Photoproduction of K^0 : Early history

Michael Albrow
Fermi National Accelerator Laboratory

Why K^0 photoproduction and mechanisms

Pre – 1970 experiments (not much)

CP-violation in K^0 discovered 1964
CCFT (Nobel)

My Ph.D. thesis experiment (Manchester/DNPL) 1964 - 1969

Beam line and detectors

Analysis and results, with H_2 and nuclear targets

K^0_L decay and interaction measurements done with that beam

PHYSICAL REVIEW VOLUME 138, NUMBER 5B 7 JUNE 1965

CP-violation (1964)
Hot topic!

Photoproduction of Neutral K Mesons*

S. D. Drell and M. Jacob†
Stanford Linear Accelerator Center, Stanford University, Stanford, California
(Received 6 January 1965)

First paper on subject

Photoproduction of a neutral K-meson beam at high energies from hydrogen is computed in terms of a K^* vector-meson exchange mechanism corrected for final-state interactions. The results are very encouraging for the intensity of high-energy K_2 beams at high-energy electron accelerators. A typical magnitude is 20 μb/sr for a lower limit of the K^0 photoproduction differential cross section, at a laboratory peak angle of 2°, for 15-BeV incident photons.

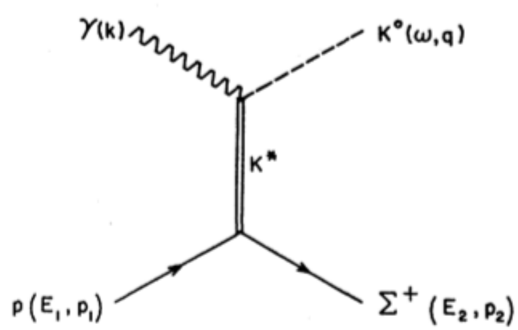


Fig. 1. K^* exchange in photoproduction.

Not dominant

50 µb/sr

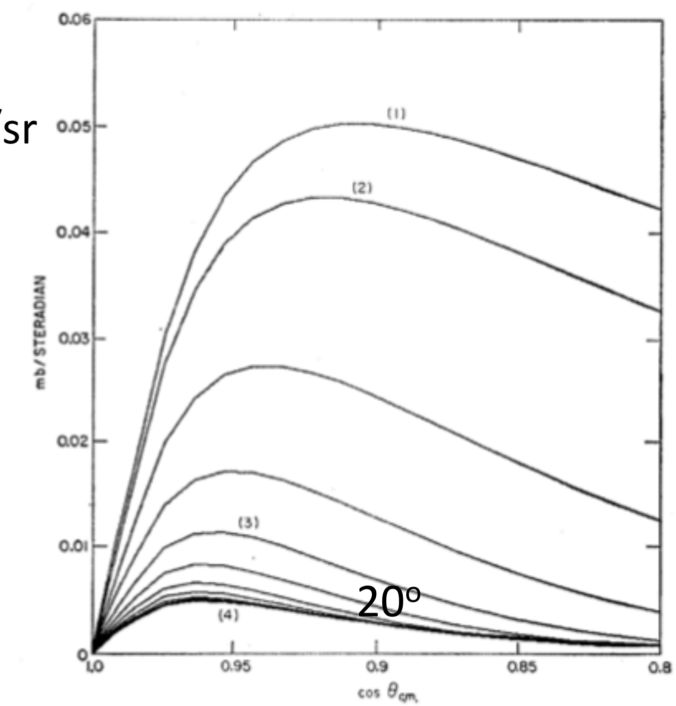


Fig. 3. Center-of-mass differential cross section at 10 BeV. Curve (1) gives the Born approximation. Curve (2) is obtained after subtraction of the $j=\frac{1}{2}$ partial wave. Curves (3) and (4) are respectively obtained after the $j=\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \frac{7}{2}$, and all partial waves have been corrected for absorption in final state. The results are shown as directly obtained from and drawn by the computer.

Our motivation in carrying out this calculation is to emphasize the strong suggestion that an intense "healthy" K_2 beam will emerge from high-energy electron accelerators (SLAC in particular) and will be available for detailed experimental studies.

We were at Manchester Univ. close
To Daresbury 5 GeV e-synchrotron

First observation of K^0 photoproduction

Bubble chamber photographs : 50 in 865,000 pictures to scan

PHYSICAL REVIEW VOLUME 156, NUMBER 5 25 APRIL 1967

Photoproduction of Strange Particles*

CAMBRIDGE BUBBLE CHAMBER GROUP†
Brown University, Providence, Rhode Island, U. S. A.,
Cambridge Electron Accelerator, Cambridge, Massachusetts, U. S. A.,
Harvard University, Cambridge, Massachusetts, U. S. A.,
Massachusetts Institute of Technology, Cambridge, Massachusetts, U. S. A.,
University of Padova, Padova, Italy,
and
The Weizmann Institute of Science, Rehovoth, Israel.

(Received 2 November 1966)

The photoproduction of strange particles at photon energies between 1 and 6 BeV was studied using a 12-in. hydrogen bubble chamber. 283 events were observed in a sample of 865 000 pictures. Cross sections are presented. Y_1^* (1382) and K^* (890) production were observed in the $\gamma+p\rightarrow\Lambda^0+K+\pi$ reaction. There is evidence for ϕ^0 production in the $\gamma+p\rightarrow p+K+\bar{K}$ reaction.

Majority are K^+ with ~ 50 $K^0_s \rightarrow \pi^+\pi^-$ in "unambiguous" class
35 classed as $\Lambda K^0 \pi^+$ and a few possible $\phi \rightarrow KK$ ("weak")

PHYSICAL REVIEW VOLUME 188, NUMBER 5 25 DECEMBER 1969

Multipion and Strange-Particle Photoproduction on Protons at Energies up to 5.8 GeV

AACHEN–BERLIN–BONN–HAMBURG–HEIDELBERG–MÜNCHEN COLLABORATION

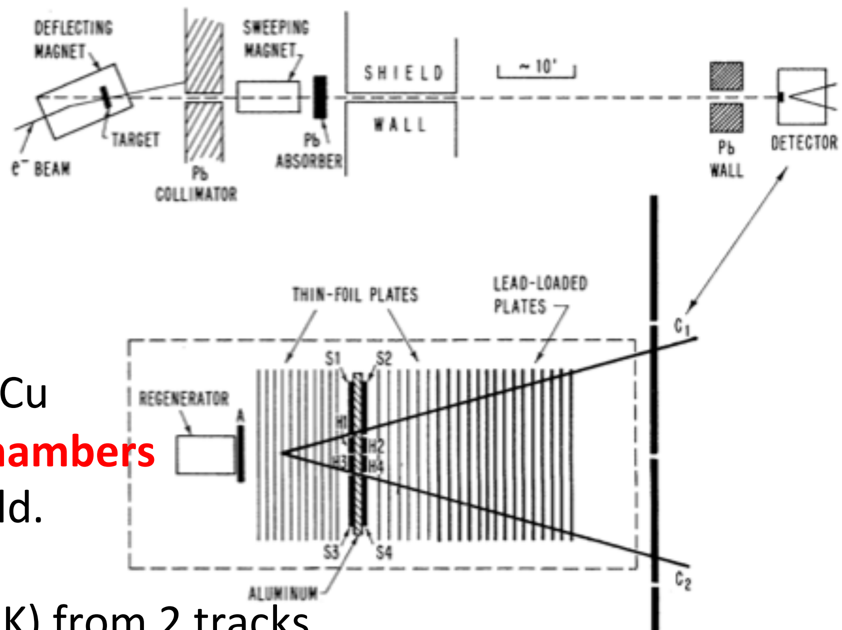
VOLUME 19, NUMBER 23 PHYSICAL REVIEW LETTERS 4 DECEMBER 1967

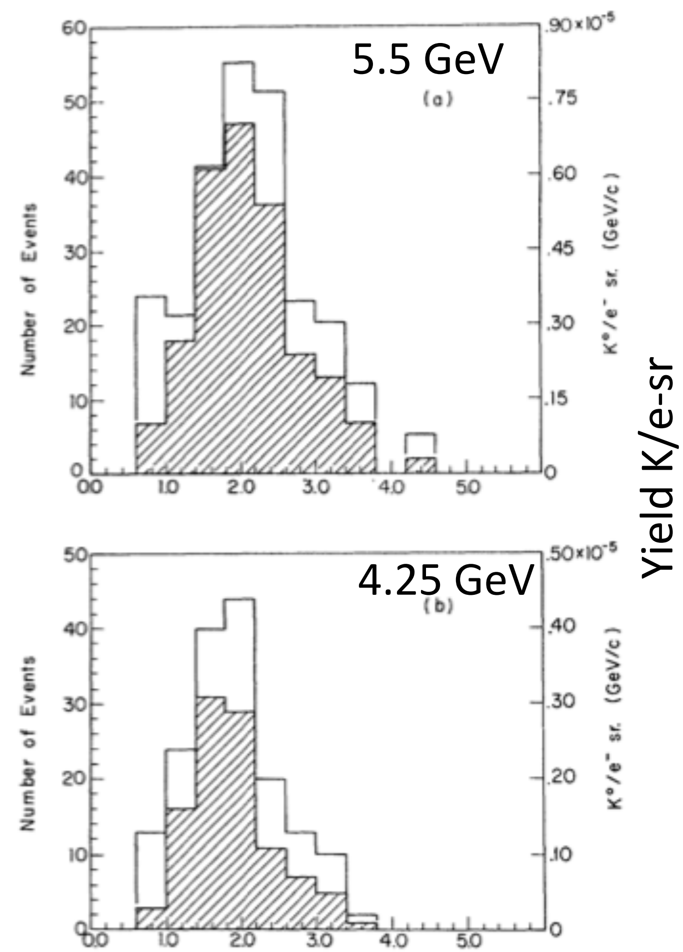
OBSERVATION OF PHOTOPRODUCED NEUTRAL *K* MESONS*

J. F. Schivell,† E. Engels, Jr., and A. Entis +Paterson, Hand, Sadoff
Harvard University, Cambridge, Massachusetts

Cambridge Electron Accelerator (CEA)
5.5 and 4.25 GeV electron beam on 1 X_o Al target
Pb collimator at 3.5°

- Electro- and photo-production not distinguished
- Other angles and Be target (not in this paper)



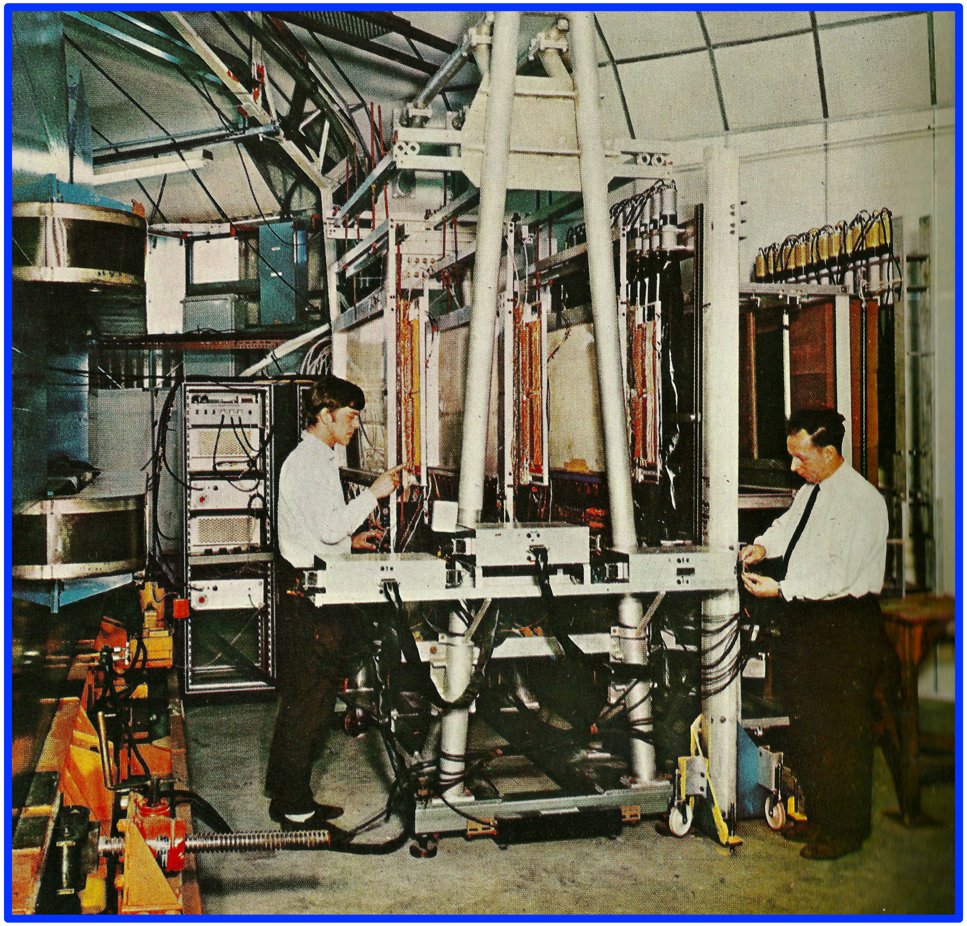


Energy K

Collimators
Regenerator 6” Cu
Optical spark chambers
No magnetic field.
$K^0 \rightarrow \pi^+\pi^-$
Selection and p(K) from 2 tracks.
Yield = 1.3 10^{-5} K^0/e-sr at 5.5 GeV (spectrum at right)

Prof. Paul Murphy arrived Manchester in 1965, started series of experiments with K^0 at Daresbury DNPL. NINA : 5 GeV Electron synchrotron. K^0 with less neutron background.

Setting up wire spark chambers at Daresbury for K^0 photoproduction experiment

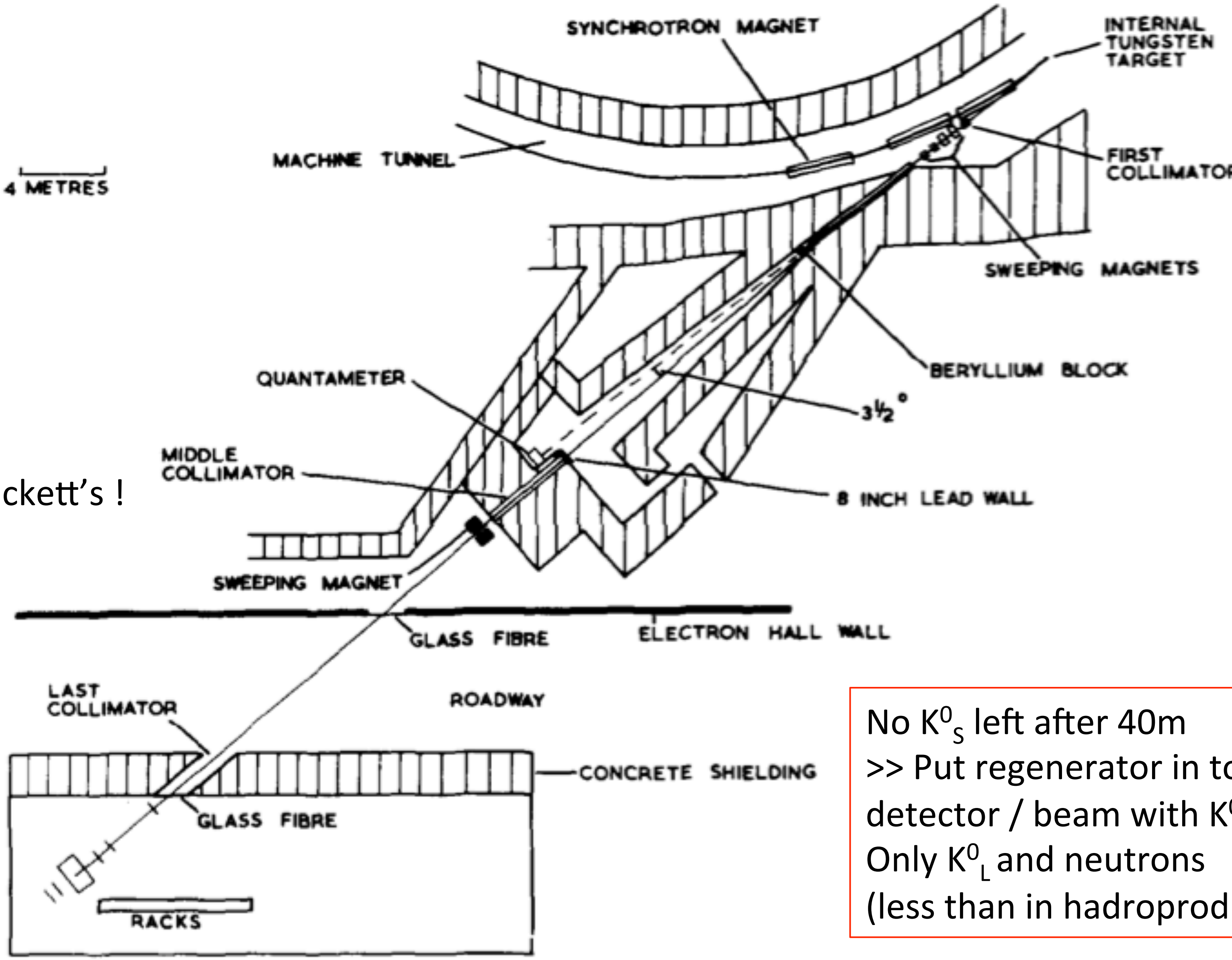


Thanks to local Fothergill & Harvey for special cloth Wires/fibreglass

Ferrite core memory
1 mm^3 / bit

Seeing sparks!

Largest “automatic spark chamber system anywhere at that time

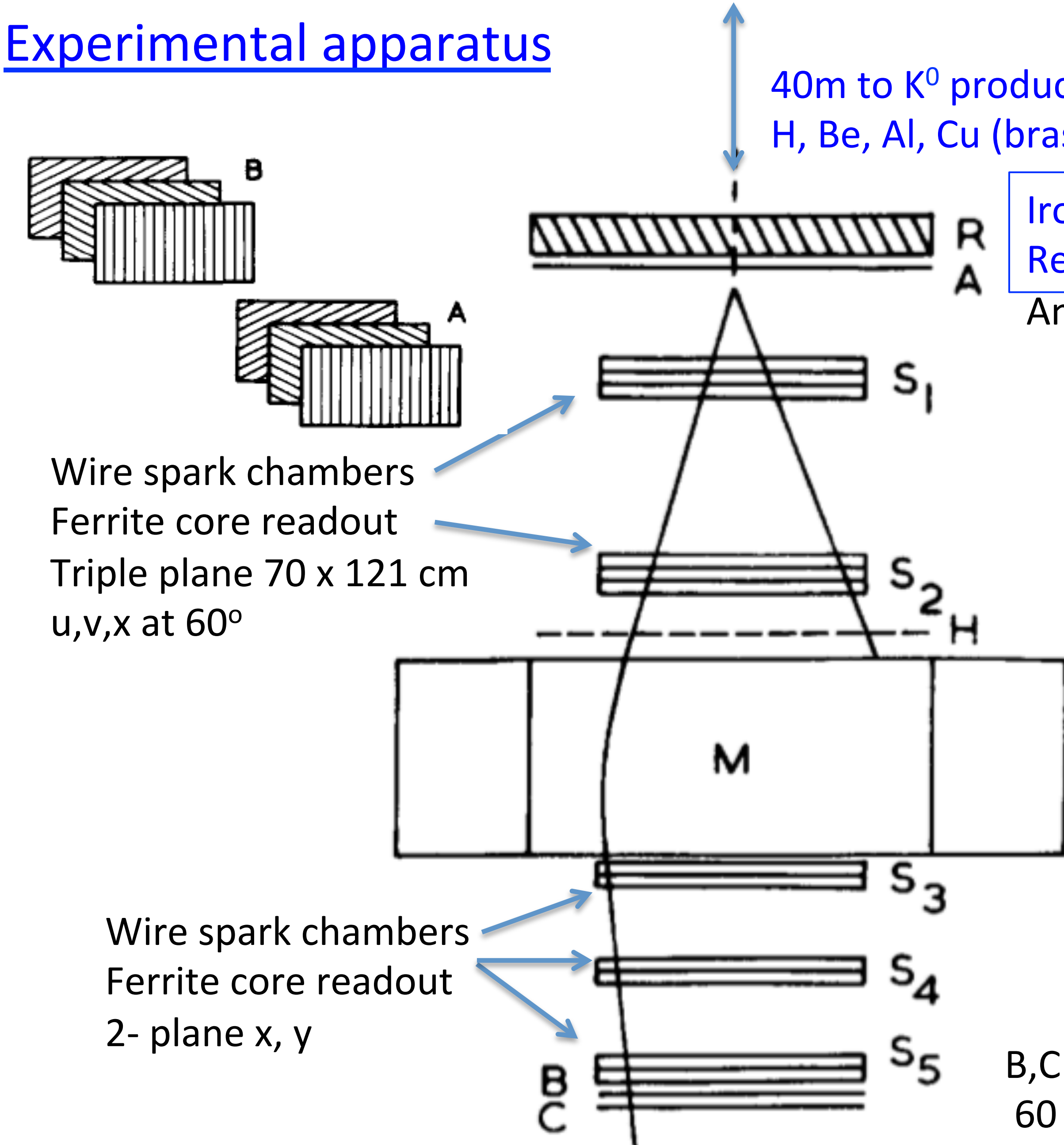


Blackett's !

No K^0_S left after 40m
>> Put regenerator in to calibrate detector / beam with $K^0_S \to \pi^+\pi^-$
Only K^0_L and neutrons
(less than in hadroproduction)

Fig. 1. Arrangement for production of the K^0_L beam from NINA.

Experimental apparatus



40m to K^0 production target
H, Be, Al, Cu (brass)

Iron regenerator 14 cm thick
Removed for K^0_L expts

Anti (veto)-counters

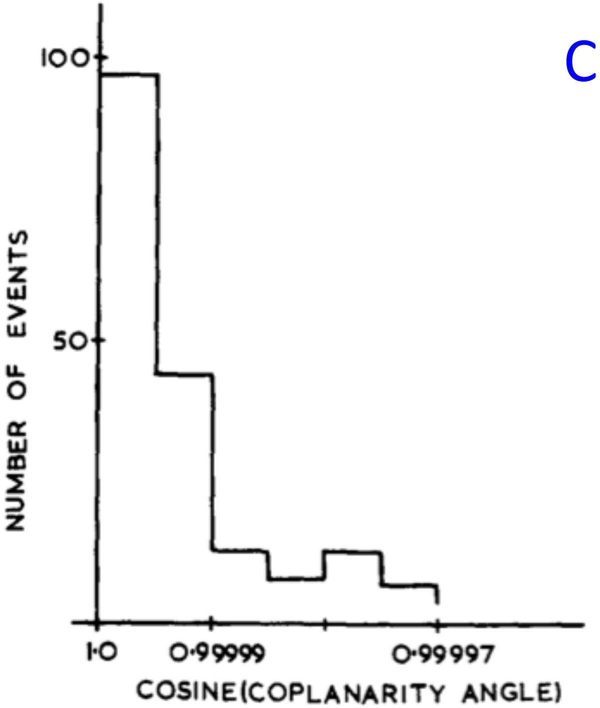
Wire spark chambers
Ferrite core readout
Triple plane 70 x 121 cm
u,v,x at 60°

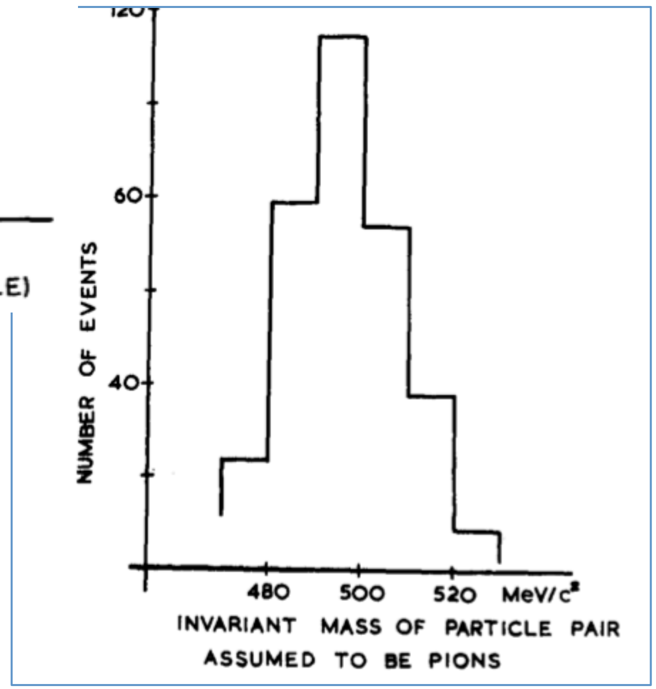
H = Scintillator hodoscope
12 slats 10 x 50 x 1 cm^3

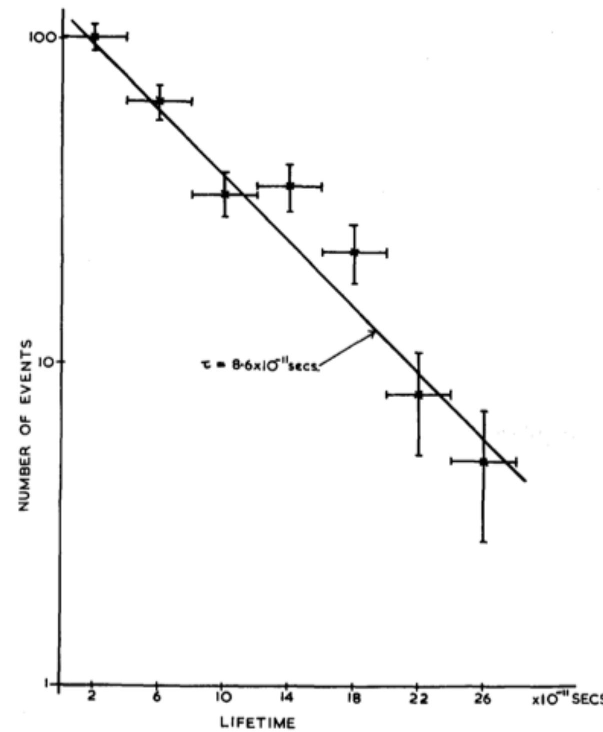
Wire spark chambers
Ferrite core readout
2- plane x, y

B,C Scintillators (trigger)
60 x 60 x 1 cm^3
1 cm steel between

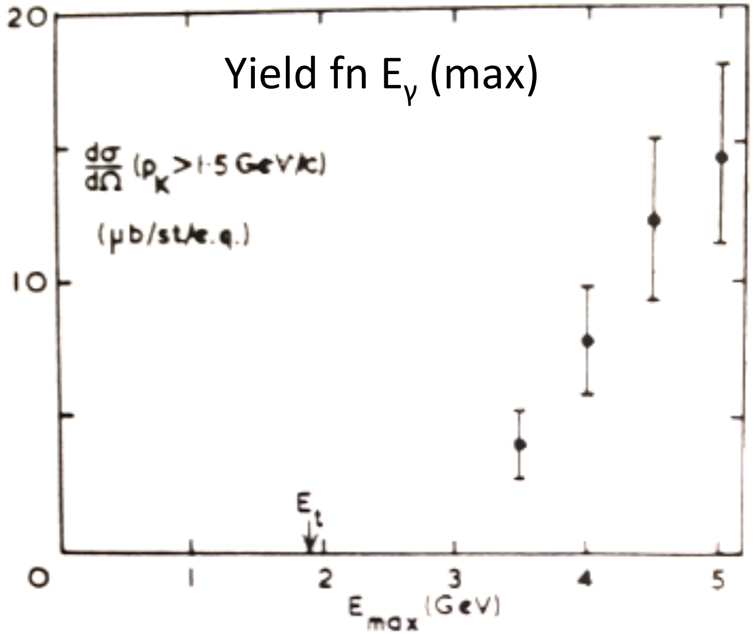
Checks of $K^0_S \rightarrow \pi^+\pi^-$

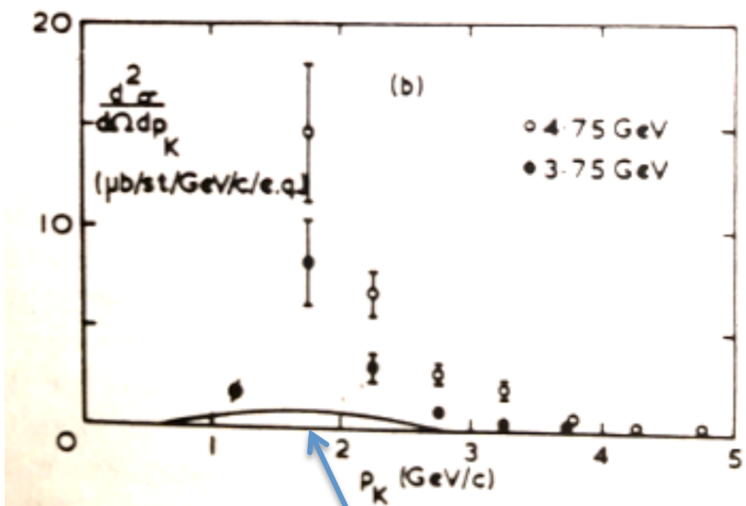






Apologies for terrible quality. Figs from Phys Lett 29B (1969) 54





VMD exclusive Φ

Momentum spectrum μb/GeV/sr E_γ = 3.75-4.75 GeV

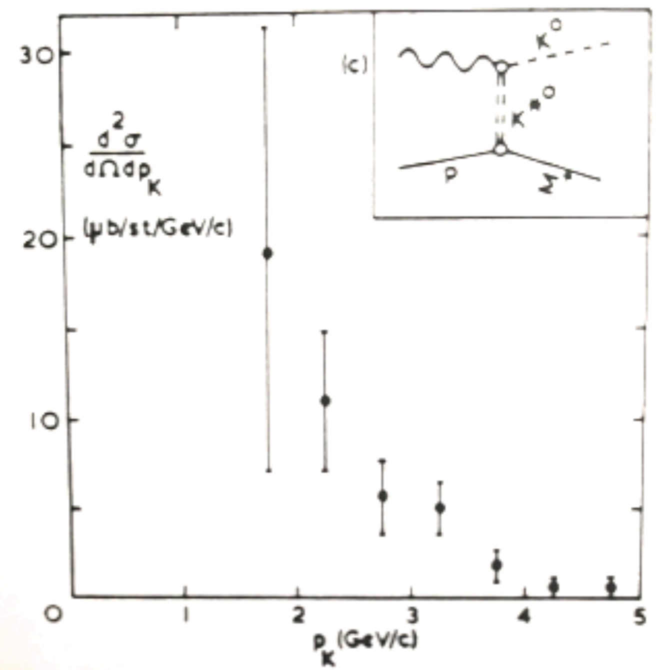


Fig. 3. a. Yield of K_L^0, in microbarns per steradian per equivalent quantum, as a function of bremsstrahlung maximum energy. For each value of E_{max} the K-spectrum is integrated from 1.5 GeV/c to the maximum. b. K_L^0 spectra for E_{max} = 3.5 GeV and 4.0 GeV combined ("3.75 GeV") and for E_{max} = 4.5 GeV and 5.0 GeV combined ("4.75 GeV"). The curve labelled ϕ is the contribution from $\gamma + p \rightarrow \phi + p$. $\phi \rightarrow K_L^0 + K_S^0$, calculated for E_{max} = 5 GeV.
c. K_L^0 spectrum in microbarns per steradian per GeV/c (per photon) for photons with E_γ = 4.25 ± 0.5 GeV. Inset is a diagram for the process discussed by Drell and Jacob [1].

Volume 29B, number 1 PHYSICS LETTERS 31 March 1969

& follow up

PHOTOPRODUCTION OF K^0 MESONS FROM PROTONS AND FROM COMPLEX NUCLEI

M. G. ALBROW ‡, D. ASTON, D. P. BARBER, L. BIRD ‡‡,
R. J. ELLISON, C. HALLIWELL, A. E. HARCKHAM ‡‡‡,
F. K. LOEBINGER, P. G. MURPHY, J. WALTERS ‡‡ and A. J. WYNROE
Schuster Laboratories, The University of Manchester, Manchester M13 9PL

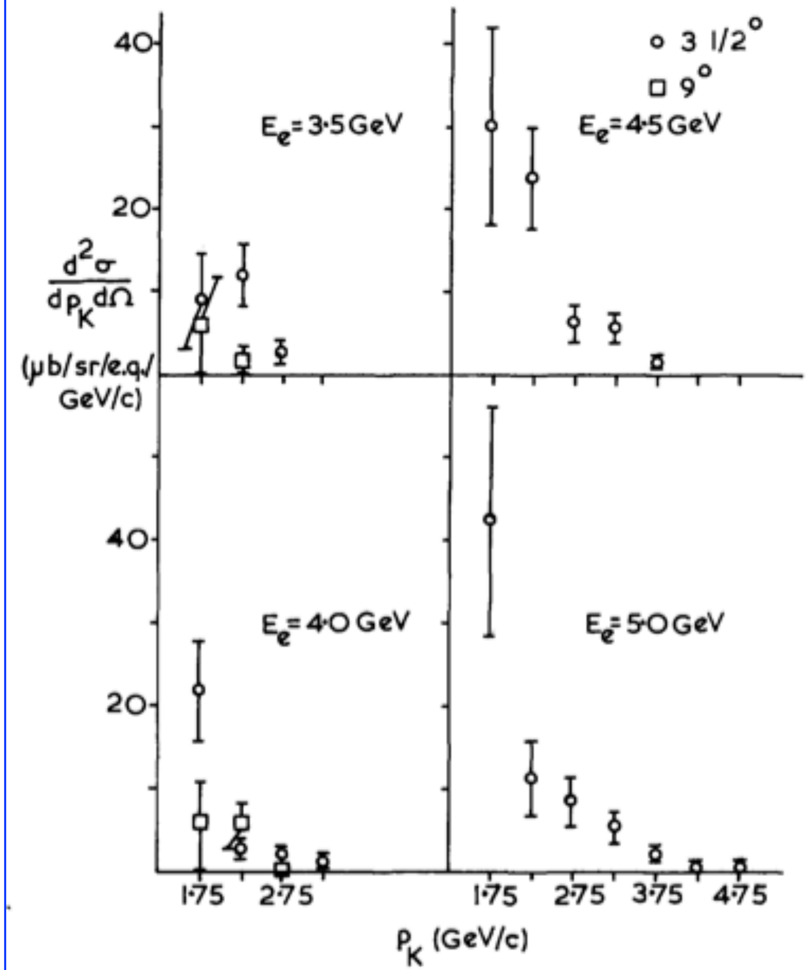
R. F. TEMPLEMAN
Daresbury Nuclear Physics Laboratory, Daresbury, Near Warrington, Lancs.

Nuclear Physics B23 (1970) 509

Abstract: The momenta spectra of neutral K-mesons photoproduced from protons and other nuclei by bremsstrahlung have been measured, for photon energies up to 5 GeV. The cross sections for production of K_L^0 from protons integrated over momenta from 1.5 GeV/c to the maximum were 11.8 ± 3.5, 14.0 ± 3.7, 33.4 ± 6.9 and 35.3 ± 7.5μb/sr/equivalent quantum at $3\frac{1}{2}^o$ to bremsstrahlung beams with maximum energies of 3.5, 4.0, 4.5 and 5.0 GeV, respectively. At 9^o the cross sections, similarly defined, were 3.6 ± 3.0 and 6.0 ± 3.5μb/sr/equivalent quantum at 3.5 and 4.0 GeV, respectively. The cross sections for production from nuclei, at $3\frac{1}{2}^o$ and with bremsstrahlung of maximum energy 4.5 GeV, were 32.0 ± 8.0, 49.1 ± 6.0 and 45.9 ± 15.7 μb/sr/equivalent quantum per nucleon for Be, Al and Cu, respectively.

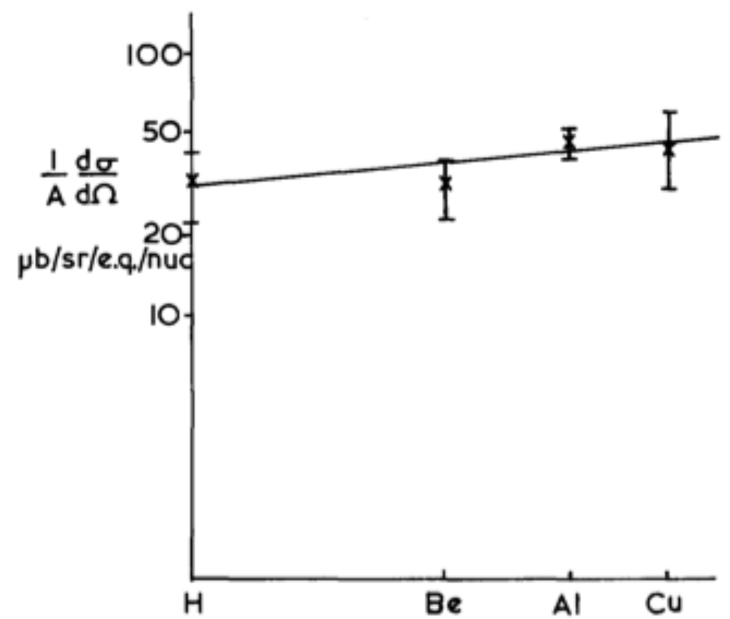
The observed spectra cannot be explained in terms of simple processes; the K-mesons are probably produced in association with several other particles.

Strong growth with E(γ)



. 10. K^0_L momentum spectra for different bremsstrahlung maxima, for hydrogen target.

Per nucleon, little A,Z dependence



11. Cross section per nucleon as a function of atomic weight for photoproduction of K^0_L, using bremsstrahlung with a maximum energy of 4.5 GeV.

A STUDY OF THE DECAY $K_L^0 \to \pi^{\pm} e^{\mp} \nu_e$

Nuclear Physics B58 (1973) 22–30.

Abstract: In a study of charged K_L^0 three-body decays a sample of 6 668 $K_L^0 \to \pi^{\pm} e^{\mp} \nu$ candidates has been obtained. The Dalitz plot distribution is in agreement with V – A theory, and limits are presented for scalar and tensot contributions to the weak current. Using a conventional expansion for the form factor f_+ we find $\lambda_+ = 0.055 \pm 0.010$ with systematic effects estimated at ± 0.01.

79,000 2-track triggers with + & - tracks through magnet, with vertex in fiducial region.
Kinematics (Astier frame:KE(K) assuming 3π decay) separates:

$K_L^0 \to \pi^+ \pi^- \pi^0$ 12.5%

$\to \pi^{\pm} \mu^{\mp} \nu_{\mu}$ 27.0%

$\to \pi^{\pm} e^{\mp} \nu_e$ 40.6%

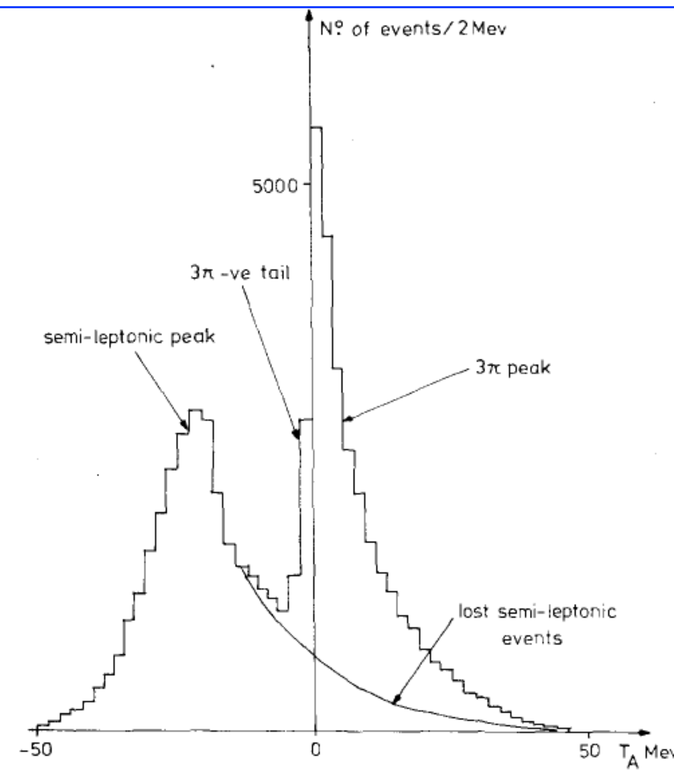
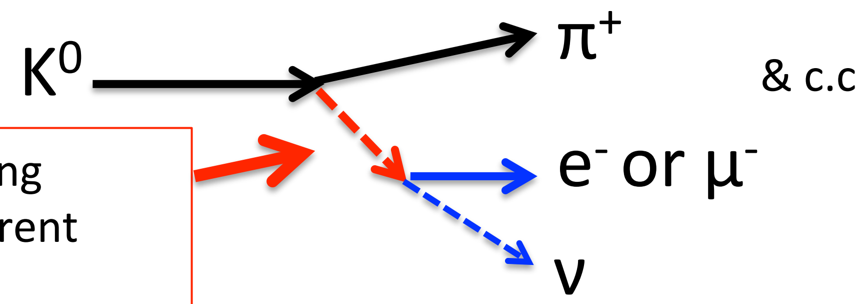


Fig. 2. Astier kinetic-energy distribution.

Semileptonic K^0_L decays → π ν (e or μ)

$$(2\pi)^3 \sqrt{4E_K E_\pi}\langle \pi(p^\pi)|V_\mu|K(p^K)\rangle = (p^K + p^\pi)_\mu f_+(q^2) + (p^K - p^\pi)_\mu f_-(q^2)$$

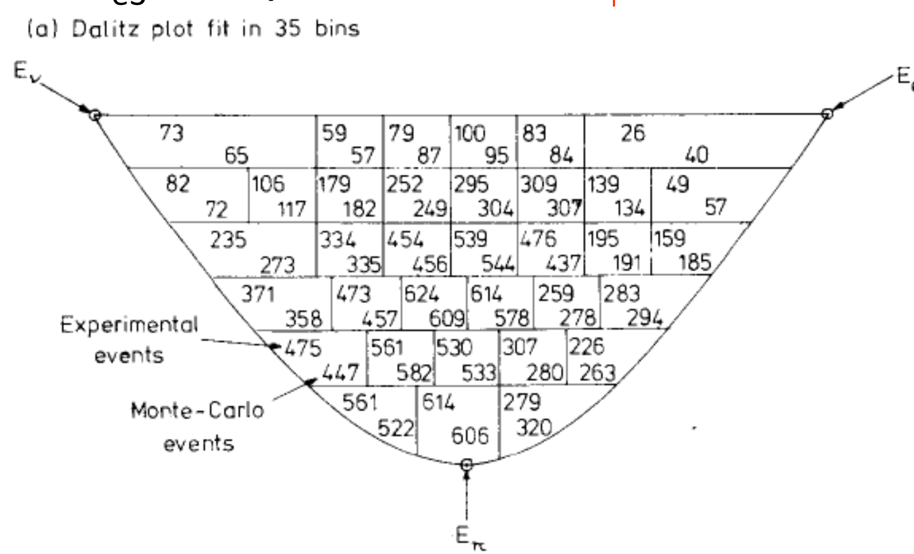


Strangeness-changing
hadronic vector current
V – A theory (W)
$q^2 = (p_K - p_\pi)^2$ (4-vectors)

Electron decay – kinematics & e-showering

Form factor $f_+(q^2)$ determined by fitting Dalitz plot of decays ($\Sigma E = M_K$)
$f_-(q^2)$ suppressed by $(m_e/M_K)^2$ and irrelevant in K_{e3} decays

3 axes at 60° because
Sum of energies = M(K)



Form factors, function of q^2

$$f_+(q^2) = f_+(0)\,[1 + \lambda_+ q^2 / m_\pi^2]$$

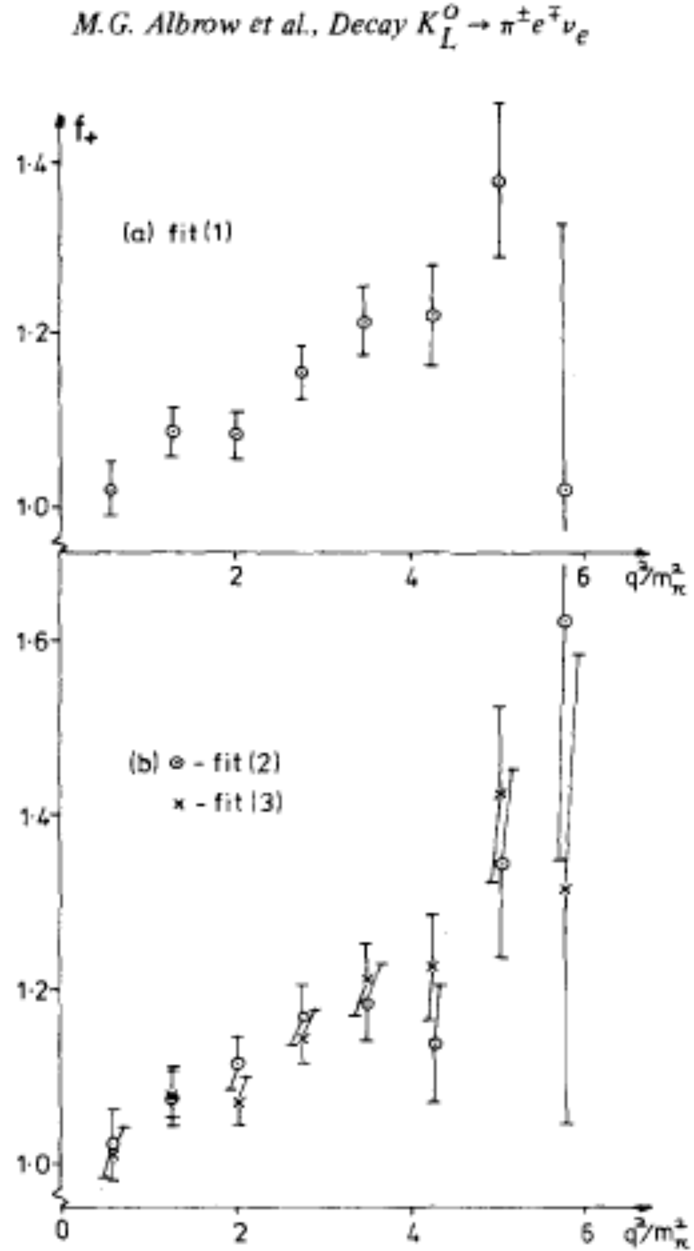
Fit: $\lambda_+ = 0.055 \pm 0.010$

Scalar and/or tensor terms? Put limits:

$f_S < 0.19\, f_+(0)$ and $f_T < 1.0\, f_+(0)$

Separately. Weak limits, and could have
Both scalar and tensor terms with
destructive interference.

Basically support V-A weak current.



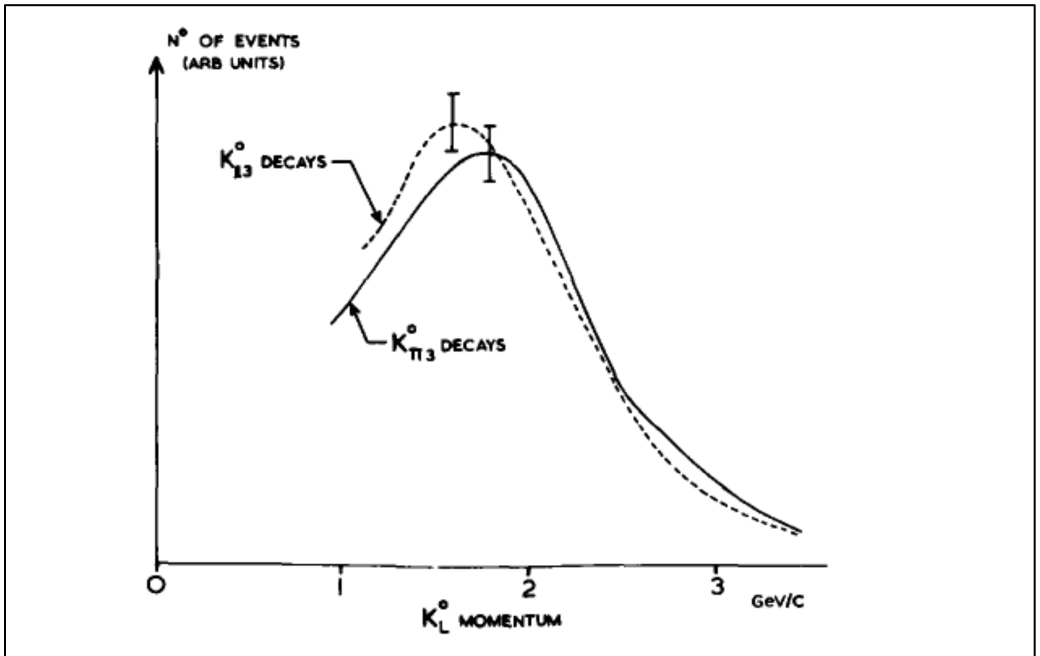
Model-independent fits to $f_+(q^2)$

AN EXPERIMENTAL STUDY OF THE DECAY MODE $K^0_L \to \pi^\pm \mu^\mp \nu$

M.G. Albrow et al. (Manchester, Daresbury) Nuclear Physics B44 (1972) p.1

NINA, 5 GeV e-synchrotron → bremsstrahlung beam → 1 X_0 (35cm) Be target (10 x 10cm^2)
Collimator at 3.5° → 35 X_0 lead filter to remove all γ + some K^0 and n (1.1 λ_{int})
Neutral hadron beam 41m (through air) to AntiCounters before fiducial decay region.
Muon signal – penetration 25cm Fe + 5 cm Pb required.

640,000 triggers. Most were K^0_L decays with one or both tracks not fully/well-measured
70,000 K^0_L decays within the fiducial volume with two momentum-measured tracks

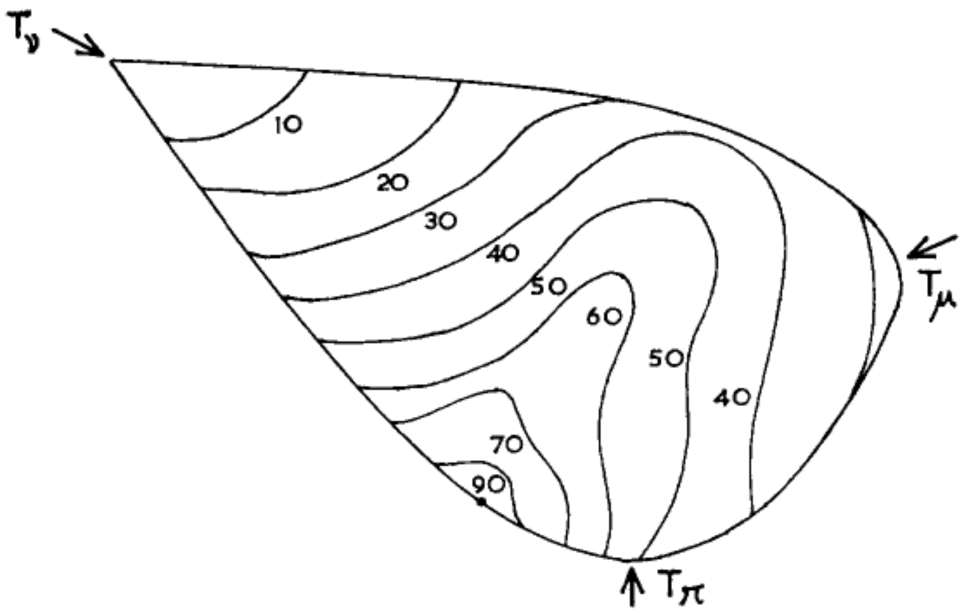


. K^0_L spectra obtained from the $K^0_{\pi3}$ decays and (independently) from the $K^0_{\ell3}$ decays.

Spectrum inferred from fits to Ke3 and Kπ3 decays, at detector (so after 41m flight).

Relative acceptance over Dalitz plot.
Absolute acceptance was only ~ 1%

Warning: If details matter go to original paper; I only show examples



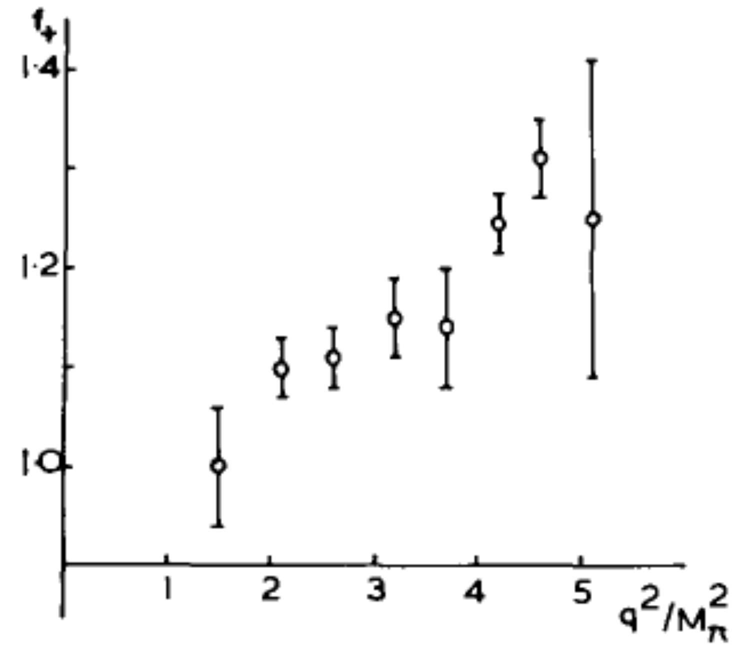


Fig. 11. $f_+(q^2)$ in bins of q^2.

Divide in 42 bins mostly 12 x 24 MeV.
events (total = 9066)
from theory x acceptance x efficiency

Minimize χ^2 → parameters in theory.

Different assumptions on variation of f^+, f^-, with q^2 → different parameters.
If assume linear get:

χ^2/d.o.f. = 1.93

& (Weak) Limits on f_S and f_T

$$\lambda_+ = 0.081 \pm 0.017\ , \quad \xi(0) = -0.7 \pm 0.5\ , \quad \lambda_- = -0.096\,^{+0.056}_{-0.074}\ , \quad \text{FIT II}\ ,$$

AN EXPERIMENTAL STUDY OF THE DECAY $K_L^0 \to \pi^+ \pi^- \pi^0$

M.G. Albrow et al., Physics Letters 33B (1970) p.516

Same 70,000 event sample →29,000 Kπ3
Did not measure π^0 : kinematics identifies mode:

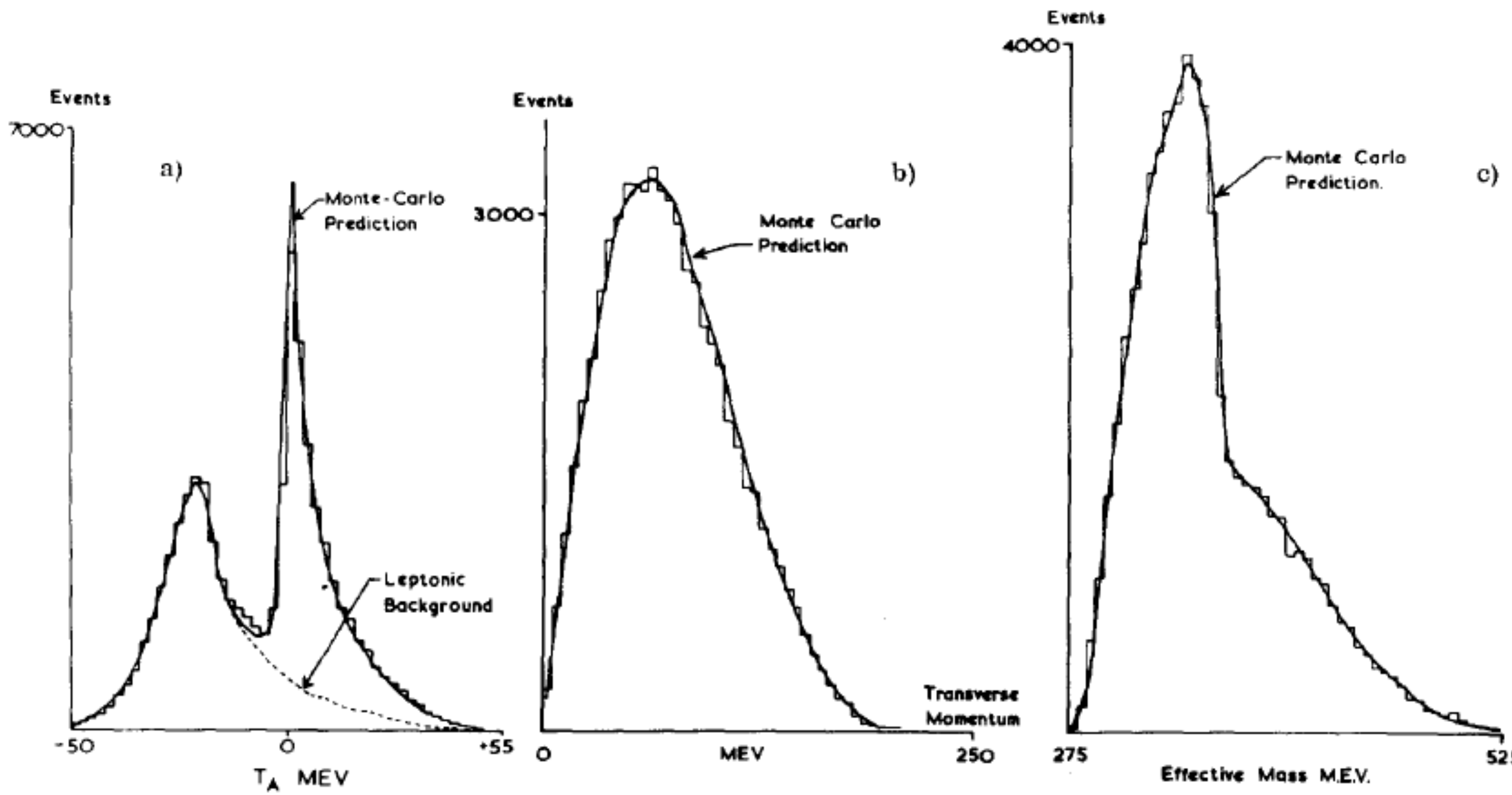


Fig. 2. (a) Distribution of the K_L^0 kinetic energy T_A in the system described in the text. The left hand peak contains leptonic decay events while the right hand peak contains predominantly $\pi^+\pi^-\pi^0$ decays. The full curve gives the Monte Carlo prediction.
(b) Distribution of the net transverse momentum of the charged particles.
(c) Effective mass distribution of the two charged particles, assuming them to be pions.

Fit to “Weinberg form” PRL 17 (1966) 153

$$|M(T_0)|^2 \alpha \, | + \alpha_1 \frac{QY}{m_k} + \alpha_2 \left(\frac{QY}{m_k}\right)^2 + \alpha_3 \left(\frac{QY}{m_k}\right)^3 + \ldots \quad (1)$$

where

$$Y = \frac{3T_0 - Q}{Q}$$

All coefficients except α_1 consistent with 0

$\alpha_1 = - 5.14 \pm 0.09$

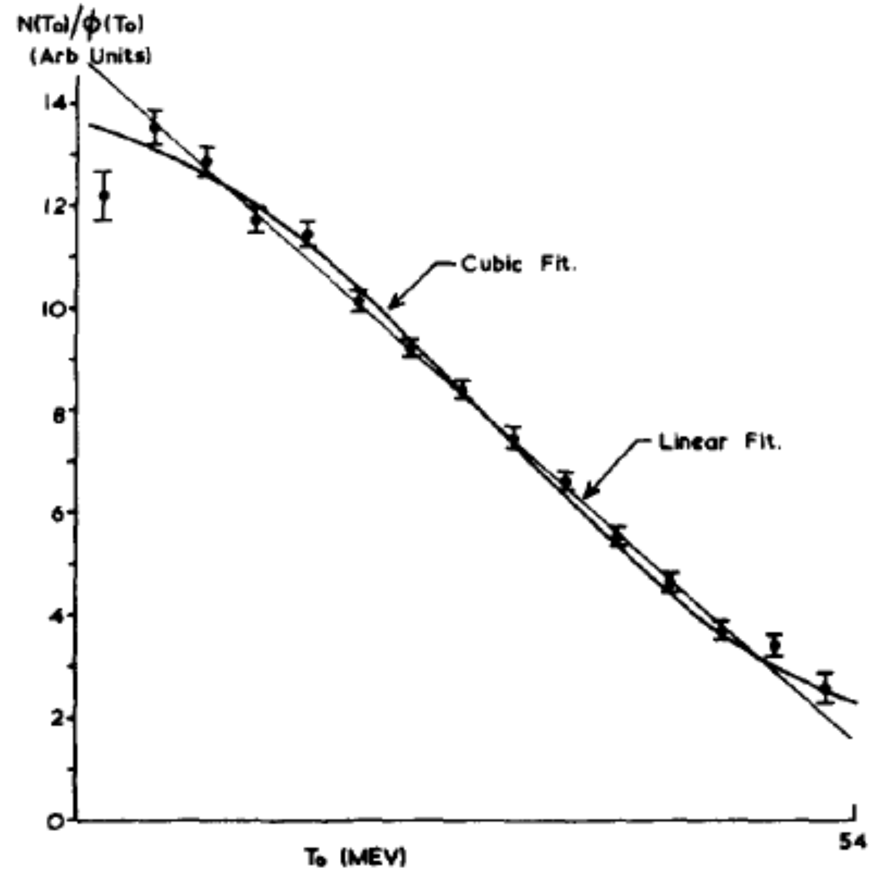


Fig. 3. The π^0 kinetic energy spectrum, divided by phase space, showing the best linear and cubic fits.

A STUDY OF K^0p CHARGE EXCHANGE SCATTERING FROM 0.6 TO 1.5 GeV/c

J.C.M. Armitage et al., Nuclear Physics B 123 (1977) p. 11 (after my time)

Search for "pentaquarks" … but that term far in the future (and is now a hot topic with c,b)
We called it a Z* (well before the Z was discovered and not related!)
Previous papers did not mention (new) "quarks", but "hadronic currents"
Introduction to paper:

The quantum numbers of the kaon-nucleon (KN) system are $B = +1, S = +1$. Any resonances with such quantum numbers (Z*) would be impossible within the simple constituent quark model in which baryons are composed of three quarks. Such a model allows only the {1}, {8} and {10} representations of SU(3) to correspond to physically realised multiplets of baryons. The presence of so-called 'exotic' resonances, such as Z*s, would have far-reaching consequences for the theory and might imply the existence of other SU(3) multiplets ($\{\overline{10}\}$ and {27}).

K^+p = {s̄uuud} and K^+n = {s̄uudd}

$K^+n \to K^+n \qquad \frac{1}{2}(f_1 + f_0)$,

$K^+n \to K^0p \qquad \frac{1}{2}(f_1 - f_0)$,

} Deuterium targets

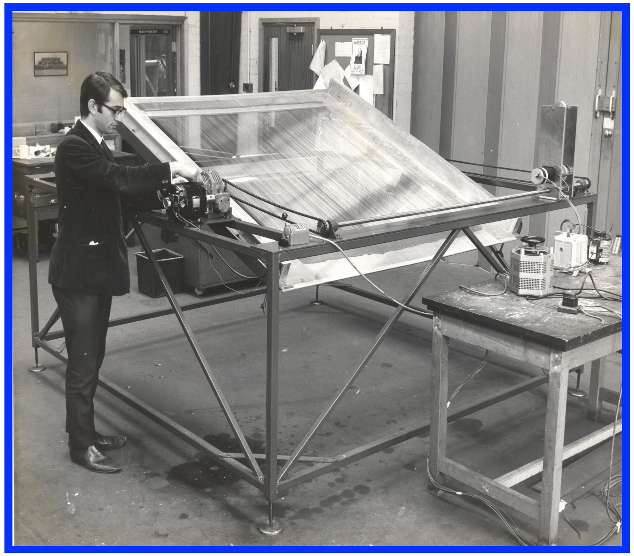
$K^0p \to K^+n \qquad \frac{1}{2}(f_1 - f_0)$. Neutron in final state

$K^+p \to K^+p$.

I did at CERN, with polarised target

Used K^0_L beam in different set-up, new wire chambers … I had left group by then (magnetostrictive readout)

Two geometries for forward and backward scattering



Grad student Fred Loebinger (now retired !)

J.C.M. Armitage et al. / K^0p charge exchange

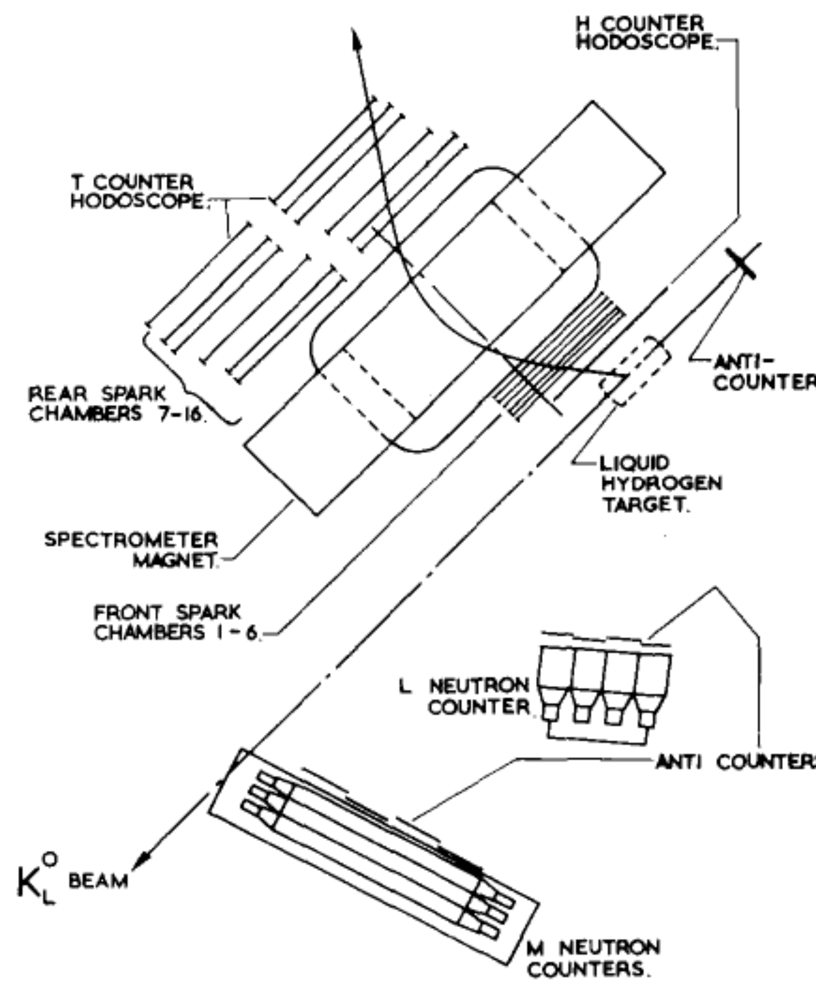


Fig. 3. Backward geometry layout.

Neutron counters: Large scintillator blocks:

Efficiency fn(E) critical calibration

Separate K^0 - K^+ and n - p in spectrometer with

time-of-flight from synchrototron RF to

T-counters σ ~ 120 – 300 ps

Beam particle goes 21m and K^+/p goes 5m

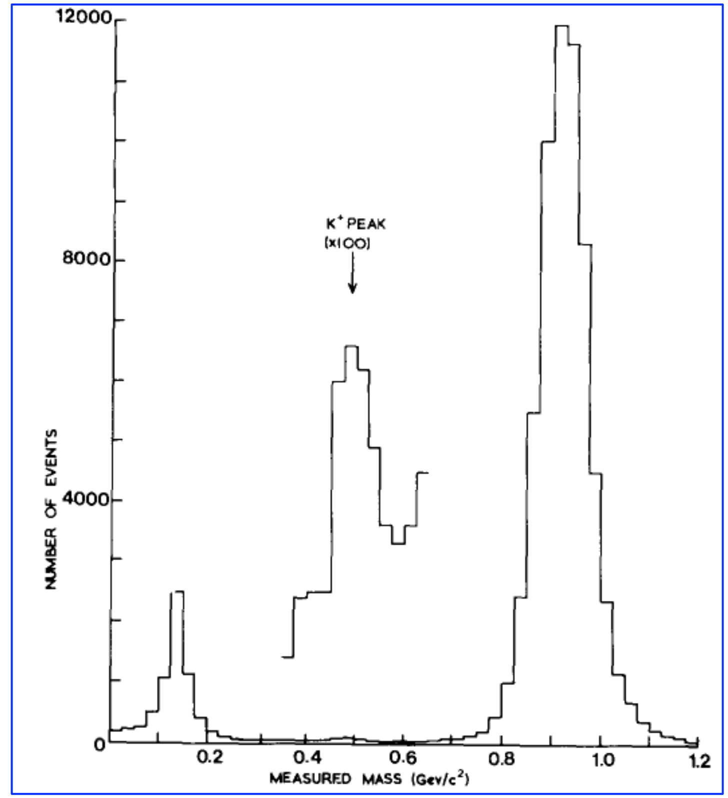
e-beam injector bunches 0.5ns every 4.908 ns

RF Signal from cavity on circulating beam

Mass spectrum of X^+ in spectrometer from TOF and momentum
10^5 triggers (2% of backward geom.)

Note K^+ peak is x 100

Large background reduced to <~ 5% with optimised fits (see paper)



Calibrations and checks of detector by inserting a regenerator and using $K^0_S \rightarrow \pi^+\pi^-$

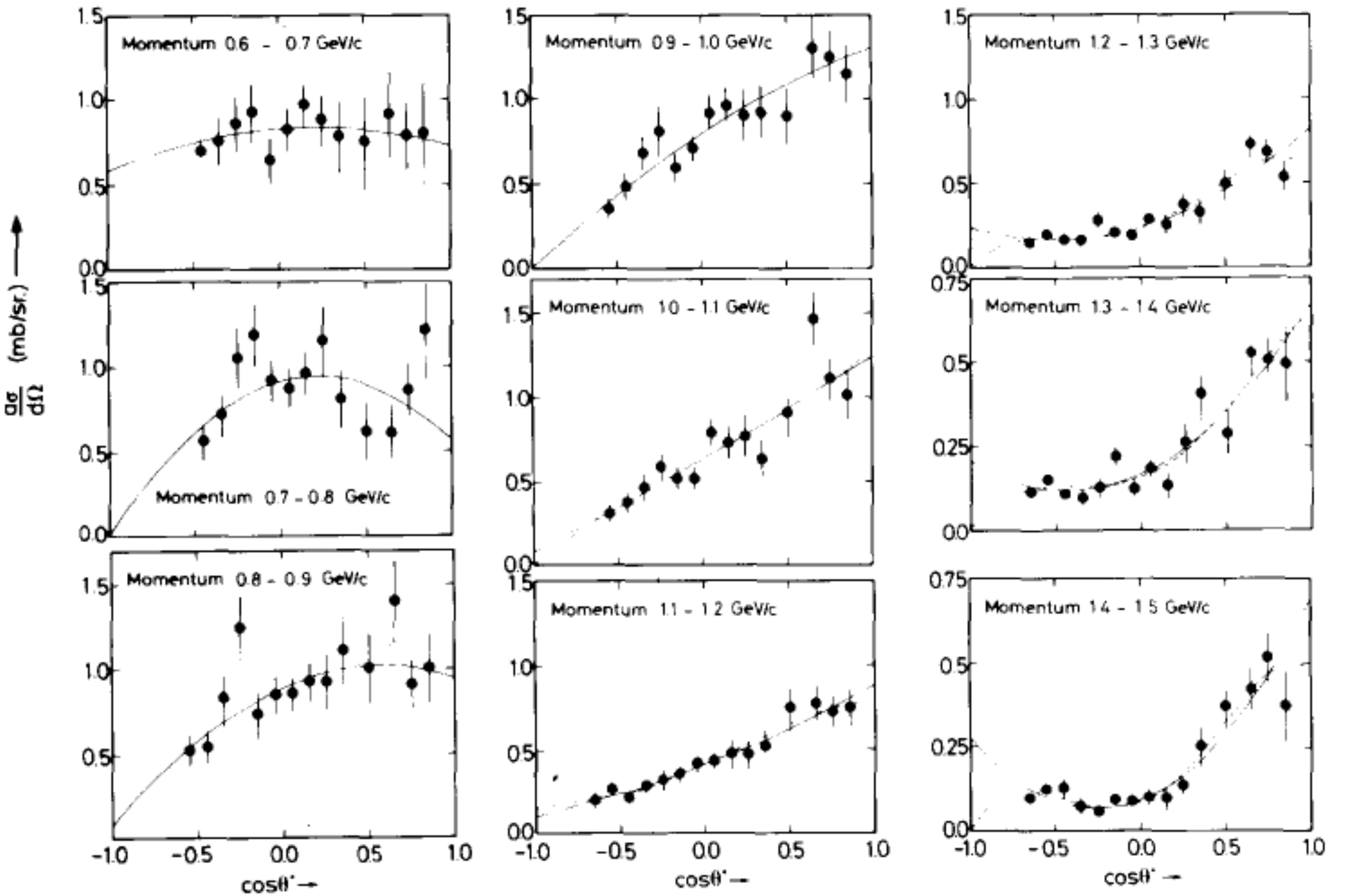
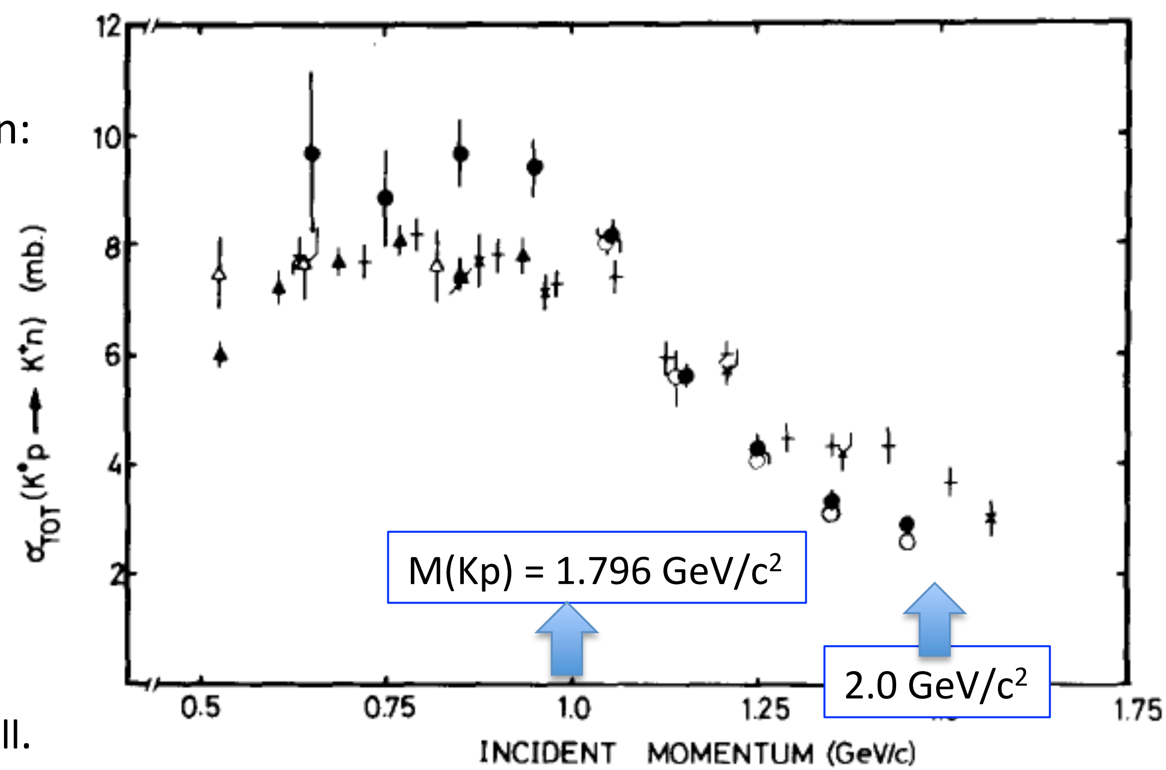


Fig. 22. $K^0p \rightarrow K^+n$ measured differential cross sections. The solid lines indicate curves from the third order Legendre fit; the dashed lines from fifth order.

Fits to Legendre polynomials
Comparisons with other channels …. Details in paper

42 *J.C.M. Armitage et al. / K^0p charge exchange*

Total cross section K^0 p → K^+ n:



[6] = German bubble chamber Coll.

Fig. 24. Total cross section measurements. The data is taken from; (●) this experiment (third order fit); (○) this experiment (fifth order fit); (+) ref. [4]; (x) ref. [5]; (▲) ref. [6]; (△) ref. [34]. The points from the other works are taken from ref. [6]. They are on $K^+d \to K^0p(p)$ and have been scaled by a factor of 1.15 to allow for deuterium corrections.

No evidence for K^0-p / K^+-n resonance (Pentaquark !)

Disclaimer : This was happening 50 years ago. Many more active neurons then!
I did not do K^0 physics since my PhD in 1969. Mostly pp colliders ISR → LHC

Response from my Professor Paul Murphy (in his late 80's) to request for background:

Mike

Happy New year to you too.

Not theoretical stuff like Drell and Yuan, but a paper by someone else at Stanford (a Chinese name which I have forgotten) was the inspiration for K zeros. He did a phenomenological study and produced detailed predictions of K0 production from high-energy electron beams. NINA was designed to produce very high currents with a favourable duty cycle; everything about NINA achieved or excelled design, as well as working 100% on the day it was switched on by Michael Crowley-Milling, who was in charge of design and construction. After he got it going in the morning, he said he had a lunch appointment and switched it off. When he came back from lunch, he turned it on again and it came straight back on. I asked him what was the secret; he had a bad stammer but managed to say "Maxwell's equations are t...r...ue". NINA was finished on time and within budget, which might be a world record. Michael previously worked at Metro-Vick in Trafford Park here building linacs for radiotherapy; I think the first one was for the Christie hospital in Withington. After that he went to CERN and was responsible for the controls for the 300Gev machine.

One thing that was not allowed for was that the photoproduction of pi-pluses at high energy has a big backward peak (baryon-exchange has a nearby pole, if you remember that language); this produces floods of high energy neutrons. In addition, NINA was not well-shielded against them. So we ended up not so much better off than a proton machine in that respect, but there were plenty of K0s. At NIMROD, which might have been seen as a high-intensity source, they did a huge experiment to measure K-long going to 2 pi-zeros (an important number in the CP saga). Their result was twice what turned out to be the correct one, so they were measuring mostly background (I think the "result" was the amplitude, so the measured rate was 4-times too high) The person in charge ended up as director of the RL, so no harm was done - and he's a nice bloke. The weakness of NIMROD was that it was only 7Gev, not enough for copious production of K0s, but plenty of neutrons.

I always believe in making the most of whatever situation one finds oneself in, so we got a thesis on n-p scattering out of it (I don't remember who; I think he went back to his family's corner shop afterwards; Fred will remember).

Yes, our K0-three particle results were good. Mary Gaillard, one of the leading theorist's in that field came over from CERN to see us about it.

I hope we see you here again soon.

Cheers! Paul

A bit more has emerged in my memory. NINA used 408MHz for the RF acceleration; we decided to use the RF time structure to record time-of-flight to discriminate between K0s and neutrons. Tony Wynroe - our electronics genius - made the necessary timing circuits. There was still ambiguity because there wasn't enough time between successive pulses, so we ran the machine at 200MHz. Tony left to start a company making burglar alarms; I don't think he ever finished his thesis.

Summary, Conclusions

Photoproduction of K^0 at these energies (< 5 GeV)
has only a small contribution from VMD $\phi \rightarrow K^0$-K^0bar
And is not dominated by simple 2 → 2 reactions such as $\gamma\, p \rightarrow K^0\, \Sigma^+$
Probably associated pions in 3- or 4-body final states (more at higher E)

But as of 1970 we did not have understanding of all production channels.
Production on nuclei : Cross section per nucleon probably has small increase with A,Z
Beam includes neutrons (~ 10^3 n/K) but less than in hadroproduction (?)
Was not a huge problem for us.

Our K^0_L fluxes and detectors provided competitive measurements of 3-body decays
and the reaction K0 + p → K+ + n with < month running time.
… and before MWPCs and with relatively primitive electronics.

I have not followed subsequent progress but presumably a modern experiment
could do orders-of-magnitude better. Higher energy photons would help too.

Thank You