	10.0±2.8		10.0±2.8		%
Acc(hadronic decay)	11.0	10.7		10.6		%
Acc($D^*/D \to e+K/K^*+X$)	3.6	2.0		2.0		%
σ(90% C.L. upper limit)	8	64	37	51	49	μb/nucleon

*) $\bar{s} = n+1.3\sqrt{n-\bar{b}}$ for σ(90% C.L.), where $\bar{b}$ is determined by fit to mass spectrum.

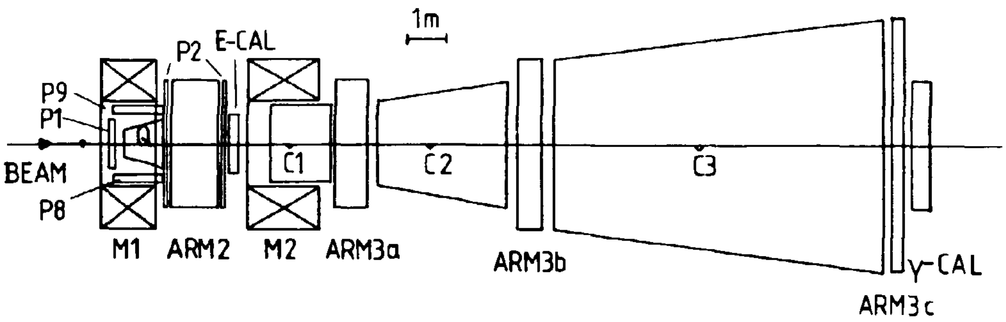
**) Weighted average using values from ref. [3].

Table 3

Variation of acceptances and upper limits with the power n in $(1 - |x_F|)^n$ and with the slope parameter b in $e^{-bp_T^2}$ (HAD = acceptance hadronic decay, SELE = acceptance semi-leptonic decay, UL = 90% confidence upper limit of cross-section).

Particle	n_{Λ_c}	b_{Λ_c}	$n_{\bar{D}}$	$b_{\bar{D}}$	HAD (%)	SELE (%)	UL (μb/nucleon)
Λ	0.5	2.9	8.0	4.0	11.8	3.6	7
	1.0	2.9	8.0	4.0	11.0	3.6	8 *)
	3.0	2.9	4.0	4.0	5.5	3.6	16
	1.0	2.9	4.0	4.0	9.5	3.0	11
	1.0	2.9	10.0	4.0	9.2	3.8	9
	1.0	1.0	8.0	4.0	9.1	3.6	10
	1.0	5.0	8.0	4.0	9.9	3.6	9
	1.0	2.9	8.0	2.0	9.2	3.6	10
	1.0	2.9	8.0	6.0	9.2	3.6	10
	n_D	b_D	$n_{\bar{D}}$	$b_{\bar{D}}$			
$D^0/\bar{D}^0$	0.5	1.1	0.5	1.1	13.6	1.9	53/31
	0.8	1.1	0.8	1.1	10.7	2.0	64/37 *)
	3.0	1.1	3.0	1.1	8.4	2.8	58/34
	0.8	5.0	0.8	5.0	17.9	1.9	40/23
D^+/D^-	0.5	1.1	0.5	1.1	11.2	1.8	54/52
	0.8	1.1	0.8	1.1	10.6	2.0	51/49 *)
	3.0	1.1	3.0	1.1	5.3	2.8	73/70
	0.8	5.0	0.8	5.0	9.0	1.8	67/64

*) Values of table 2.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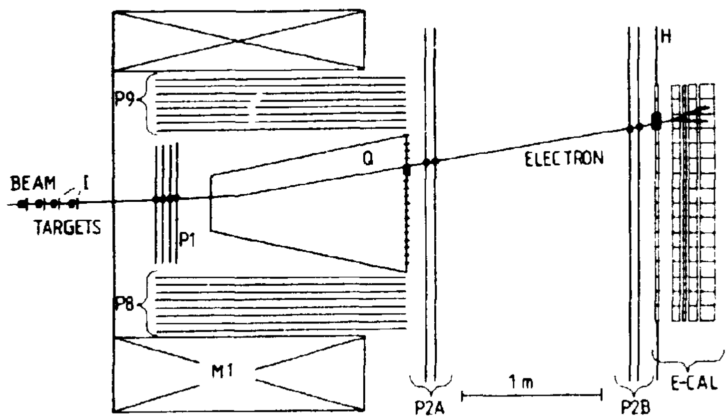
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Fig. 1

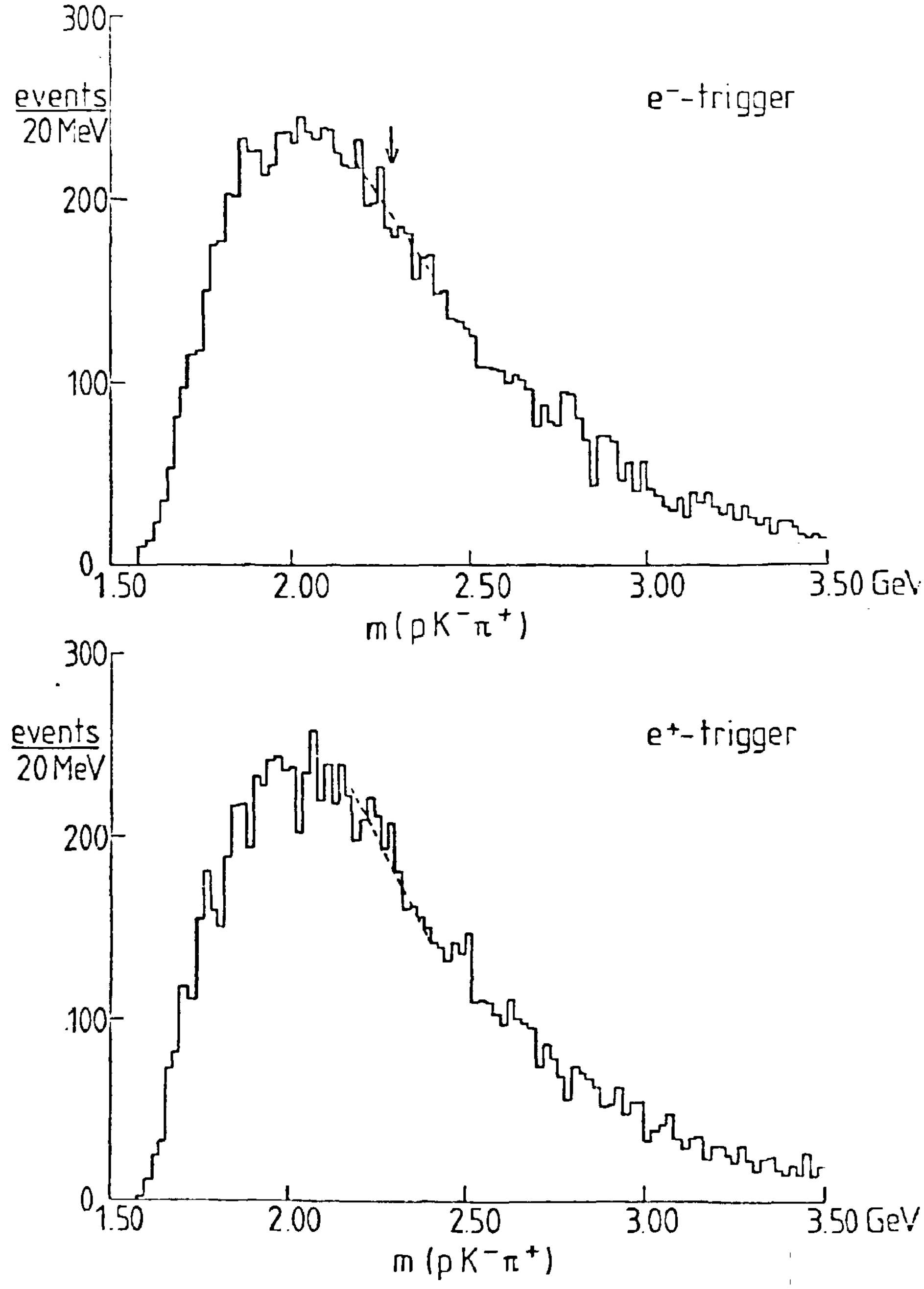
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Fig. 2

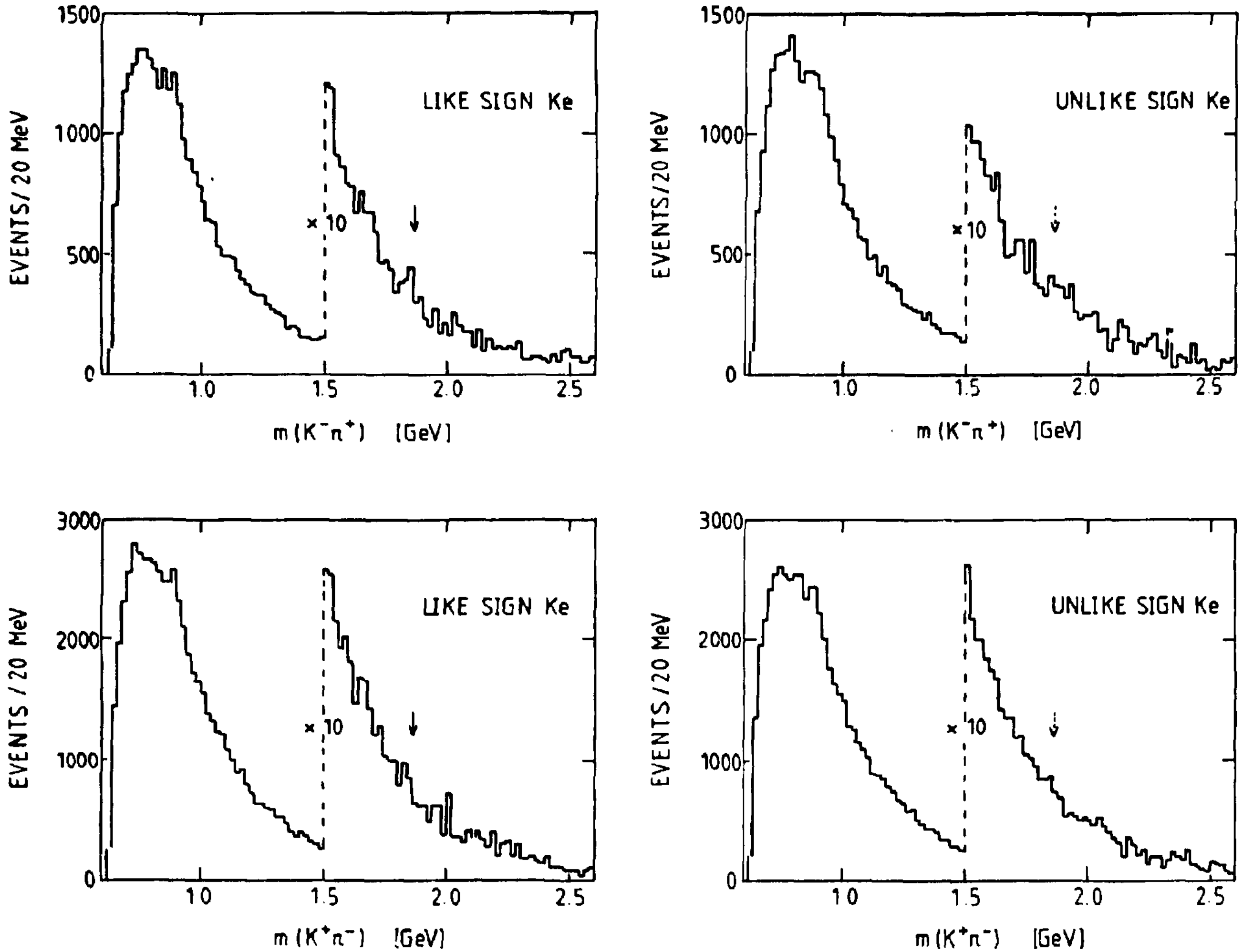
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Fig. 3

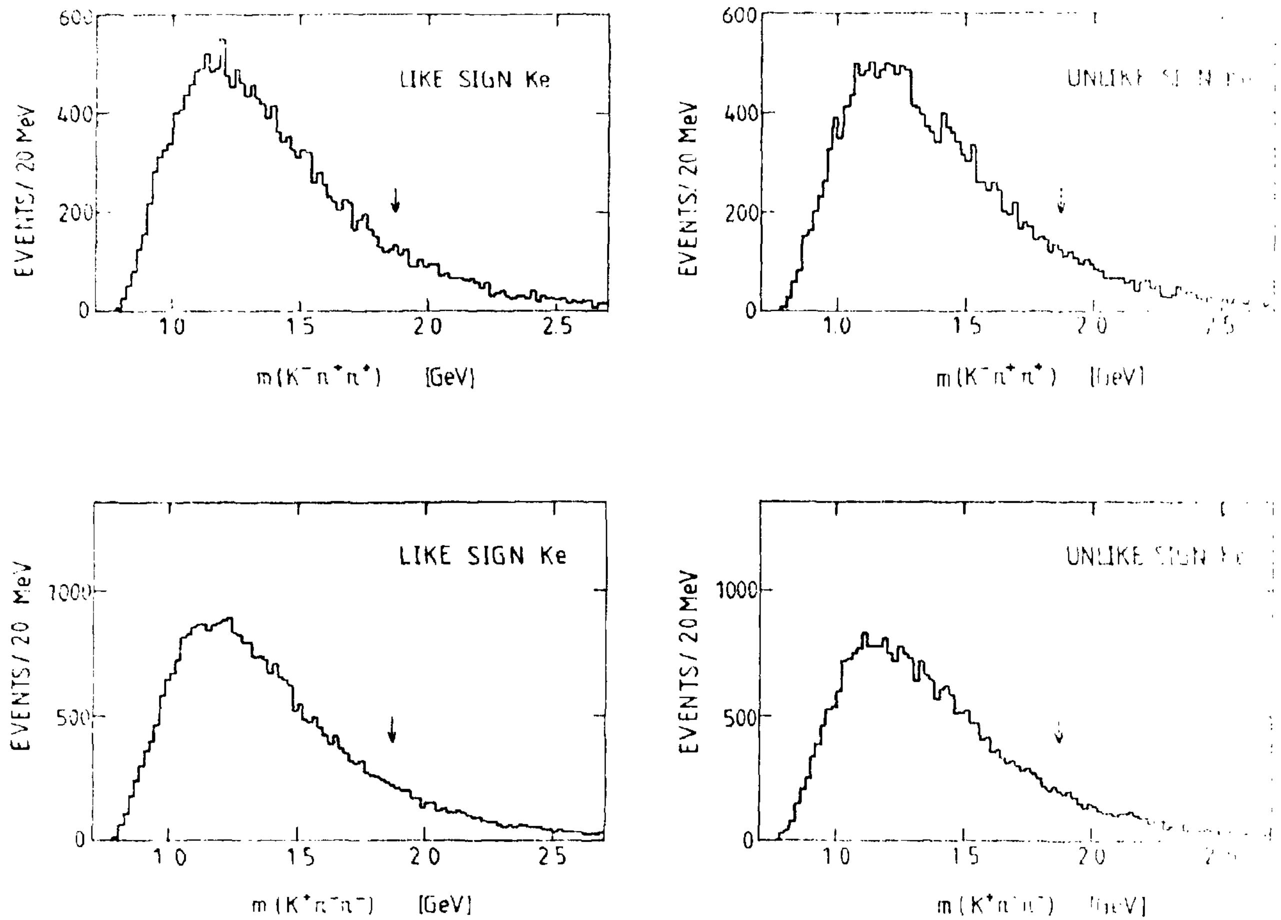

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Fig. 4