BNL – 52611
FORMAL REPORT

Ted Kycia Memorial Symposium

May 19, 2000

Physics Department

Brookhaven National Laboratory
Brookhaven Science Associates
Upton, NY 11973

Electronic Detector Group
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Organizing Committee:

Laurence Littenberg & Roy Rubinstein

Master of Ceremonies:
Nicholas Samios

Authors:
K. Li, G. Giacomelli, R. Rubinstein, P.Mockett, L. Littenberg,
A. Carroll, R. Johnson, D. Bryman, B. Tippens

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INTRODUCTION

On the afternoon of May 19 2000, a Memorial Seminar was held in the BNL Physics Large Seminar Room to honor the memory of Ted Kycia, a prominent particle physicist who had been a member of the BNL staff for 40 years. Although it was understandably a somewhat sad occasion because Ted was no longer with us, nevertheless there was much for his colleagues and friends to celebrate in recalling the outstanding contributions that he had made in those four decades. The Seminar speakers were all people who had worked with Ted during that period; each discussed one aspect of his career, but also included anecdotes and personal reminiscences. This booklet contains the Seminar program, listing the speakers, and also copies of transparencies of the talks (and one paper which was a later expansion of a talk); sadly, not all of the personal remarks appeared on the transparencies.

The Master of Ceremonies for the Seminar was BNL former director Nick Samios; he provided the exact mix of seriousness and humor appropriate for such an occasion. Particularly appreciated by all was the presence in the audience of Ted's wife Helen and four of his children, Jan, Stefan, Adam, and Annia, two of whom are themselves now professional physicists.

Following the Seminar, there was a reception and dinner in Berkner Hall, at which Ted's family, the Seminar speakers and many friends were present; it was an occasion to renew acquaintances and meet former colleagues who all had in common the fact that they and their careers had been significantly influenced by Ted.

The Seminar organizers would like to thank many people who made this occasion possible and memorable: the speakers, some of whom traveled thousands of miles to take part; Nick Samios for his excellent chairing of the Seminar; Tom Kirk for hosting the reception; and Michael Murtagh for hosting the dinner.

Laurence Littenberg
Roy Rubinstein

Outline of Ted Kycia's Career

Ted Kycia received his PhD in 1959 from the University of California at Berkeley, at that time arguably the world's foremost center for particle physics. His thesis experiment, at the then highest energy accelerator, the Bevatron, was a study of K^+-proton scattering; his thesis advisor was Ed McMillan. Among the measurements made were of total cross sections, and further studies of this process subsequently became a cornerstone of Ted's career for many years.

Ted joined Brookhaven National Laboratory in 1959, and spent the remainder of his career there. Initially he was a member of the group led by Rod Cool; he later became the group leader and a BNL Senior Physicist. In the 1960s and early 1970s, Ted led a series of hadron-nucleon (and also hadron-nucleus) total cross section measurements at the AGS, from momenta of 100's of MeV/c to over 20 GeV/c. He constantly improved the precision of this technique. In the process, he and his collaborators discovered many new pion-nucleon and kaon-nucleon resonances; these entered the Particle Data tables, and subsequently were input to quark model calculations. The final measurements in this series were carried out as Experiment E-104 at the newly operating Fermilab in the 1970s. This experiment, covering the range 23 to 370 GeV/c, achieved a precision of about a part in a thousand. It showed that all hadron-nucleon total cross sections had the same behavior with energy: as the incident energy increases, the total cross sections fall, reach a minimum, and then rise. Previously this had only been demonstrated in some isolated cases. This phenomenon is still not completely understood.

In the early 1960s, Ted participated in some of the earliest measurements of hyperon magnetic moments, using BNL's Cosmotron and AGS accelerators. Among other innovations of this work was the use of a superconducting magnet in the first measurement of the Ξ^- magnetic moment. These measurements were useful in establishing the quark model of hadron structure.

In the late 1960s, Ted embarked on studies of rare decays of kaons; the first experiment studied $K^\pm \rightarrow \pi^\pm \pi^0 \gamma$. There could be an asymmetry between the K^+ and K^- rates and Dalitz plots for this decay if the origin of CP-violation observed in $K_L \rightarrow 2\pi$ decay is electromagnetic in origin, as was postulated at the time by some theorists; no asymmetry was observed. The experiment also established limits on some decay modes which are still the best to date. The second experiment, this time studying neutral kaons, discovered several new decay modes of the K_L, as well as a form factor dependence in the decay $K_L \rightarrow \pi^+ \pi^- \gamma$ that has been confirmed but never really explained.

At the end of the 1970's Ted led a series of experiments to check predictions of various new particles, and/or claims of discoveries of such. One was a claim of an observation of the η_c produced in the reaction $\pi^- p \rightarrow \eta_c n$ and decaying to two photons. AGS Experiment 732 did not confirm this result, and also set a limit on the reaction $\pi^- p \rightarrow J/\psi n$ at 13 GeV/c. Another experiment was stimulated by a theoretical prediction of a new particle, the H di-hyperon. E703 used the reaction $pp \rightarrow K^+ K^+ H$ with the incoming proton below threshold for the production of $K^+ \Lambda K^+ \Lambda$ to search for the H. The H was not observed, and the stringent limit set by E703 established that this particle could not have the typical hadronic production cross section that had originally been proposed. It was also the first of many dedicated H searches done at the AGS. An extension of this experiment refuted a claim of observation of an example of baryonium.

In the mid-1980's Ted returned to the subject of rare kaon decays. He was one of the initiators of AGS Experiment 787, the search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. This process is of particular interest because it is highly sensitive to the otherwise elusive coupling of the top to the down quark, as well as to many varieties of possible new interactions. Ted's vision for the experiment was to design a detector whose basic structure was capable of detecting this process at the Standard Model level, which at the time of the proposal was some four orders of magnitude beyond what had been done previously. After many years, this decay mode was discovered by E787, opening up a new window into short distance physics. This work continues.

At the time of his death, Ted was working on a new experiment, AGS E927, to make a precise measurement of the Cabibbo angle, one of the fundamental parameters of the Standard Model, through the study of the decay $K^+ \rightarrow \pi^0 e^+ \nu$. The object of the experiment is to increase the precision on this important quantity to less than 0.5%.

Ted was a leader in the design, construction and use of Cerenkov counters, especially with gas radiators, for beam particle identification. He built several of these, and their performance always impressed his colleagues. However, he rarely described them in print, and consequently did not receive all of the credit which he certainly deserved. Ted always employed two simple design principles in his counters, namely simultaneous detection and veto of unwanted particle species in the beam, and the use of small Cerenkov angles to minimize optical dispersion effects. His counters achieved resolutions not reached by others. At Fermilab in the 1970s, one of Ted's counters cleanly separated pions and kaons at 340GeV/c; a few years later, others made some modifications to it and achieved pion-kaon separation at 530 GeV/c. It is unlikely that this record will be exceeded at anytime soon.

CONTENTS

Ted Kycia Memorial Symposium

Physics Large Seminar Room at 1:30 p.m. on May 19

Master of Ceremonies - Nick Samios

Subject	Speaker	Affiliation
Hyperon magnetic moments	Kelvin Li	BNL
Total cross sections	Giorgio Giacomelli	Bologna
Cerenkov Work	Roy Rubinstein	FNAL
$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$ (E414)	Paul Mockett	Washington
$K_L \rightarrow \pi^{+}\pi^{-}\gamma$ (E631)	Laurie Littenberg	BNL
H-search (E703)	Alan Carroll	BNL
Search for η_C (E732)	Randy Johnson	Cincinnati
Search for $K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$ (E787)	Doug Bryman	TRIUMF
K_{e3} (Cabibbo angle measurement)	Brad Tippens	UCLA

Approximate times (Note this includes 5-10 minutes for questions and comments from the audience.):

1:30	K. Li
2:00	G. Giacomelli
2:40	R. Rubinstein
3:00	P. Mockett
3:30	Coffee break
3:45	L. Littenberg
4:15	A. Carroll
4:45	R. Johnson
5:15	D. Bryman
5:45	B. Tippens
6:00	N. Samios
6:15	Adjourn

6:30 Reception at Berkner Hall, followed by dinner at 7:00. Dinner price is $25/person. Please reserve space at the dinner by Tuesday, May 16.

Hyperon Magnetic Moments

Kelvin Li - BNL

Ted Kycia Memorial Symposium - 19 May 2000

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Printed in U. S. A.

Measurement of the Magnetic Moment of the Λ^0 Hyperon*

R. L. Cool, E. W. Jenkins, and T. F. Kycia
Brookhaven National Laboratory, Upton, New York

D. A. Hill
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

L. Marshall
New York University, New York, New York

and

R. A. Schluter
Argonne National Laboratory, Argonne, Illinois, and Northwestern University, Evanston, Illinois

(Received May 3, 1962)

Volume 15, Number 2 PHYSICAL REVIEW LETTERS 12 July 1965

NEW MEASUREMENT OF THE Λ MAGNETIC MOMENT*

D. A. Hill† and K. K. Li†

Laboratory for Nuclear Science and Physics Department, Massachusetts Institute of Technology,
Cambridge, Massachusetts

and

E. W. Jenkins,‡ T. F. Kycia, and H. Ruderman

Brookhaven National Laboratory, Upton, New York

(Received 15 June 1965)

PHYSICAL REVIEW D VOLUME 4, NUMBER 7 1 OCTOBER 1971

Measurement of the Λ Magnetic Moment*

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(Received 4 July 1971)

Volume 29, Number 24 PHYSICAL REVIEW LETTERS 11 December 1972

Measurement of the Ξ^- Magnetic Moment*

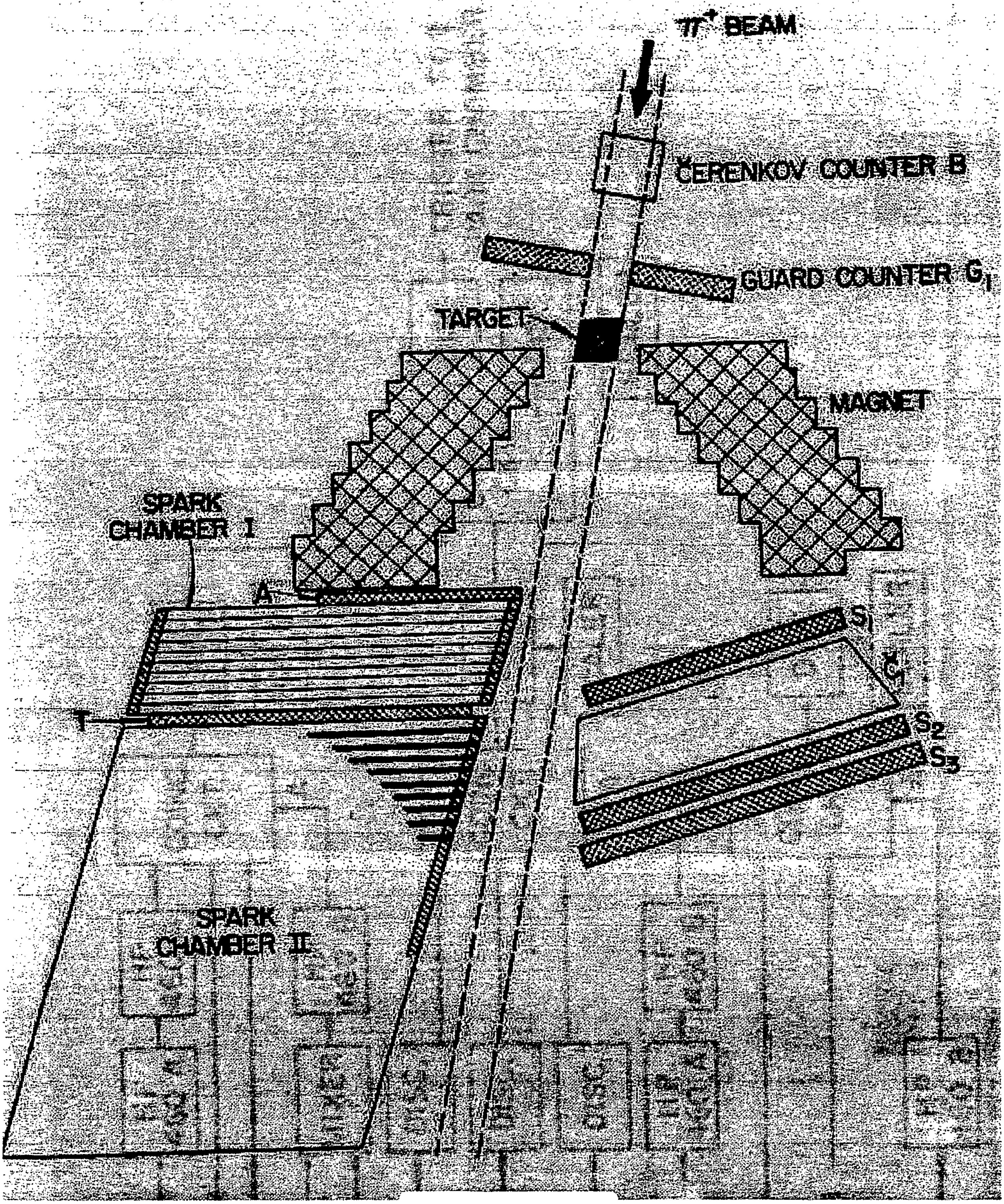
R. L. Cool,† G. Giacomelli,‡ E. W. Jenkins,§ T. F. Kycia, B. A. Leontic,‖ K. K. Li, and J. Teiger**
Brookhaven National Laboratory, Upton, New York 11973

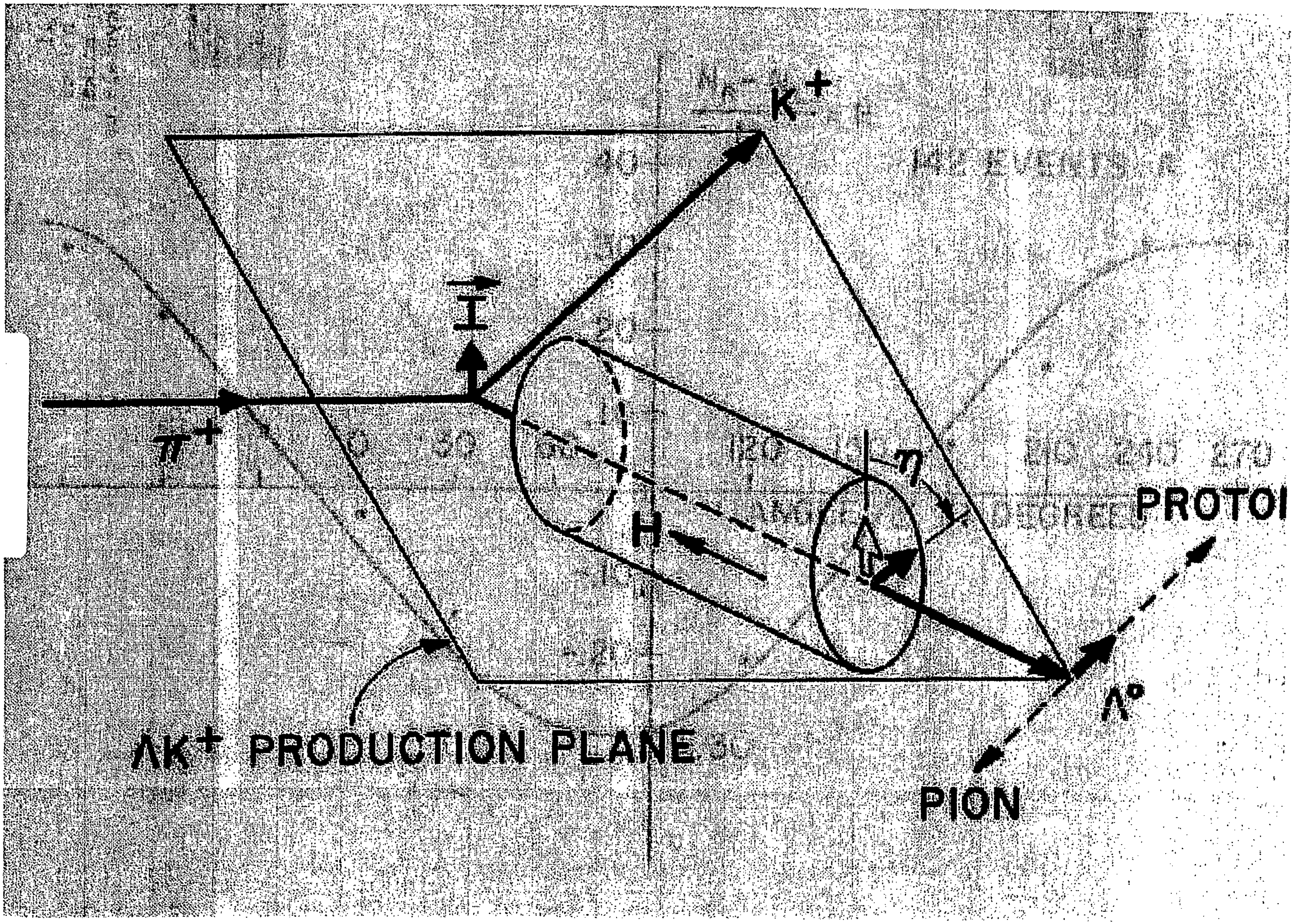
(Received 11 October 1972)

PHYSICAL REVIEW D VOLUME 10, NUMBER 3 1 AUGUST 1974

Measurement of the magnetic moment and of the decay parameters of the Ξ^- hyperon*

R. L. Cool,† G. Giacomelli,‡ E. W. Jenkins,§ T. F. Kycia,
B. A. Leontic,‖ K. K. Li, and J. Teiger¶
Brookhaven National Laboratory, Upton, New York 11973

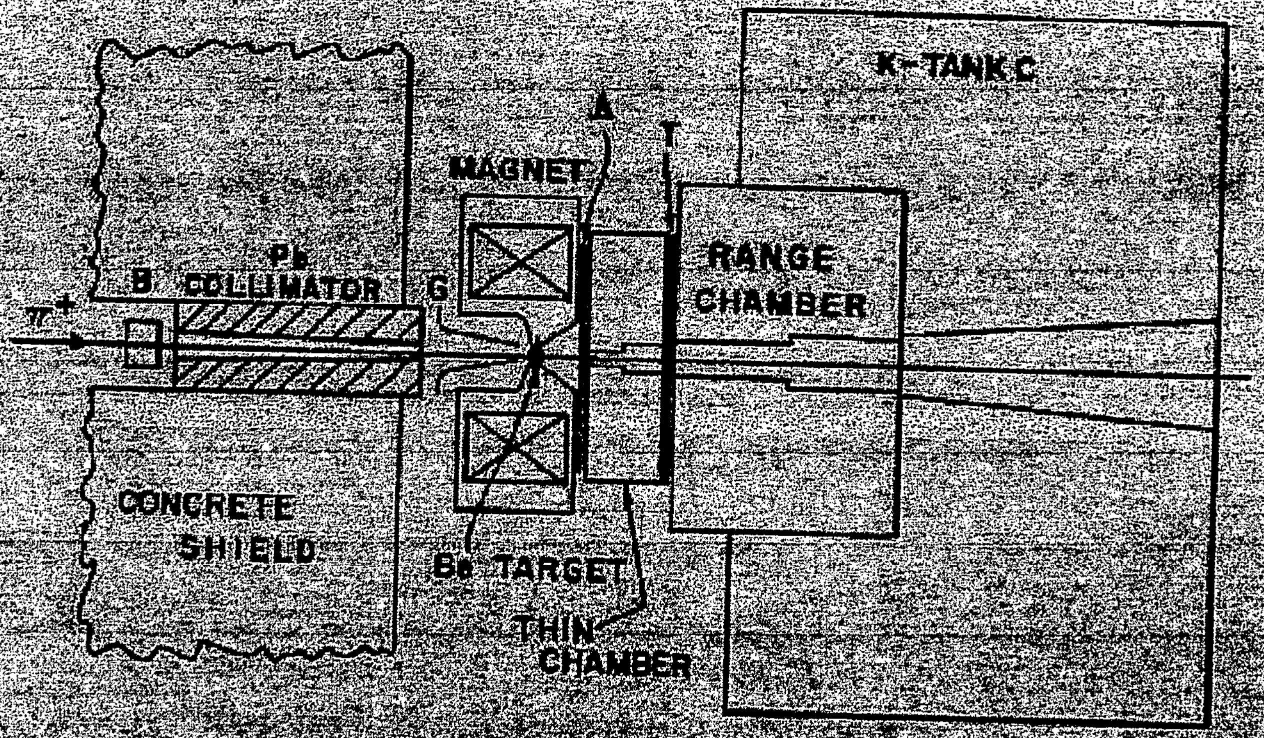

π⁺ BEAM
ČERENKOV COUNTER B
GUARD COUNTER G₁
TARGET
MAGNET
SPARK CHAMBER I
A
T
S₁
Č₁
S₂
S₃
SPARK CHAMBER II



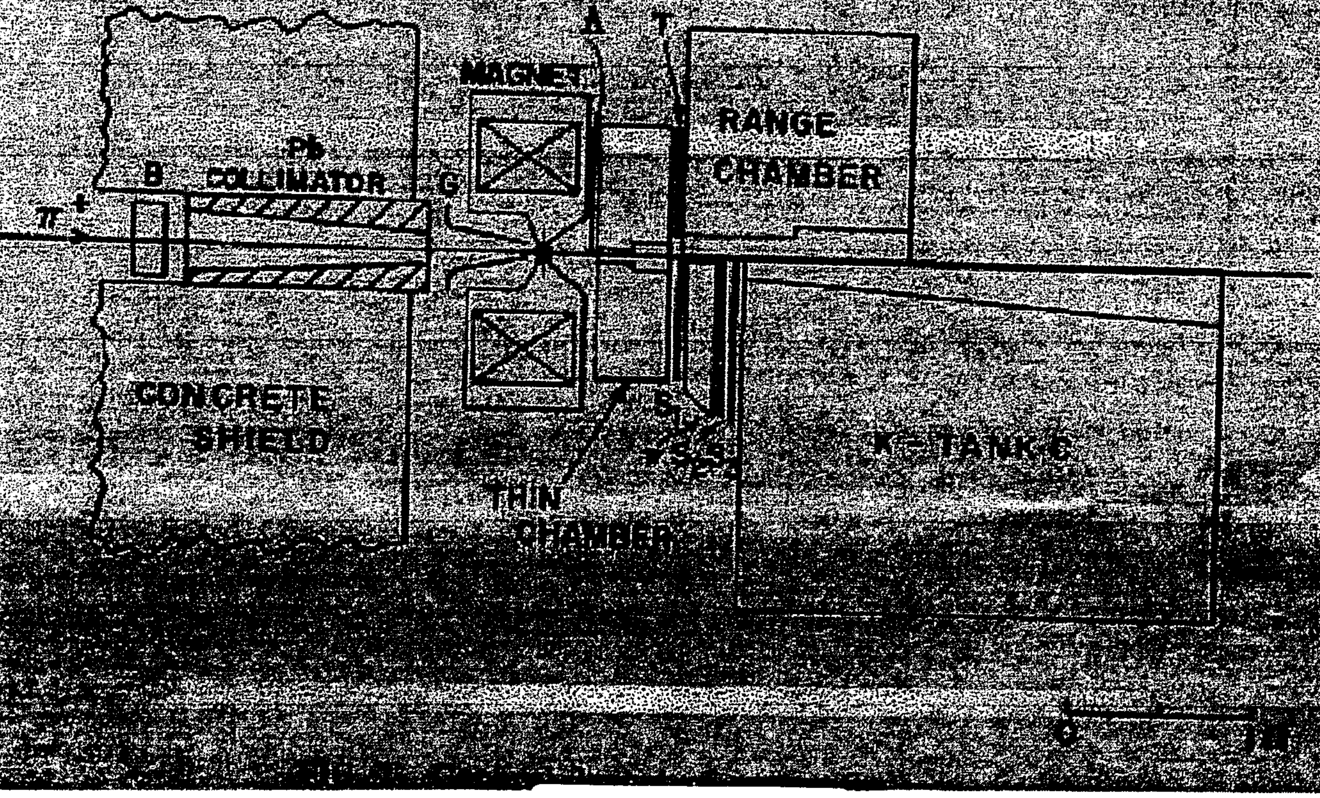
K+
$\vec{H}$
π+
η
H
PROTO
Λ°
PION
ΛK+ PRODUCTION PLANE

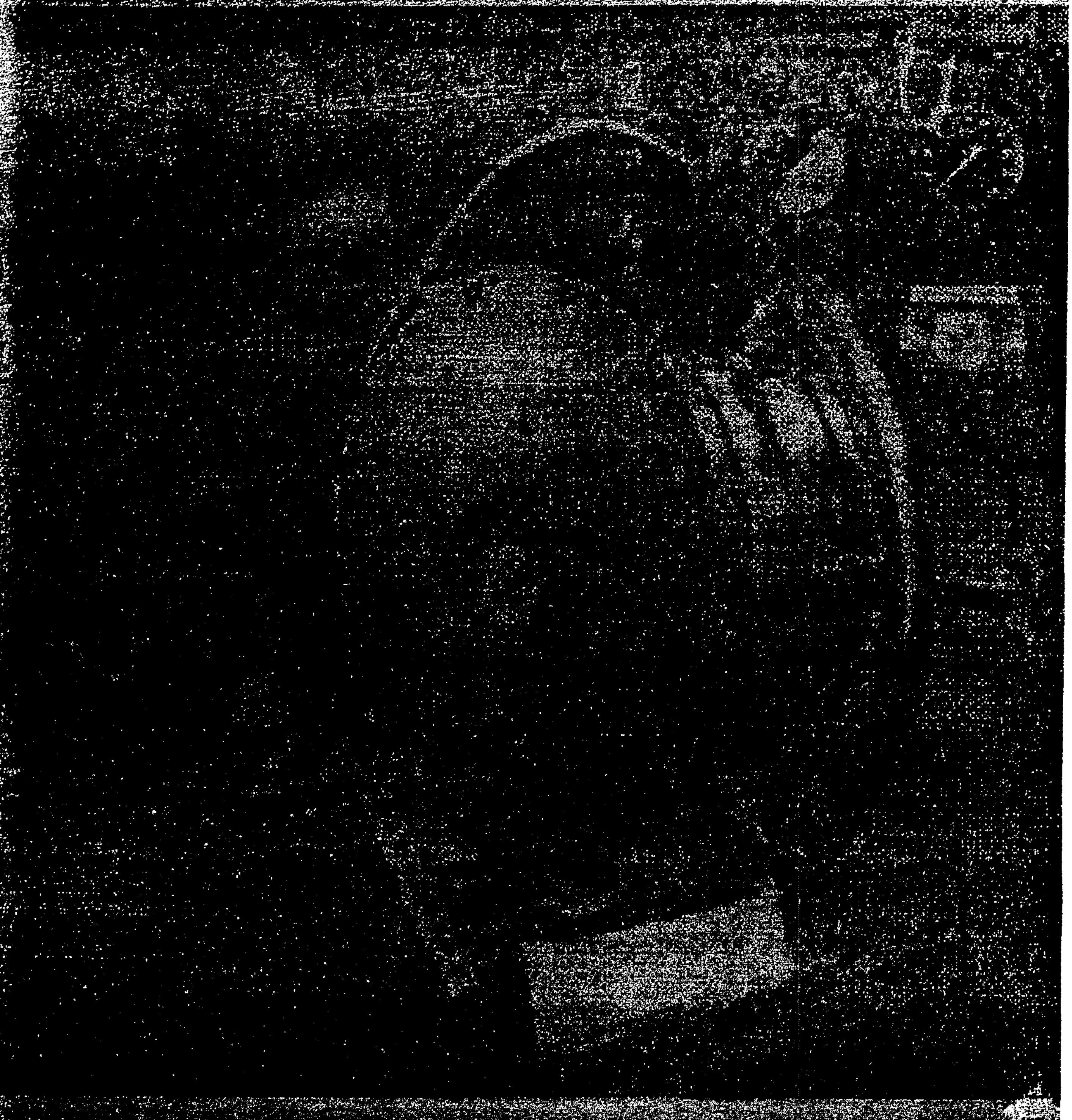
MEASUREMENT OF THE Λ MAGNETIC MOMENT

TOP VIEW



SIDE VIEW





[illegible] concentration within [illegible]

[illegible] measuring probe [illegible]

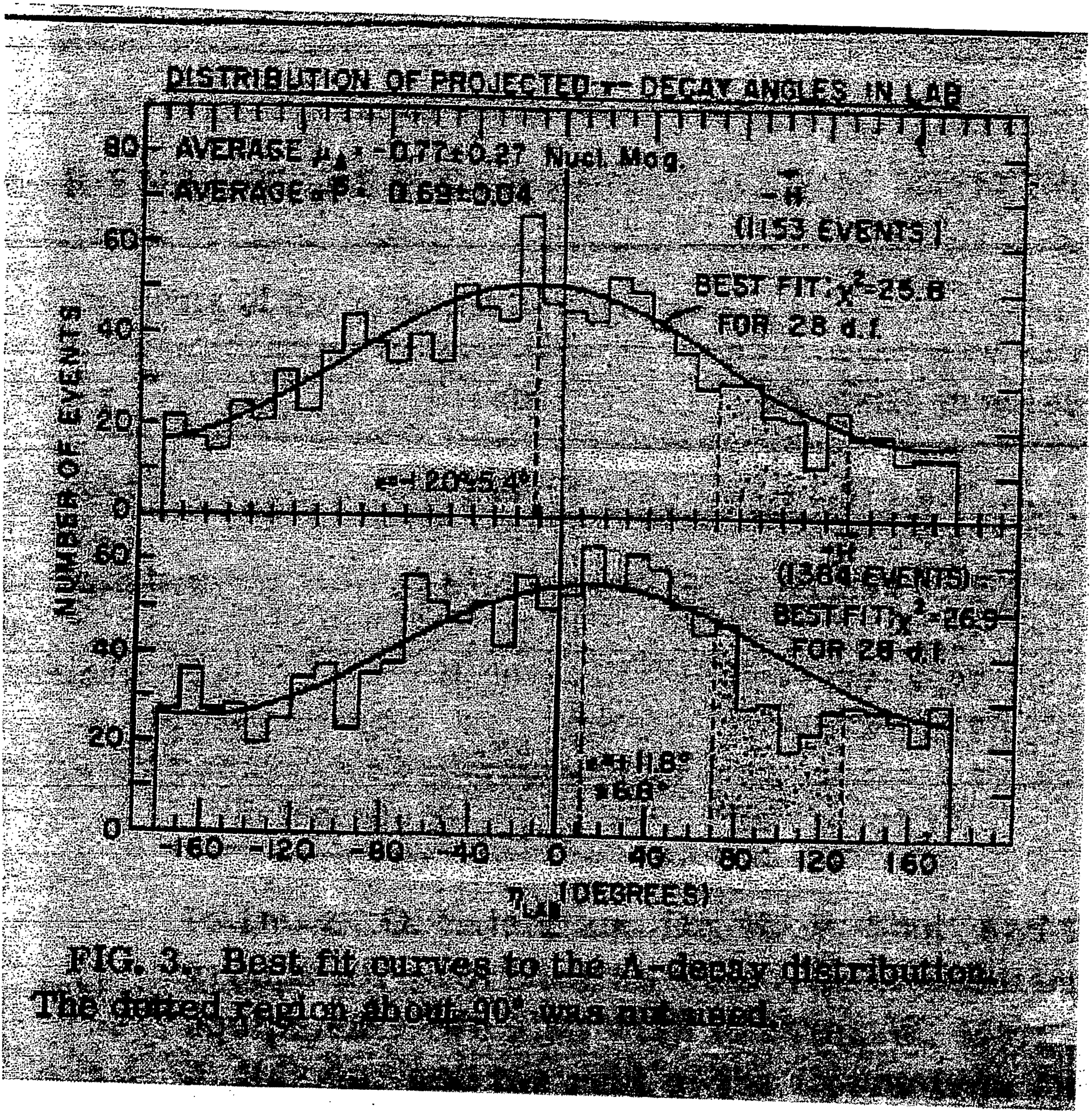
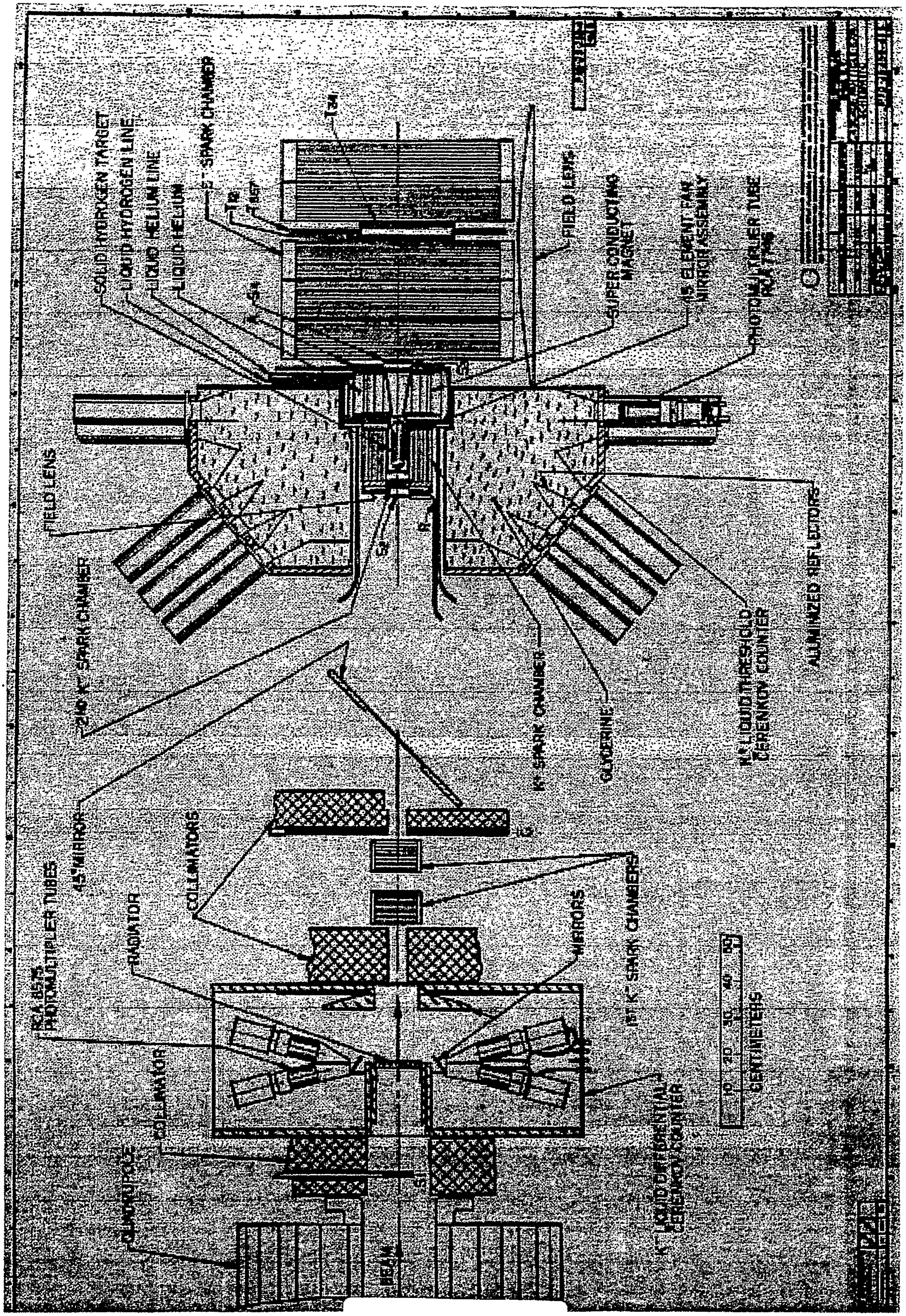


FIG. 3. Best fit curves to the Λ-decay distribution. The dotted region about 90° was not used.

$$
\begin{array}{llll}
K^- p \longrightarrow & \Xi^- K^+ & & \\
 & \llcorner\!\!\longrightarrow & \Lambda \pi^- & \\
 & & \llcorner\!\!\longrightarrow & p \pi^-
\end{array}
$$


QUADRUPOLE
BEAM
S1
COLLIMATOR
RCA 8575 PHOTOMULTIPLIER TUBES
RADIATOR
K⁻ LIQUID DIFFERENTIAL CERENKOV COUNTER
10 20 30 40 50
CENTIMETERS
COLLIMATORS
MIRRORS
1ST K⁻ SPARK CHAMBERS
45° MIRROR
2ND K⁻ SPARK CHAMBER
K⁻ SPARK CHAMBER
GLYCERINE
K⁻ LIQUID THRESHOLD CERENKOV COUNTER
ALUMINIZED REFLECTORS
FIELD LENS
SOLID HYDROGEN TARGET
LIQUID HYDROGEN LINE
LIQUID HELIUM LINE
LIQUID HELIUM
Σ⁻ SPARK CHAMBER
FIELD LENS
SUPERCONDUCTING MAGNET
15 ELEMENT FAN MIRROR ASSEMBLY
PHOTOMULTIPLIER TUBE RCA 7746

User: li
Host: bnlku3
Class: bnlku3
Job: kycia21.ps

$\cos\theta = +1$ $\bar{p}$ in beam direction

	2 GeV/c	
P average	.38 ± .11	
-1.0 - -.4	.64 ± .24	
-.4 - +.4	.68 ± .28	
+.4 - +1.0	.21 ± .13	
-1 - -.7	.24 ± .33	
-.7 - -.4	1.11 ± .33	
-.4 - 0	1.14 ± .39	χ^2=9.5
0 - +.4	.43 ± .37	
+.4 - +.7	.26 ± .24	χ^2=8.0
+.7 - +1.0	.24 ± .17	

$\cos\theta$

470 events

1.8 GeV/c	
65 events	
P ave	0.75 ± .25
-1 - 0	1.55 ± .45
0 - +1	0.47 ± .30
-1 - -.4	1.11 ± .42
-.4 - +.4	.91 ± .84
+.4 - +1.0	.50 ± .37

χ^2=4.3

1.95 GeV/c	
63 events	
P ave	0.40 ± .29
-1 - 0	0.59 ± .43
0 - +1	0.24 ± .39
-1 - -.4	0.48 ± .46
-.4 - +.4	0.16 ± .60
+.4 - +1	0.32 ± .42

150 events

$\alpha_{\Xi} = -.41 \pm .047$

$\alpha_{\Lambda} = 0.662 \pm .052$

$\gamma = 0.912 \pm .028$

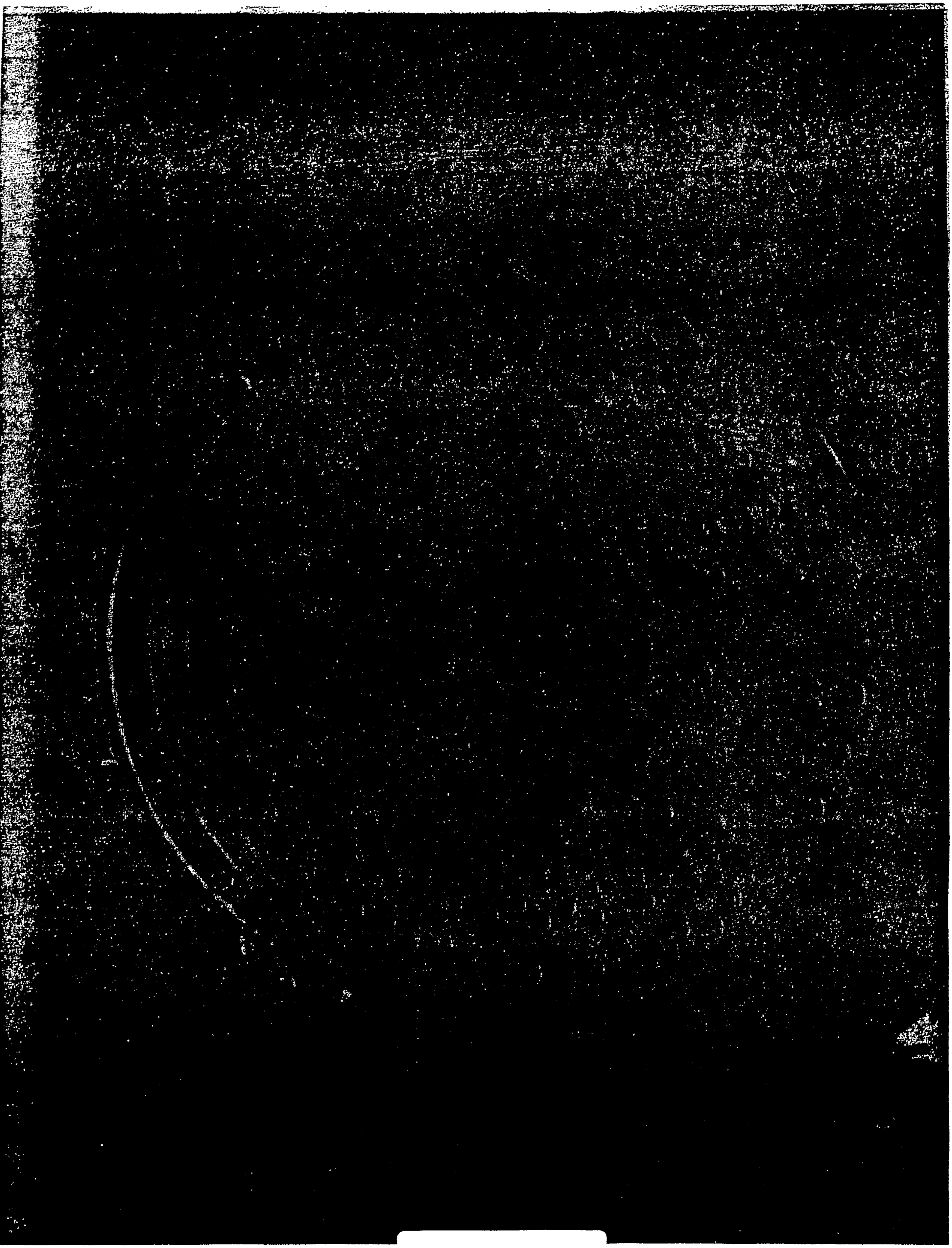
$\beta = 0.007 \pm .172$

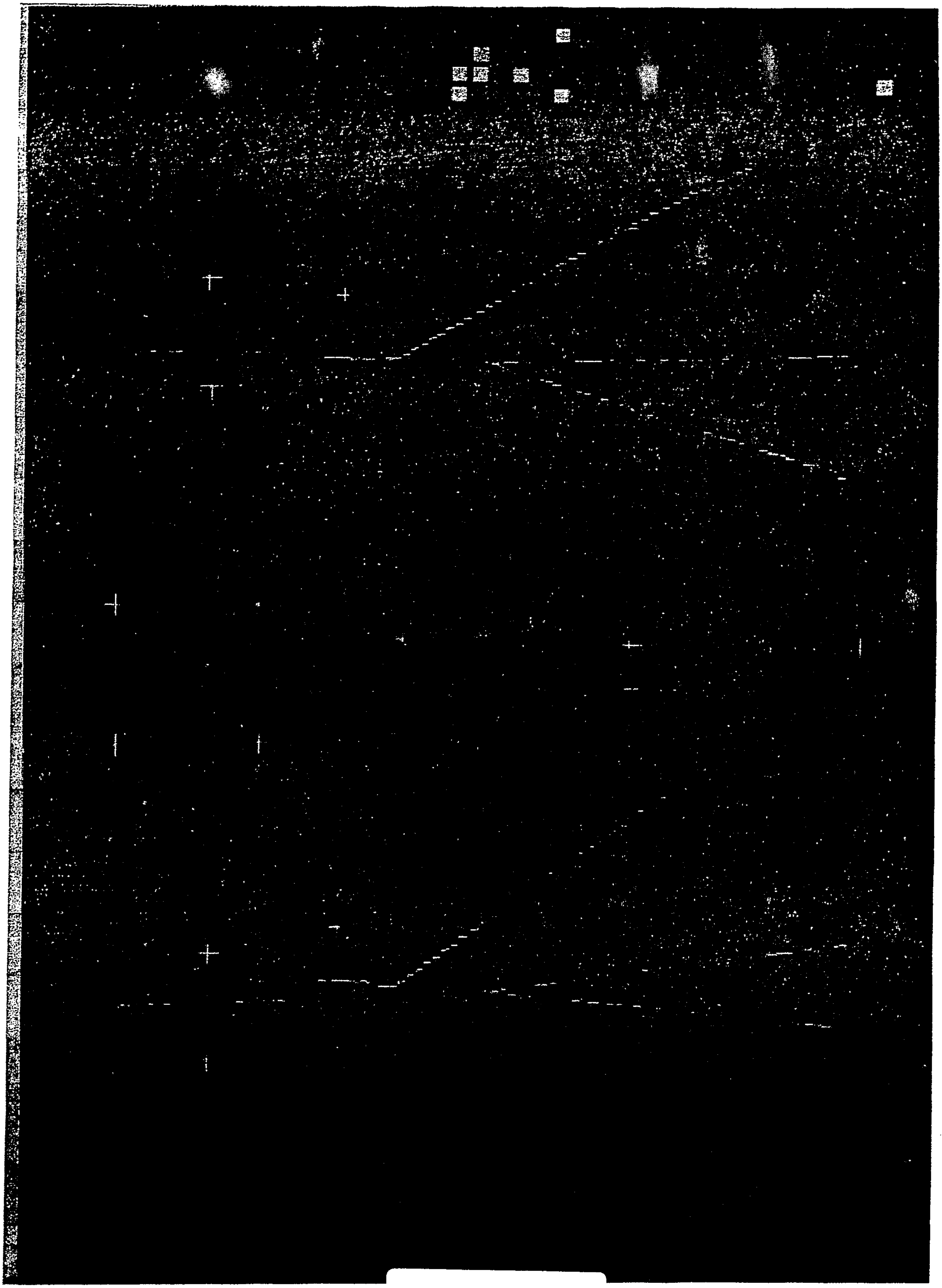
Λ polarization reduces exactly

[illegible]

[illegible]

[illegible]





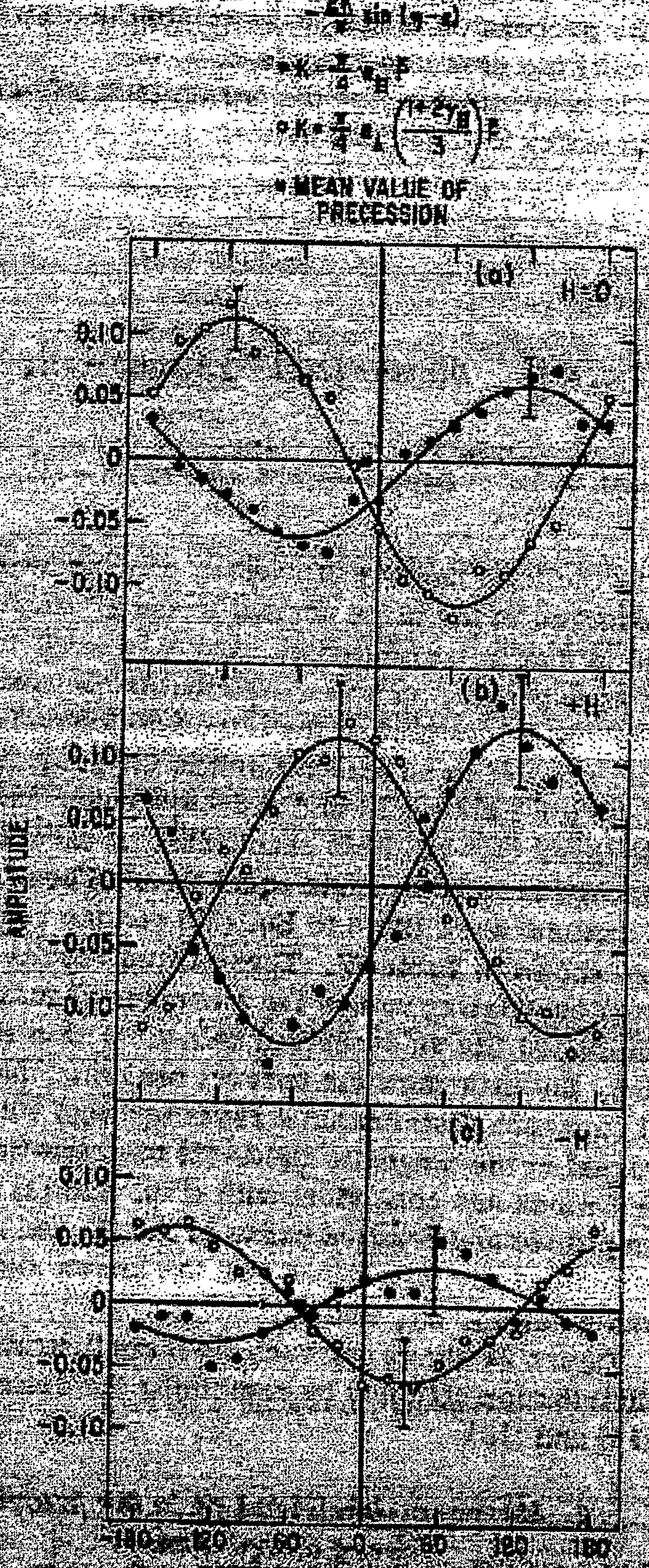


FIG. 20. The left-right decay asymmetry distributions from the Ξ^- and Λ decays for (a) no-field events, (b) positive-field events, and (c) negative-field events. The curves are the results from χ^2 fits to the asymmetry R

	Pinc (GeV/c)	<B.dl> (kG-cm)	total #events	<aP>	m. moment (n.m)	world ave. (n.m.)
1962	1.02	540	254	.55 (.10)	-1.5 (0.5)	
1965-1971	1.02	450	3868	.61 (.03)	-0.73(0.17)	-0.613
1972-1974	1.83	1500	2436	-.119(.020)	-2.1 (0.8)	-0.652

Total Cross Sections

Giorgio Giacomelli - INFN Bologna

Ted Kycia Memorial Symposium - 19 May 2000

TOTAL CROSS SECTIONS

KYCIA MEMORIAL SYMP.
BNL, MAY 19, 2000
G.G.

1. INTRODUCTION
2. TOTAL CROSS SECTIONS AT BNL
3. " " " " FERMILAB
4. EVEN HIGHER ENERGIES
5. CONCLUSIONS

IT WAS A PLEASURE TO WORK WITH TED,
IN A FRIENDLY ATMOSPHERE

ROD COOL IS THE MISSING COLLABORATOR

1. INTRODUCTION

σ_{TOT} : FIRST MEASUREMENTS AT EVERY NEW ACCELERATOR, IN A NEW ENERGY RANGE

AT LOW ENERGIES : RESONANCES
AT HIGH " : "ASYMPTOTIC BEHAVIOUR.
ALL σ_{TOT} RISE WITH ENER

TED's CURRICULUM

2. TOTAL CROSS SECTIONS AT BNL (1960's)

SEARCH FOR NEW STRUCTURES ($P_{LAB} < 3.3$ GeV
FOUND MANY !

3. TOTAL CROSS SECTIONS AT FERMILAB (1970's)

($P_{LAB} < 340$ GeV)
ALL σ_{TOT} RISE !
PRESS CONFERENCE

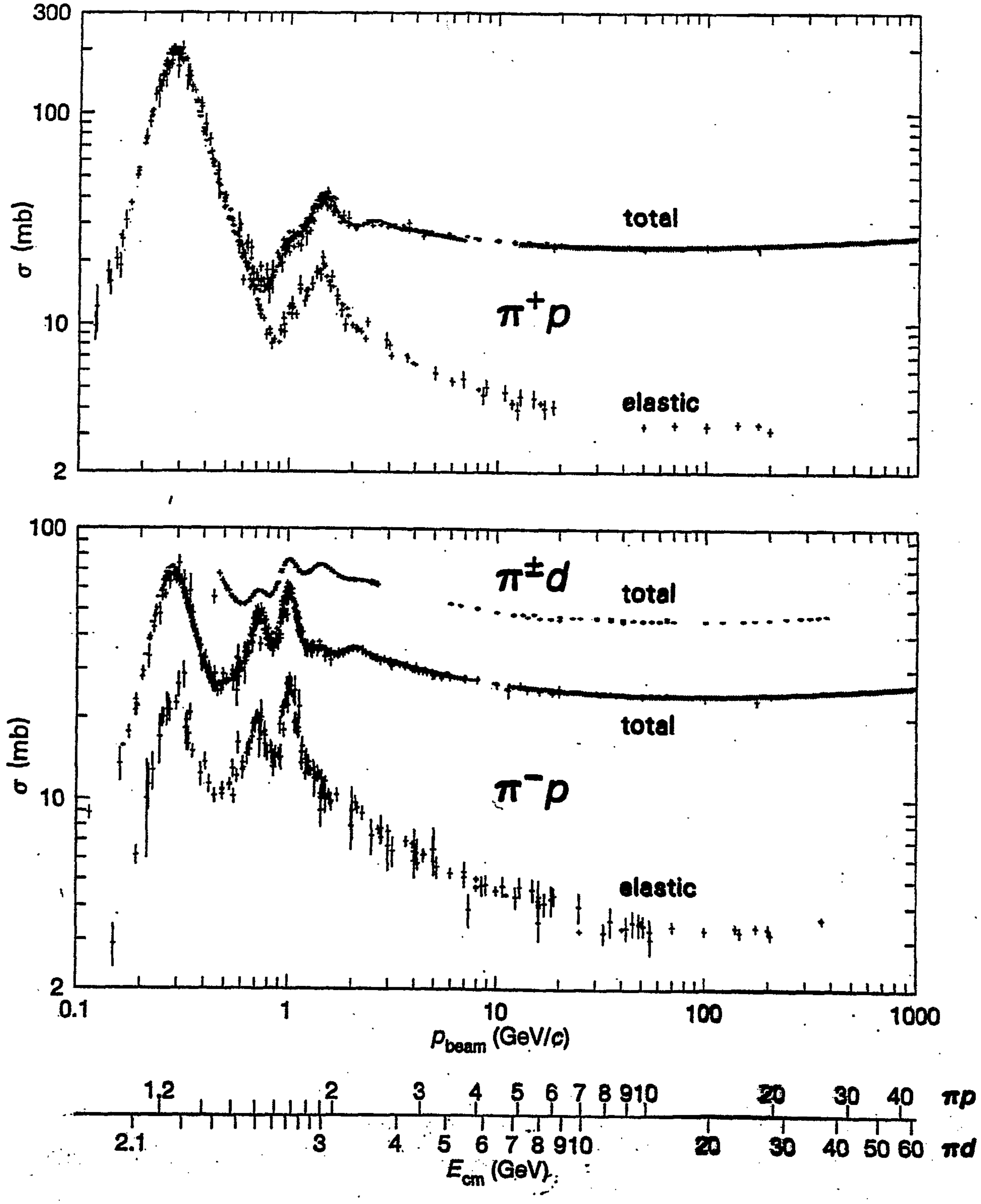
4. HIGHER ENERGIES

PART OF THE COLLABORATION ⇒ FERMILAB COLLIDER
σ_{TOT} $(\bar{p}p)$ KEEPS RISING

5. CONCLUSIONS

THE σ_{TOT} RESULTS ARE IN THE HISTORY OF PHYSIC

" TED's EXPERTISE : DESIGN, PLANNING, EXECUTION OF EXPERIMENTS, OBTAINING CORRECT AND ACCURATE RESUL



Hadronic total and elastic cross sections vs. laboratory beam momentum and total center-of-mass energy. Data courtesy A. Baldini, V. Flaminio, W.G. Moorhead, and D.R.O. Morrison, CERN; and COMPAS Group, IHEP, Serpukhov, Russia. See *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series Vol. I/12 a and I/12 b, ed. H. Schopper (1988). Gray curve shows Regge fit from Table 33.2 .

CV

IN 1970'?

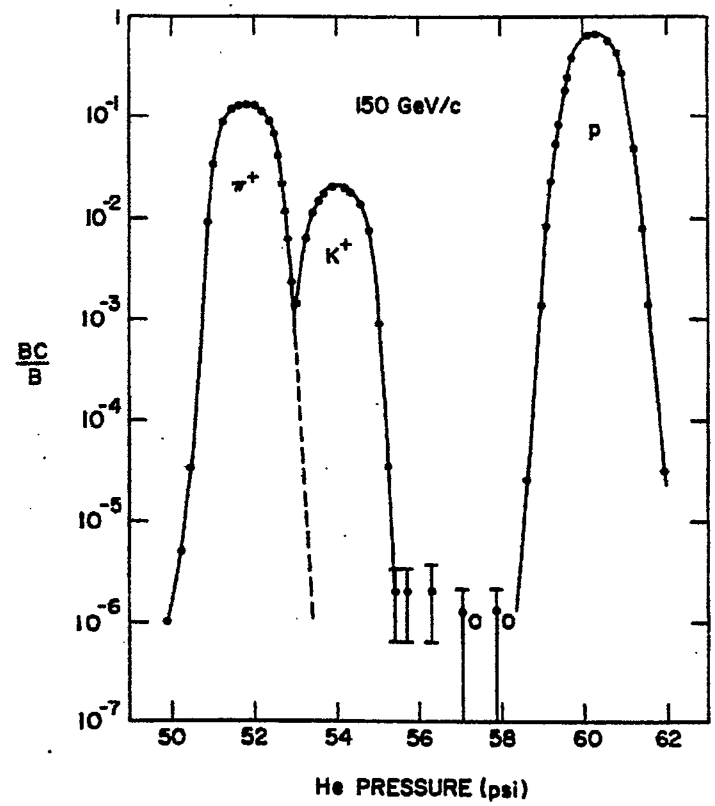
4?

THADDEUS F. KYCIA

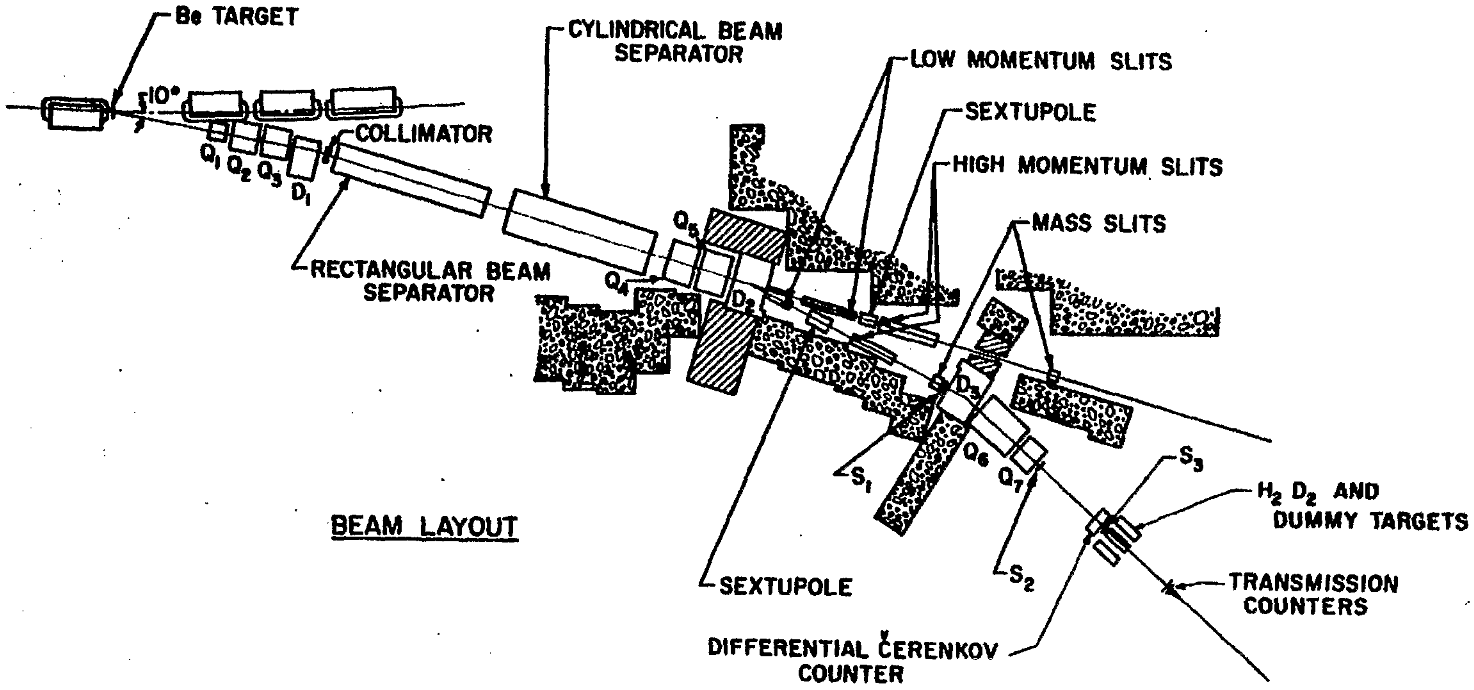
. . . . .

Since 1960 he has led the development and construction of differential Cerenkov counters for use in charged secondary beams. Their function has been to electronically identify selected types of particles with a very high rejection of all other particles. The counters which were built spanned the full range of velocities available at the AGS. Most recently, he designed and built two gas differential Cerenkov counters for use at Fermi National Laboratory in the total cross section experiment. The resolution of one counter was adequate to separate K mesons from π mesons even at a momentum of 200 GeV/c. → 340 GeV

Over the last decade Ted Kycia led an effort to improve the precision with which total cross sections of charged particles could be measured. This led to the discovery of six massive π meson-nucleon resonances. This was followed by a series of measurements of total cross sections of K^- mesons, K^+ mesons and antiprotons on nucleons in search of structure. The high precision systematic measurements revealed a large number of previously unobserved resonances and structures. A number of hyperon resonances were found in both isotopic spin zero and isotopic spin one states. A number of structures were found in the antiproton-proton total cross section which would be due to previously unobserved massi~~ng~~ve pion resonances. In the K^+ meson-nucleon total cross section measurements a number of structures also were discovered. These have subsequently been studied by groups in this country and in Europe. The question of whether any of the K^+ meson-nucleon structures could be due to the existence of exotic Z^*'s is still unresolved. The techniques developed at BNL for measuring total cross sections to a high precision were then applied to the measurement of total cross sections at FNAL. This latter experiment was carried out in collaboration with . . . . .



150 GeV/c
π^+
K^+
p
$\frac{BC}{B}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
0
50
52
54
56
58
60
62
He PRESSURE (psi)


Be TARGET
10°
Q$_1$ Q$_2$ Q$_3$ D$_1$
COLLIMATOR
RECTANGULAR BEAM SEPARATOR
CYLINDRICAL BEAM SEPARATOR
Q$_4$
Q$_5$
D$_2$
LOW MOMENTUM SLITS
SEXTUPOLE
HIGH MOMENTUM SLITS
MASS SLITS
D$_3$
Q$_6$
Q$_7$
S$_1$
S$_2$
S$_3$
H$_2$ D$_2$ AND DUMMY TARGETS
TRANSMISSION COUNTERS
SEXTUPOLE
DIFFERENTIAL ČERENKOV COUNTER

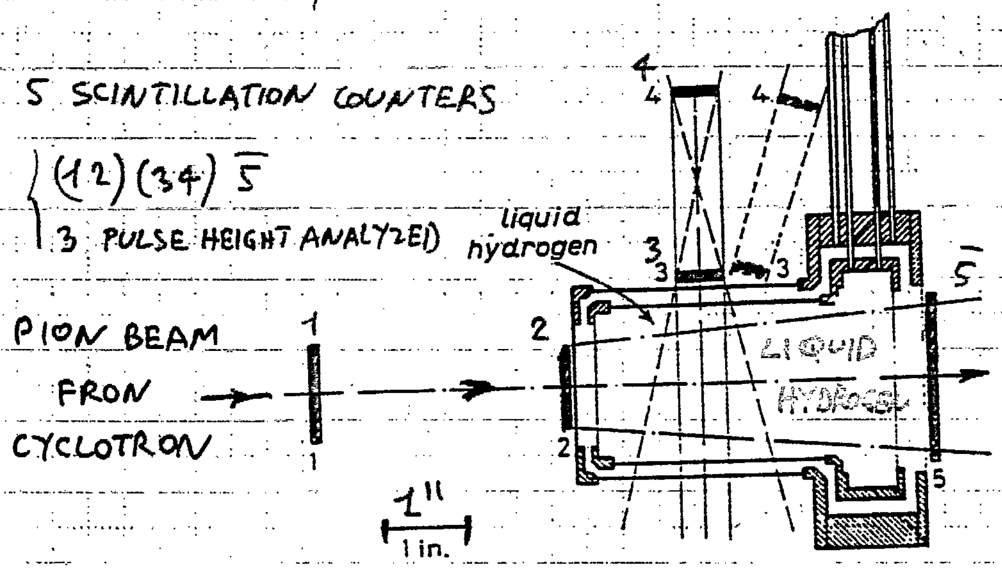
BEAM LAYOUT

ROCHESTER, 1954 – 1960, CYCLOTRON, 20 – 40 MeV PION BEAM

5 SCINTILLATION COUNTERS

(12) (34) $\bar{5}$

3 PULSE HEIGHT ANALYZED



$\left(\frac{d\sigma}{d\Omega}\right)_{ELASTIC}$

Fig. 4.1. – The geometry for a typical elastic-scattering low-energy Rochester measurement [322]. It is a tight geometry, with no-wall scattering. Scintillation counters 1-2 detect the incoming pion, 3-4 the scattered pion, $\bar{5}$ is an anticoincidence. Counter 3 is pulse-height analysed.

$\boxed{\sigma_{TOT}}$

BROOKHAVEN 1960's, 33 GeV AGS, $0.3 < p_{BEAM} < 10$ GeV/c

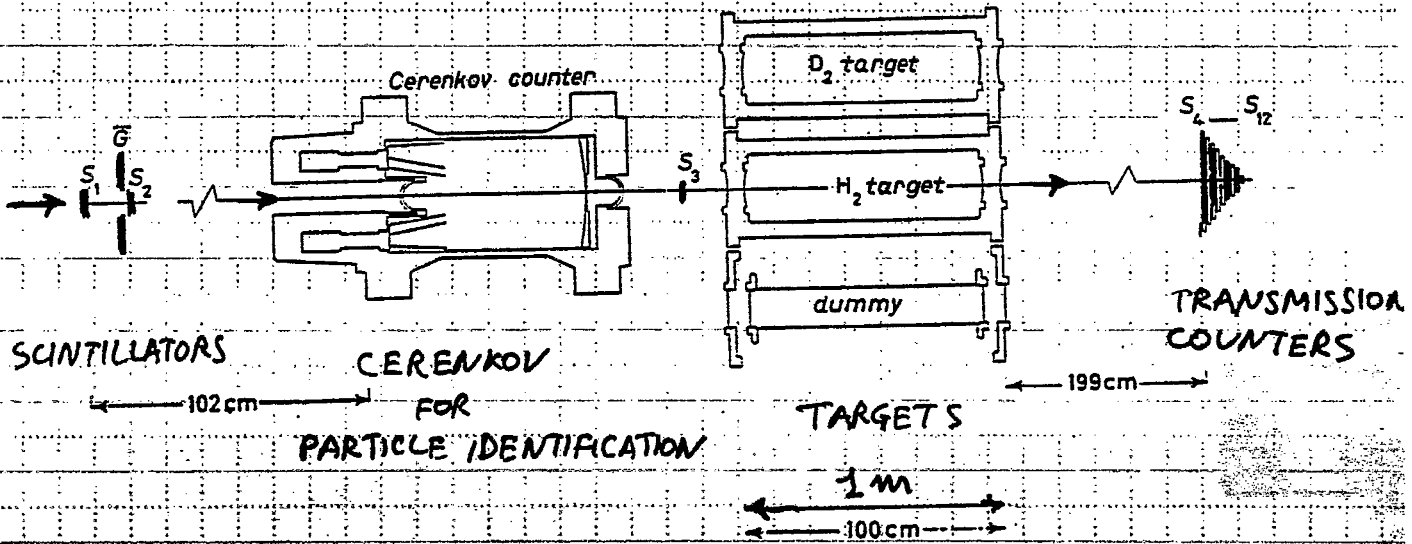
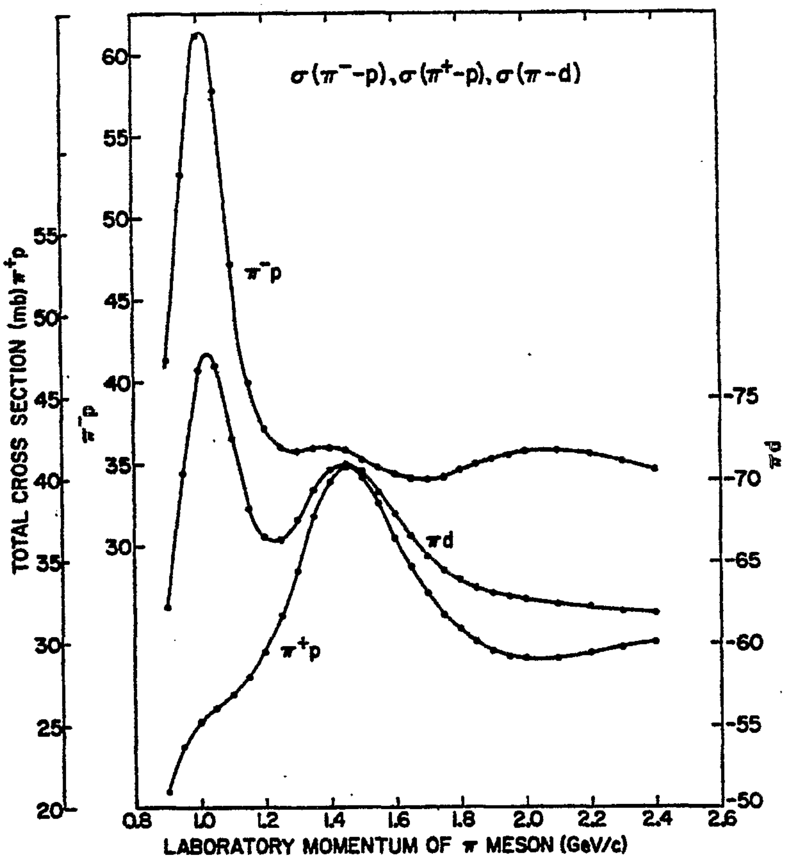


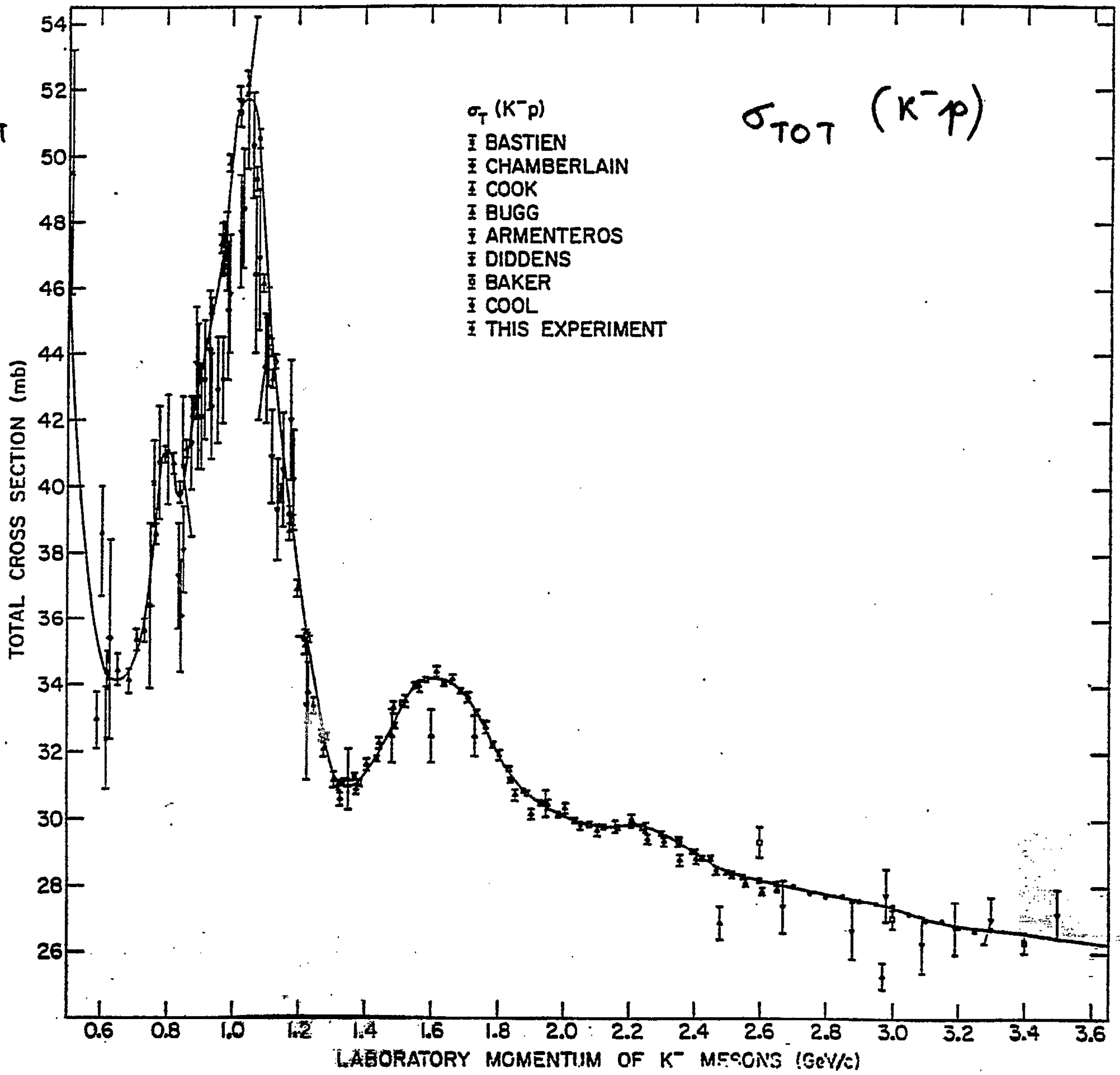
Fig. 3.2. – The geometry of a total cross-section measurement, using the absorption technique [210]. The gas Čerenkov counter in the beam separates pions from protons and, with less efficiency, from electrons and muons. S_1-S_{12} are scintillation counters S_1-S_2 count the incident beam; S_4-S_{12} are the transmission counters. The various


σ(π⁻-p), σ(π⁺-p), σ(π-d)
TOTAL CROSS SECTION (mb) π⁺p
π⁻p
πd
π⁻p
π⁺p
πd
20
25
30
35
40
45
50
55
30
35
40
45
50
55
60
-50
-55
-60
-65
-70
-75
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
LABORATORY MOMENTUM OF π MESON (GeV/c)

BROOKHAVEN, 1960's, BEAMS FROM AGS

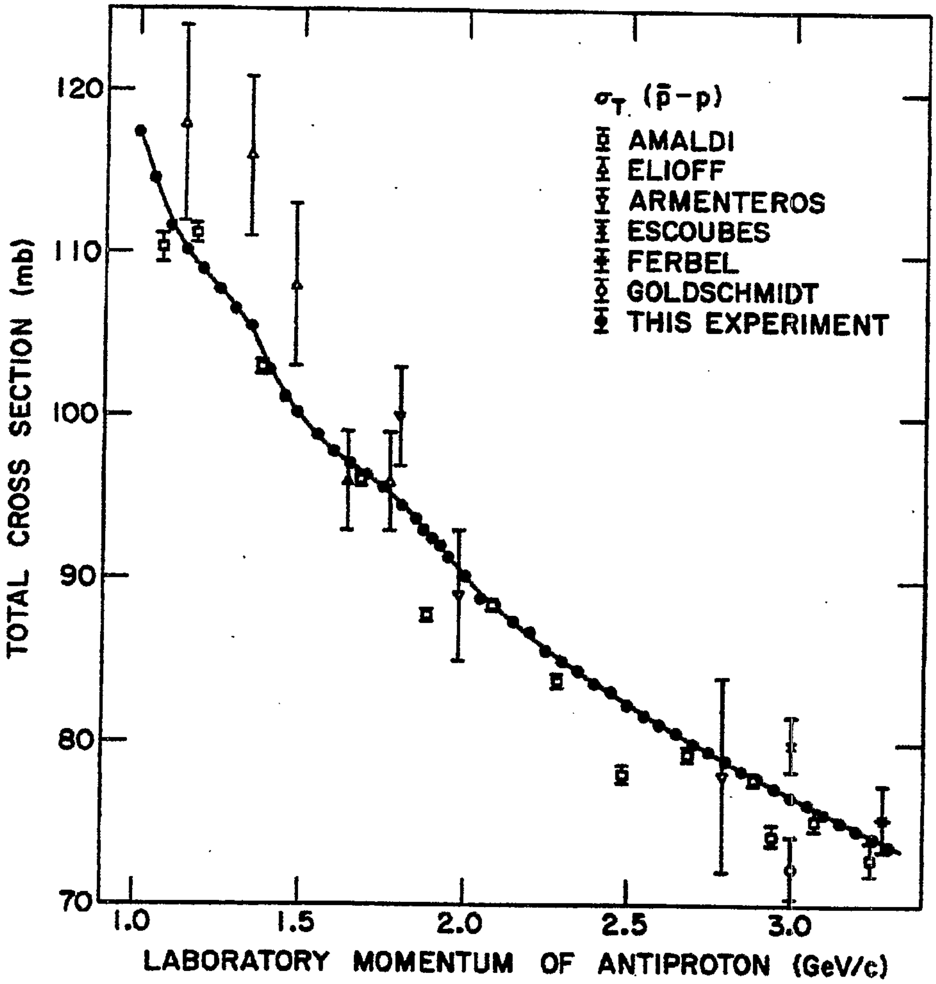
SEARCH FOR SMALL STRUCTURES (RESONANCES) IN $1 < P_{LAB} < 3$ GeV/c

σ_{TOT}



σ_{TOT} $(K^- p)$

p



σ_T ($\bar{p}$−p)
AMALDI
ELIOFF
ARMENTEROS
ESCOUBES
FERBEL
GOLDSCHMIDT
THIS EXPERIMENT
TOTAL CROSS SECTION (mb)
120
110
100
90
80
70
1.0
1.5
2.0
2.5
3.0
LABORATORY MOMENTUM OF ANTIPROTON (GeV/c)

FERMILAB - FIXED TARGET
1970's

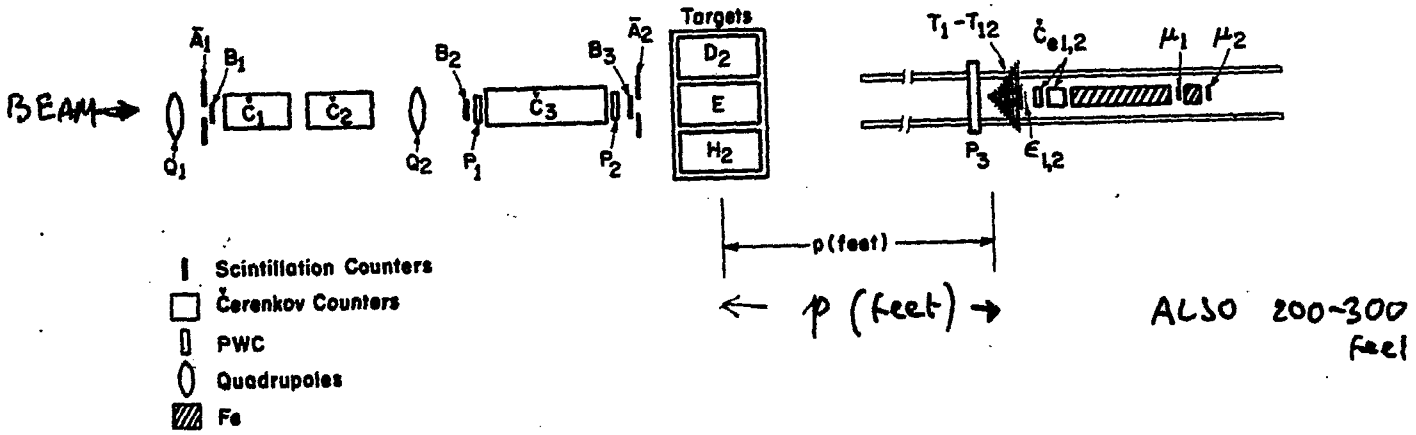


Fig. 4.1. Layout of the charged-particle cross section measurement performed at Fermilab [74C1−2]. The incoming beam is counted as $B = B_{123}\bar{A}_{12}C_l$, where C_l is one or a combination of the three gas Čerenkov counters. PWC1−3 are proportional wire chambers. D_2, VAC and H_2 are targets. T_1-T_{12} are transmission counters. E_1 and E_2 are small counters used for beam tuning and for the measurement of the efficiencies of the transmission counters. $\hat{C}_e$ is a lead glass Čerenkov counter; μ is a combination of two large scintillation counters.

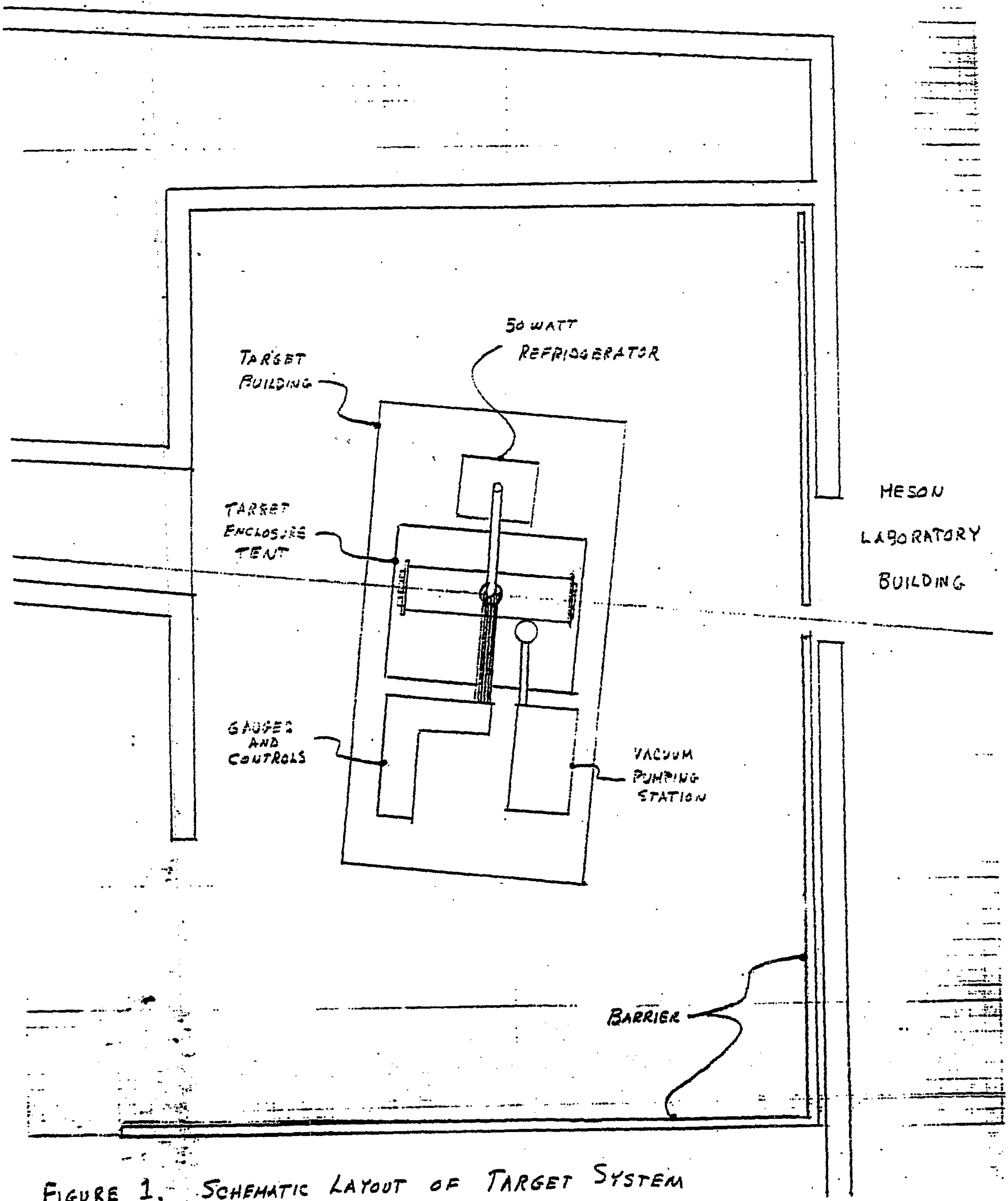
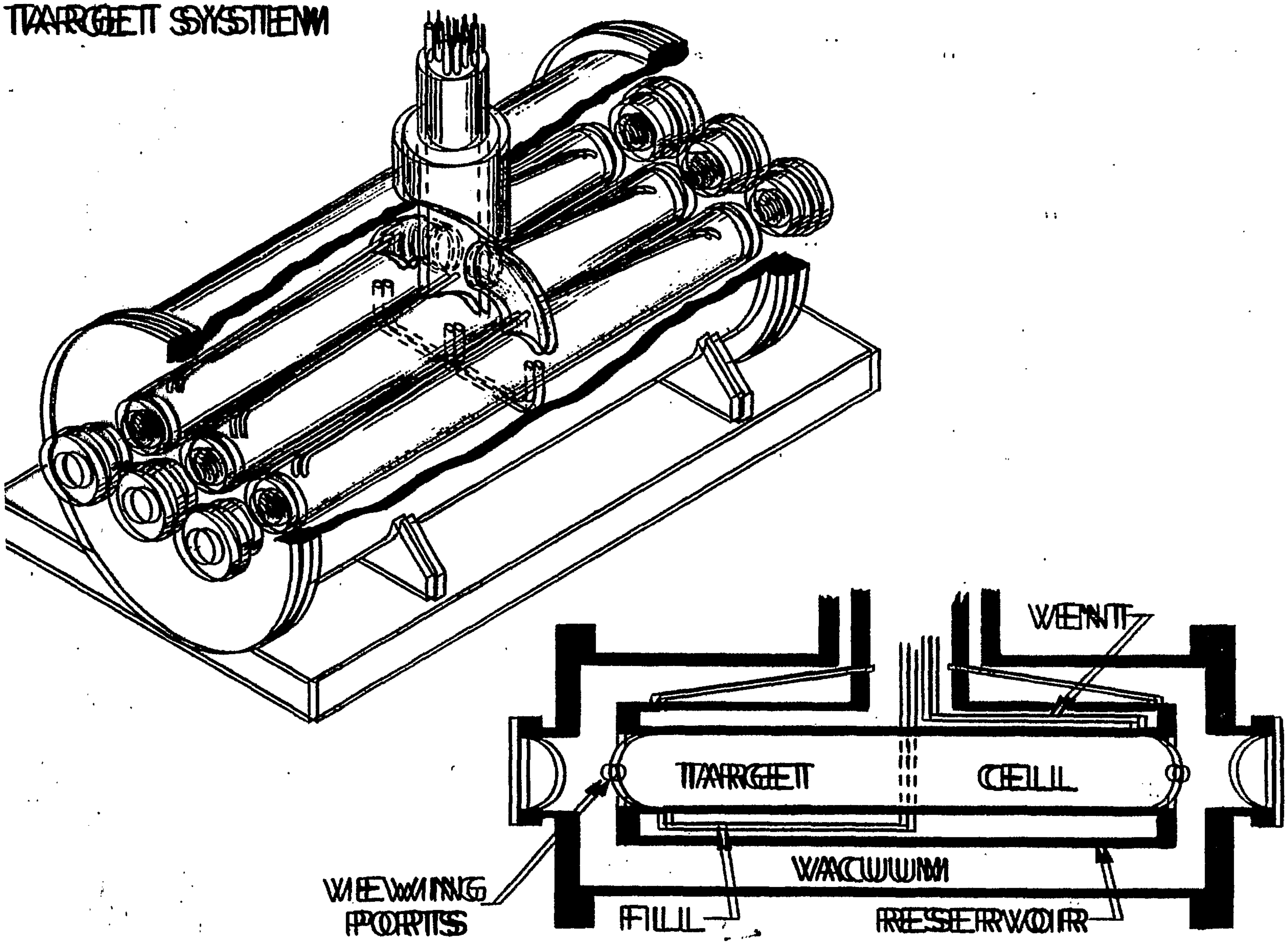
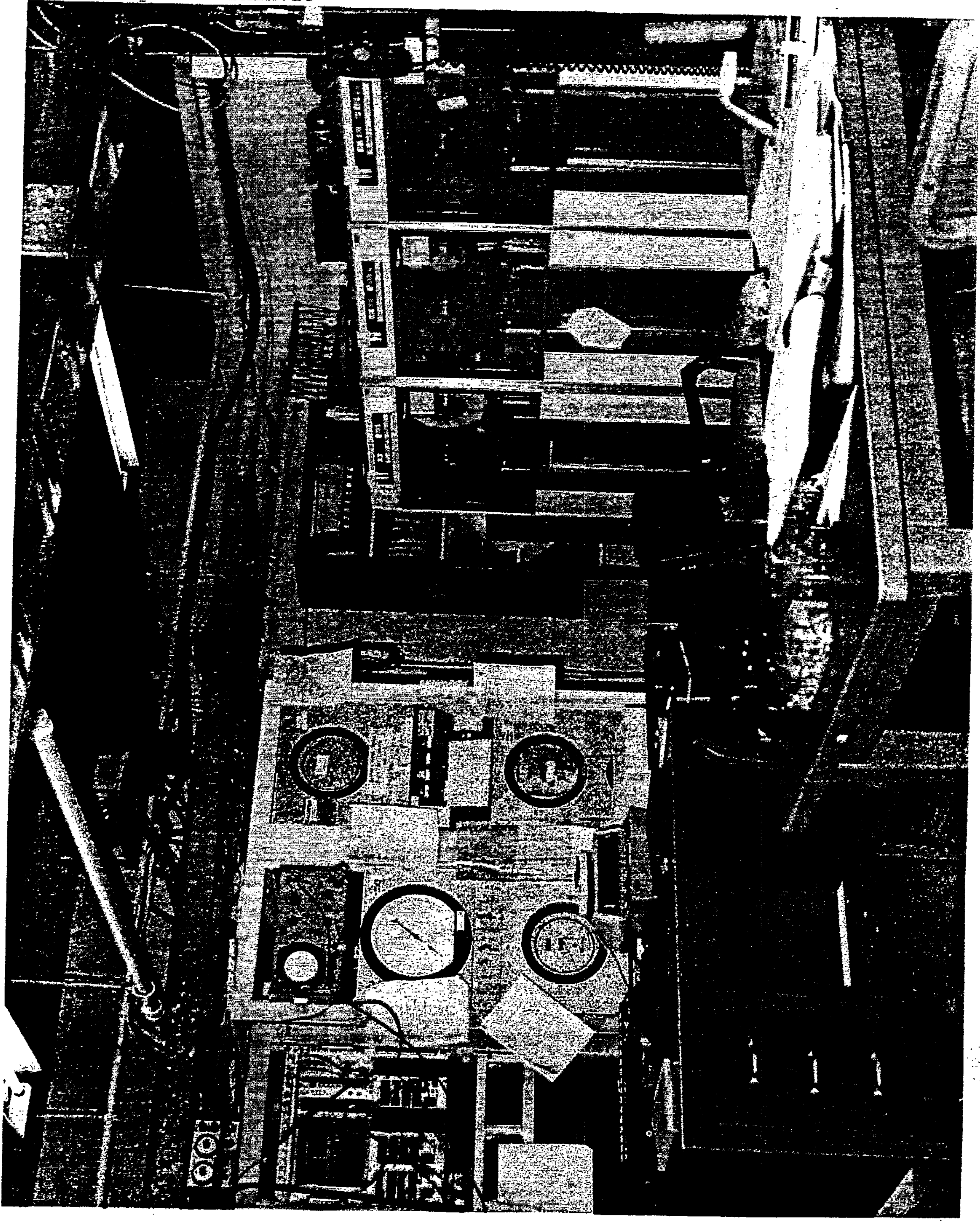


FIGURE 1. SCHEMATIC LAYOUT OF TARGET SYSTEM

10 FT, 300 LITER LH$_2$/LD$_2$ TARGET SYSTEM





BROOKHAVEN, FERMILAB AND ROCKEFELLER UNIVERSITY PHYSICISTS OPEN NEW WINDOW ON STRONG NUCLEAR HIGH ENERGY INTERACTIONS

London, July 2 1974 : A new experiment announced today at the 17th International Conference on High Energy Physics held at Imperial College in London, England indicates the surprisingly systematic character of the interaction of the fundamental particles of matter at high energies.

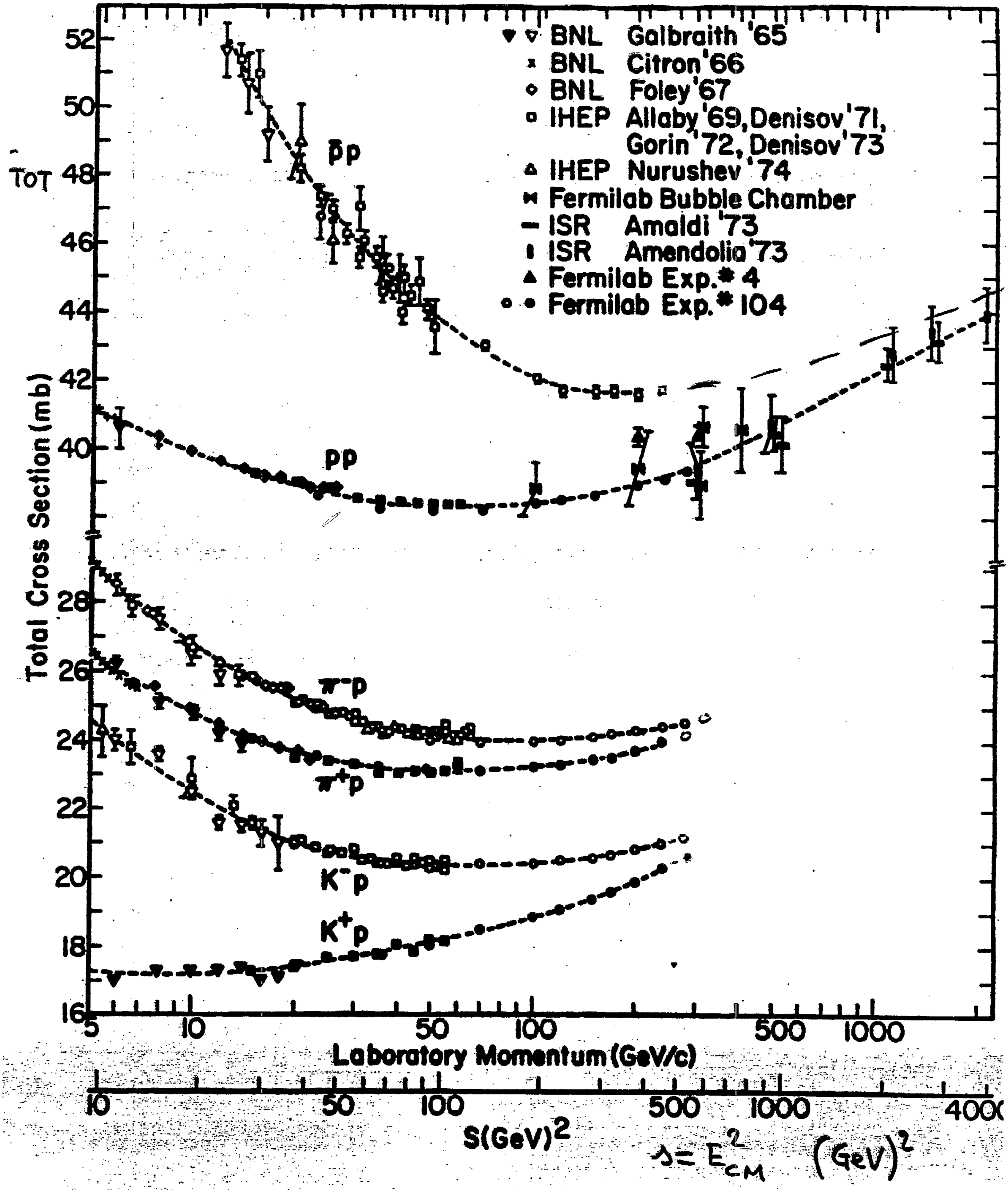
The report describes the results of bombarding protons and neutrons, the basic constituents of atomic nuclei, with six different types of very high energy sub-nuclear particles produced by the new U.S. Fermi National Accelerator Laboratory located near Chicago, Illinois.

These precise measurements, with an accuracy of about one part in 500, reveal that the effective size of both the proton and neutron increase for five of the six probes when their energy is increased from 50 to 200 GeV. For the sixth, the antiproton, the rapid decrease in size previously observed below 50 GeV has dramatically slowed and the apparent size becomes essentially constant between 150 and 200 GeV.

The phenomenon of cross sections rising with energy was first suggested in 1971 by scientists working with a beam of positively charged K-mesons at energies up to 55 GeV at the U.S.S.R. Serpukhov Accelerator. In 1973, Western European scientists working at the European Center for Nuclear Research (CERN) near Geneva, Switzerland announced an increase in proton-proton cross sections.

The principal findings announced today are:

1. The increase of the size of a proton with increasing energy appears to be a general and systematic property of strongly interacting nuclear forces. Five of the particles employed were the pi-meson, plus and minus, the K-meson plus and minus, and the proton itself. The cross sections of



$s = E_{CM}^2 \ (GeV)^2$

FIG. 4.10

T1

The experiment will be continued up to about 400 GeV. When the higher energies are employed in this same experiment, it is possible that all of the cross sections will rise. If this behavior is a universal phenomenon, it will give strong clues as to the fundamental character of the strong nuclear interactions and may assist in reaching a general theory of the strong nuclear forces which has been sought for many years.

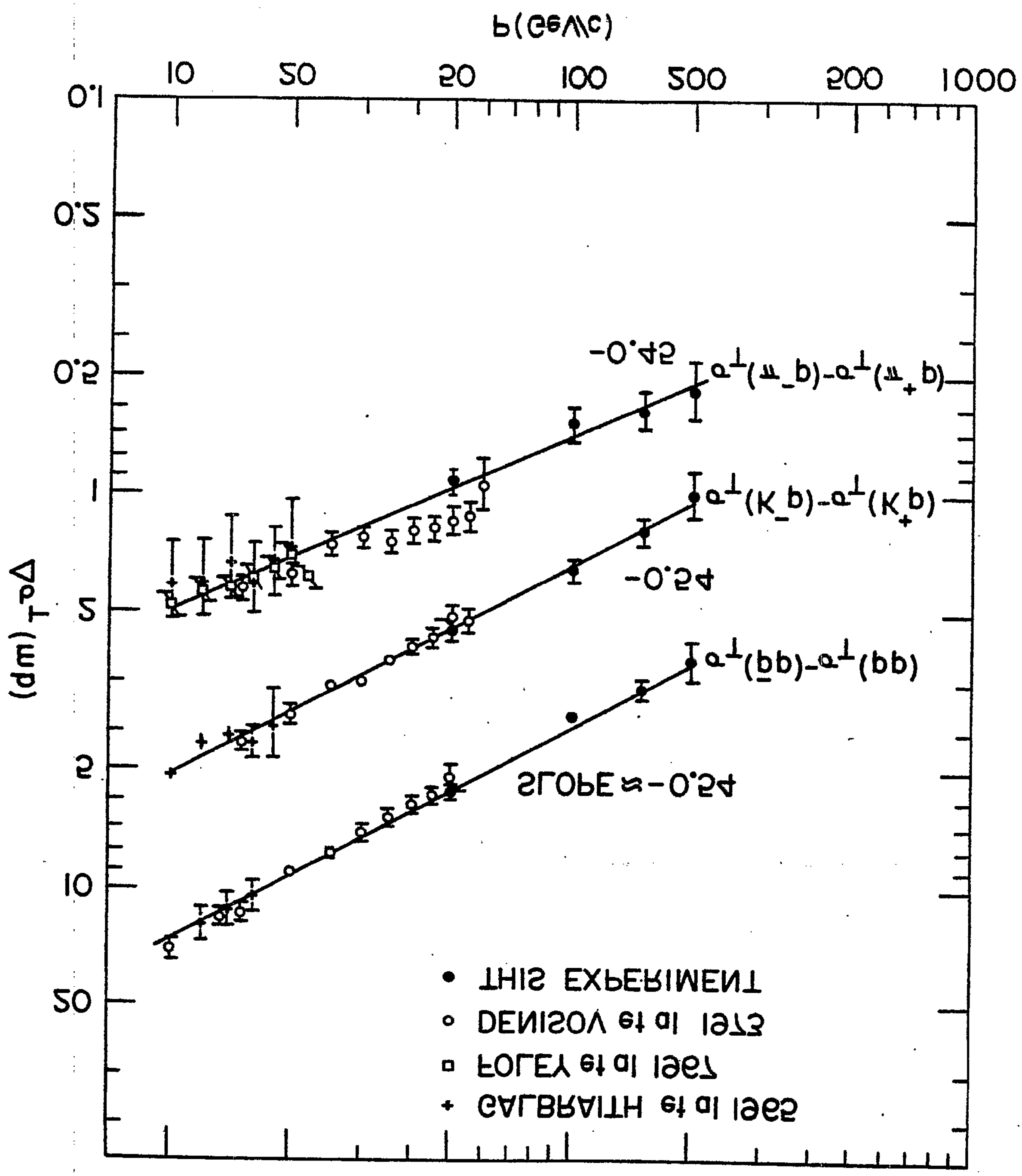
2. All of the particle-proton and antiparticle-proton cross section pairs uniformly approach each other approximately inversely proportional to the square root of their energy. The theorem that the difference between a particle cross section and that of its antiparticle on the same target should approach zero at very high energies was enunciated by the Russian theorist, Isaak Ya. Pomeranchuk in 1958.

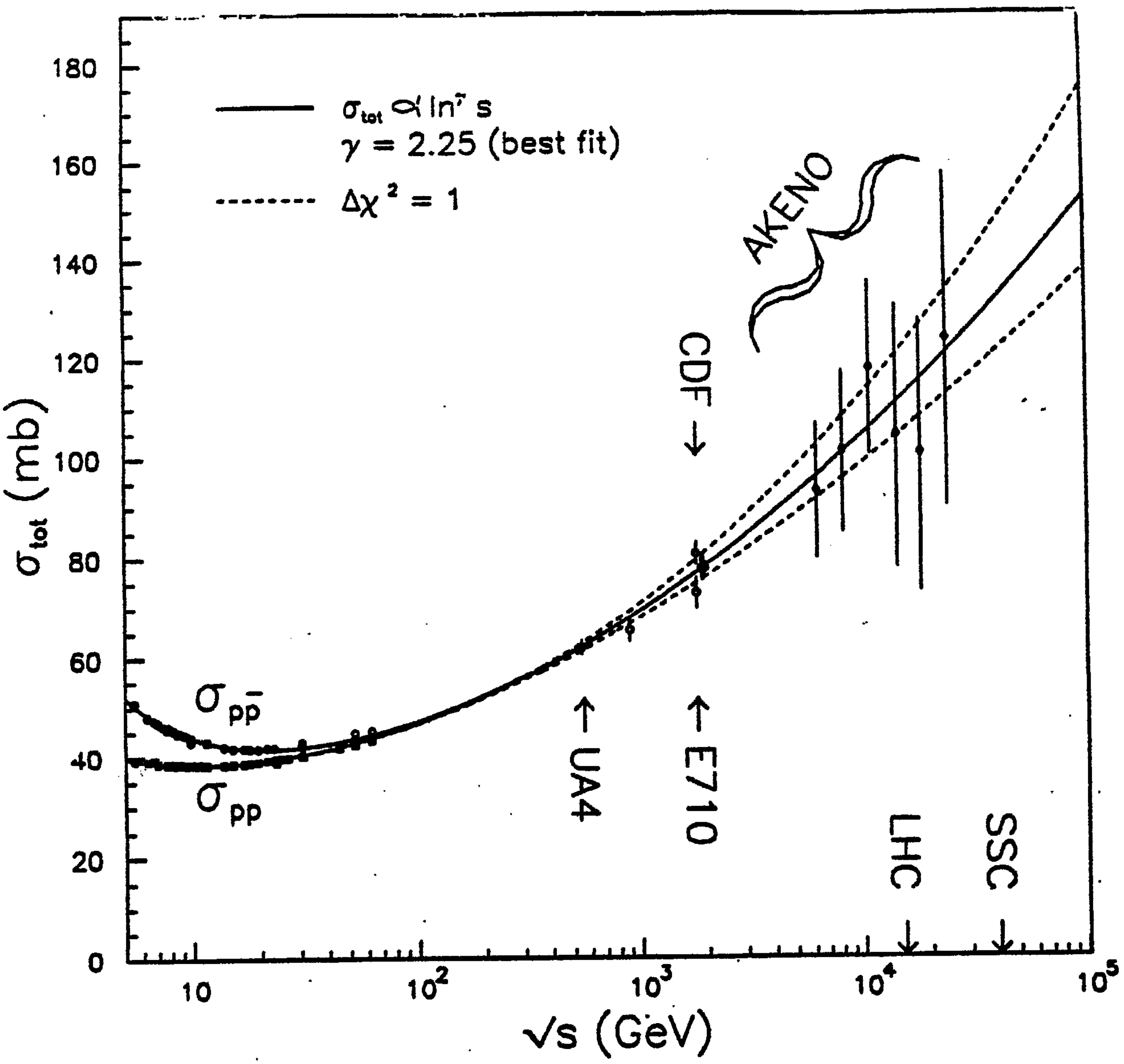
3. Since it is not possible to have a target of pure neutrons, the other basic ingredient of the atomic nucleus, the deuteron--which is composed of one proton and one neutron--was used as a target. By comparing the proton cross section and the deuteron cross section, the neutron cross sections were deduced.

For each probe particle, the neutron cross section is very nearly equal to the proton cross section at these ultra high energies.

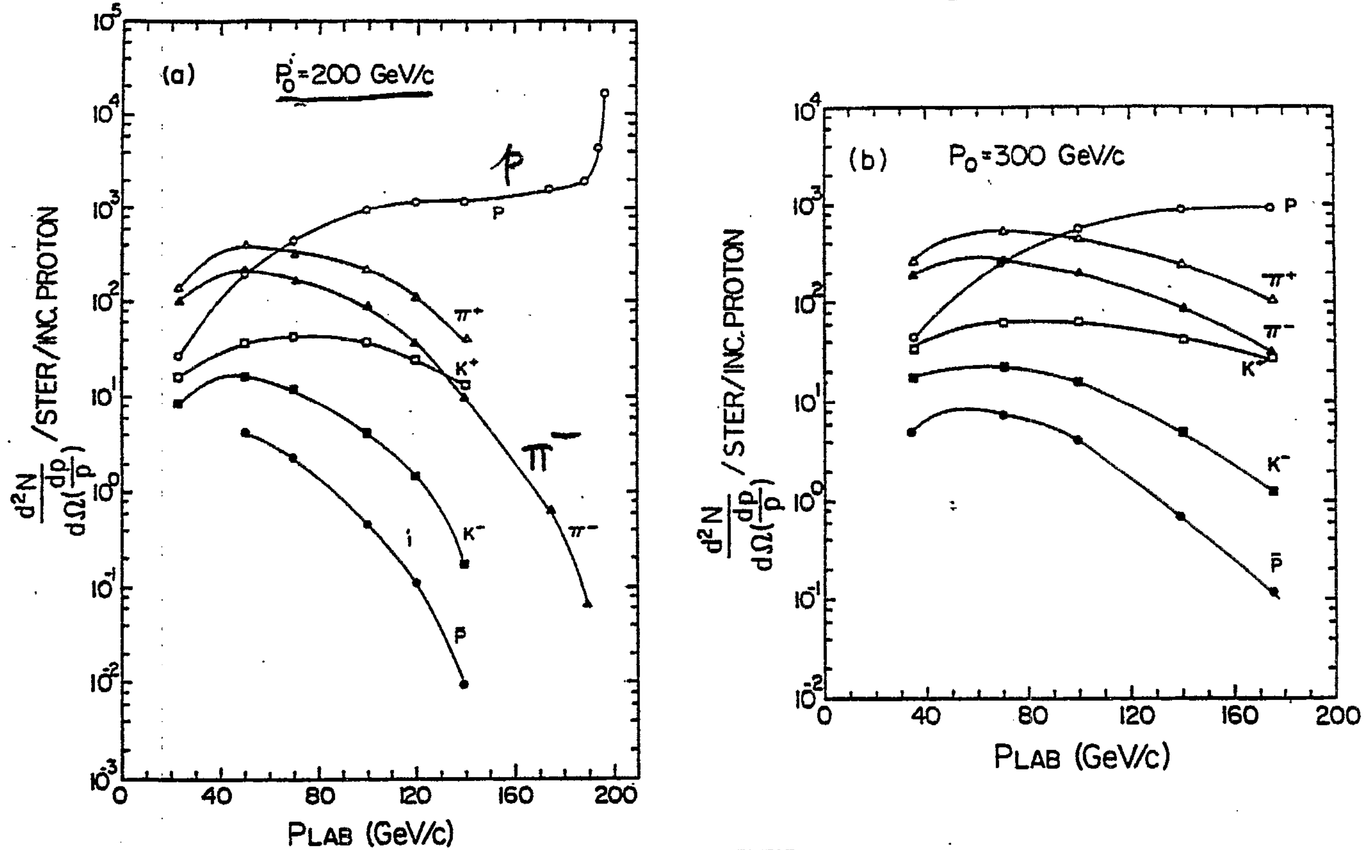
4. The nuclear forces continue to be charge symmetric. The cross section for a charged pion on a proton is equal to that of the oppositely charged pion on a neutron.

5. This experiment provides the "systematics" of the behavior of an entire class of interactions. The proton and neutron appear to have cross sections nearly equal to each other for all of the probes. The differences between particle and antiparticle pairs seem to be disappearing at extremely high energies. Even the difference in cross section between


P(GeV/c)
10
20
50
100
200
500
1000
Δσ_T (mb)
0.1
0.2
0.5
1
2
5
10
20
-0.45
σ_T(π⁻p)-σ_T(π⁺p)
σ_T(K⁻p)-σ_T(K⁺p)
-0.54
σ_T(p̄p)-σ_T(pp)
SLOPE ≈ -0.54
● THIS EXPERIMENT
○ DENISOV et al 1973
□ FOLEY et al 1967
+ GALBRAITH et al 1965


σtot ∝ ln^γ s
γ = 2.25 (best fit)
Δχ² = 1
AKENO
CDF
UA4
E710
LHC
SSC
σpp̄
σpp
σtot (mb)
0
20
40
60
80
100
120
140
160
180
10
10²
10³
10⁴
10⁵
√s (GeV)

SECONDARY BEAM COMPOSITION



$\pi^\pm, K^\pm, p^\pm$

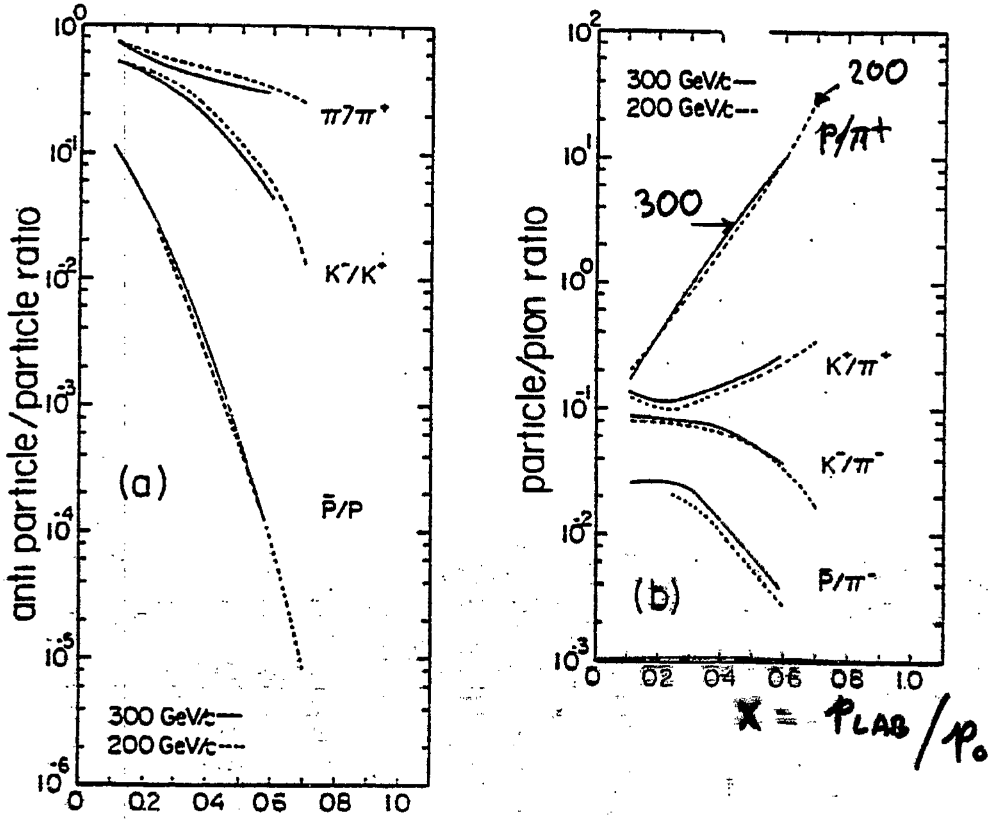
PRODUCTION

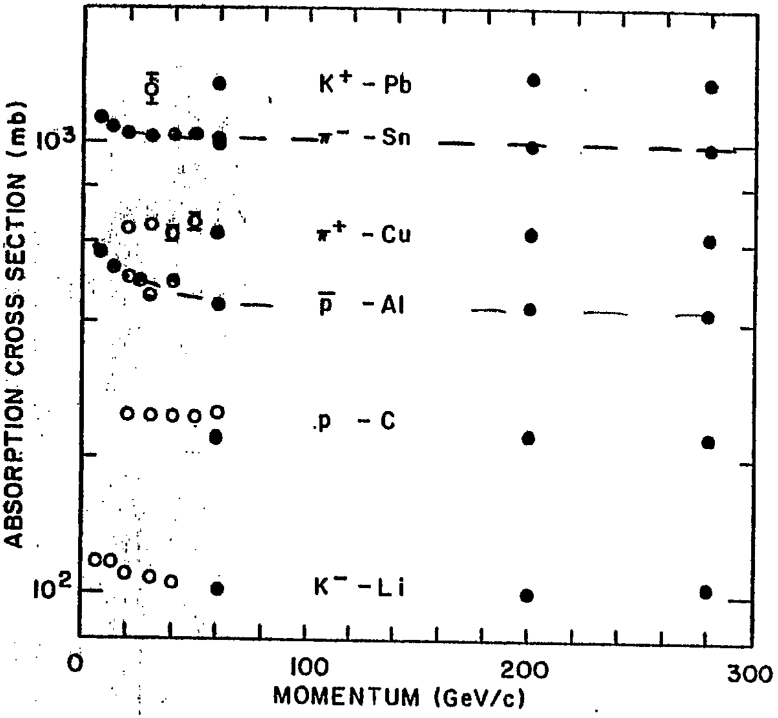
BY 200,300 Ge

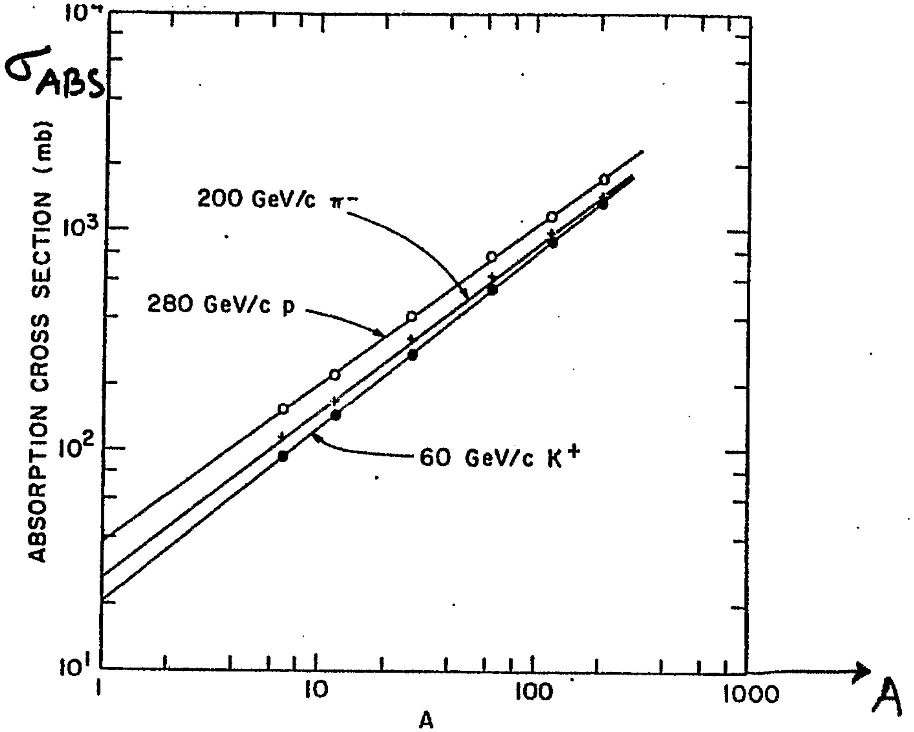
PROTONS

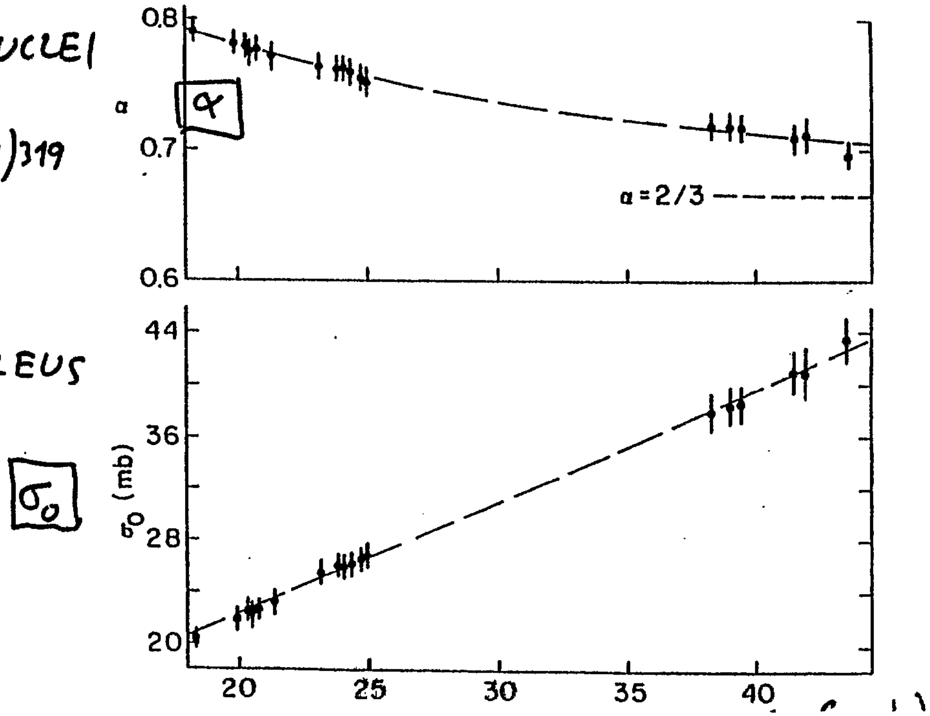
(PHYS. LETT. 51B(74,

3









ORPTION OF $\pi^\pm$, $K^\pm$, $p^\pm$ ON NUCLEI

ILAB, 1979 }, PHYS. LETT. 80B (1979) 319
160, IHEP 1970, }

$(A) = \sigma_0 A^\alpha$

ATOMIC WEIGHT OF TARGET NUCLEUS

DEPEND ON σ_{hp}

hep-ex/0006038

DFUB 2000-10
21/6/2000

Total Cross Sections

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Kycia Memorial Symposium
Brookhaven National Laboratory, Upton, N.Y. 11973-5000, U.S.A.
Friday May 19, 2000

1. Introduction

The measurements of the hadron-hadron total cross sections are the first measurements performed when a new hadron accelerator opens up a new energy region; the measurements were made as function of the incoming beam momentum or c.m. energy and have often been repeated with improved accuracy and finer energy spacing.

Most of the systematic total cross section measurements of the long-lived charged hadrons ($\pi^{\pm}$, $k^{\pm}$, $p^{\pm}$) on hydrogen and deuteron targets at fixed target accelerators were performed using the transmission method pioneered at Brookhaven National Laboratory; the method is capable of high precisions, typically point to point precisions of 0.1 - 0.2 % and a systematic scale uncertainty of 0.4 – 1.0 %.

Fig. 1, from the Data Particle Group, shows the behaviour with energy of the total cross sections of different hadrons. At low energies, in the so called *resonance region*, one observes a number of peaks and structures which decrease in size as the energy increases. Above 5 GeV lab momentum, in the *continuum region*, there are no more structures: the cross sections decrease smoothly, reach a minimum and then slowly rise with increasing energy (the *asymptotic region*). In the low energy region the cross sections depend strongly on the type of colliding hadrons and on the total isotopic spin, whilst in the high energy region these dependences tend to disappear as the energy increases.

I shall recall some of the measurements and of the discoveries made by Ted Kycia and by our colleagues, some of whom are present in the audience. Besides Ted, we are missing Rod Cool, who was the leader and a driving force for the measurements.

Among Ted's papers, I found his Curriculum Vitae, probably written around 1974; it is written in a very simple form and it well states Ted's interests and achievements in total cross section measurements; the part concerning total cross section measurements is reproduced below.

Curriculum Vitae

THADDEUS F. KYCIA

... Since 1960 he has led the development and construction of differential Cherenkov counters for use in charged secondary beams. Their function has been to electronically identify selected types of particles with a very high rejection of all other particles. The counters which were built spanned the full range of velocities available at the AGS. Most

National Laboratory in the total cross section experiment. The resolution of one counter was adequate to separate K mesons from π mesons even at a momentum of 200 GeV/c.

Over the last decade Ted Kycia led an effort to improve the precision with which total cross sections of charged particles could be measured. This led to the dicovery of six massive π meson-nucleon resonances. This was followed by a series of measurements of total cross sections of K^- mesons, K^+ mesons and antiprotons on nucleons in search of structure. The high precision systematic measurements revealed a large number of previously unobserved resonances and structures. A number of hyperon resonances were found in both isotopic spin zero and isotopic spin one states. A number of structures were found in the antiproton-proton total cross section which would be due to previously unobserved massive pion resonances. In the K^+ meson-nucleon total cross section measurements a number of structures also were discovered. These have subsequently been studied by groups in this country and in Europe. The question of whether any of the K^+ meson-nucleon structures could be due to the existence of exotic Z^* 's is still unresolved.

The techniques developed at BNL for measuring total cross sections to a high precision were then applied to the measurement of total cross sections at FNAL. This latter experiment was carried out in collaboration with physicists from Rockefeller and Fermilab. ...

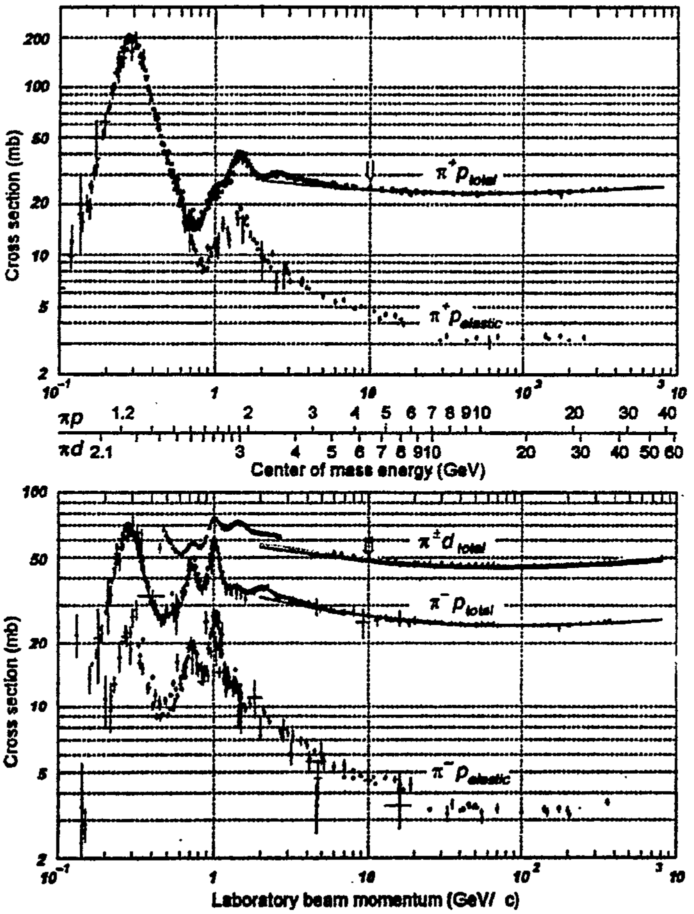


Fig. 1. Compilations of data of the total and of the integrated elastic cross sections versus lab momentum for $\pi^{\pm}p$ and $\pi^{\pm}d$ scattering [Particle Data Group].

2. Total cross sections at Brookhaven

At BNL a series of measurements were made with different beams covering the resonance region [1-2, 4-9] and the beginning of the continuum region [3]. The cross sections were measured on protons and deuterons and also on various nuclei [9].

A systematic and precise total cross section measurement in the resonance region may be thought of as a method for detecting the existence of new resonances: this was the main aim of the Brookhaven measurements. Low mass rersonances are easy to detect because they produce large effects. Higher mass resonances, however, show up as broad and non prominent structures, often overlapping with one another, so that one needs to measure the total cross sections with high precision at many closely spaced points. Errors in the absolute values can be tolerated only if they are essentially energy independent.

Ted had a particular way of searching by eye for new mini-structures at relatively high energies: he carefully plotted the measured points on a large graph, which he then was viewing along the points, trying to see if there were mini-structures.

The π^+p, K^+p, and pp are pure isospin states. In the other cases one has a mixture of two isospin states. The determination of the pure isotopic spin cross sections requires the measurement of two cross sections, which involves changing either the incident or the target particle. For pions it is easy to measure both π^+p and π^-p total cross sections, and hence to derive the total cross sections $\sigma_{1/2}$ and $\sigma_{3/2}$ for pure isospin states. For the other cases the simplest solution is to measure the cross sections off protons and off neutrons. Unfortunately, the best neutron target is a bound neutron-proton state (the deuteron), so that in this case the problems of nuclear physics in the deuteron severely limit the analysis of the data. A careful unfolding procedure has to be performed to extract the pure isospin cross sections.

If a structure is found in a total cross section measurement, and assuming that it is due to a resonance, the information that it yields includes the mass M (the c.m. energy of the peak), the width at half height Γ, the height σ_R, and the isotopic spin I.

The total cross section method of resonance-hunting must be considered as a "coarse spectrometer", with a not-so-good energy resolution. In fact "spectrometers" with higher resolutions have been used, like elastic scattering and "phase-shift analyses".

Total cross section measurements do not provide enough information to establish conclusively that a peak in a definite isospin state is a resonant state, i.e. a state with definite quantum numbers. In fact, a structure could also come from a threshold effect, such as the opening up of a new important channel, or other kinematical effects.

The principle of the method used for measuring total cross sections is that of a standard transmission good geometry experiment.

The low energy beams were partially separated secondary beams, see for example Fig. 2.

After momentum and mass separation, the beam is defined by a sysytem of scintillation counters and by a Cherenkov counter, which further electronically distinguishes between wanted and unwanted particles. The beam then alternatively passes through a hydrogen, deuterium, or dummy target and converges to a focus at the location of the transmission counters, each of which subtends a different solid angle at the center of the target (see Fig. 3). The method is thus to evaluate the partial cross sections σ_i measured by each individual transmission counter and to extrapolate these cross sections to zero solid angle to obtain the total cross section.

The momentum spread of a beam was typically 0.75 %. With a circulating beam of 10^{12} protons the used K^+-meson flux was about 3500 per pulse at 1.6 GeV/c, increasing at lower energies. The K^- meson fluxes were typically one third of the K^+-meson fluxes. The antiproton fluxes reached about 10000 $\bar{p}$'s per pulse at 2.5-3.0 GeV/c, and smaller values at lower momenta.

The separation achieved with the electrostatic separators was considerable, giving at worst a ratio of 2:1 between the wanted and unwanted particles; the contamination of unwanted particles was assured to be less than 0.1 % by the Cherenkov counters.

Figures 4 to 8 show some of the experimental results obtained. Figs. 4 and 5 show the K^-p, data and the K^-N, I=0 and I=1data, respectively. Notice the quality of the data in Fig. 4 and Fig. 7 compared to previous measurements. Fig. 5 shows the I=0 and the I=1 total cross sections for the K^-N scattering after proper unfolding. Notice the structures which decrease in size as the energy increases. For small structures at the highest energies, global analyses do not still give final conclusions on their parameters.

The pion nucleon system, Fig. 6, is clearly overdetermined since one can measure the π^-p, π^+p, π^-d, π^+d total cross sections.

In the $\bar{p}p$ system the structures in the covered energy range are very small (Fig. 7).

In the K^+N, I=0 state there is a structure at the center of mass (c.m.) energy of about 1910 MeV (Fig. 8). Many measurements have been made on this system, without reaching a final conclusion, though a possible I=0 resonant state seems to be indicated for this "exotic system" [10]. Further work on this system may be worthwhile.

During the period of total cross section measurements at BNL other important measurements were made there: (i) the first measurements of the magnetic moments of the hyperons, (ii) elastic scattering measurements with the discovery of the shrinking of the diffraction pattern, (iii) bubble chamber measurements with the discovery of the Ω^- [11, 12]. The scientific atmosphere at BNL was at its best. But also the human atmosphere was at its best; in particular the collaborators in the total cross section measurements became friends and the frienship lasted for all subsequent measurements at other accelerators.

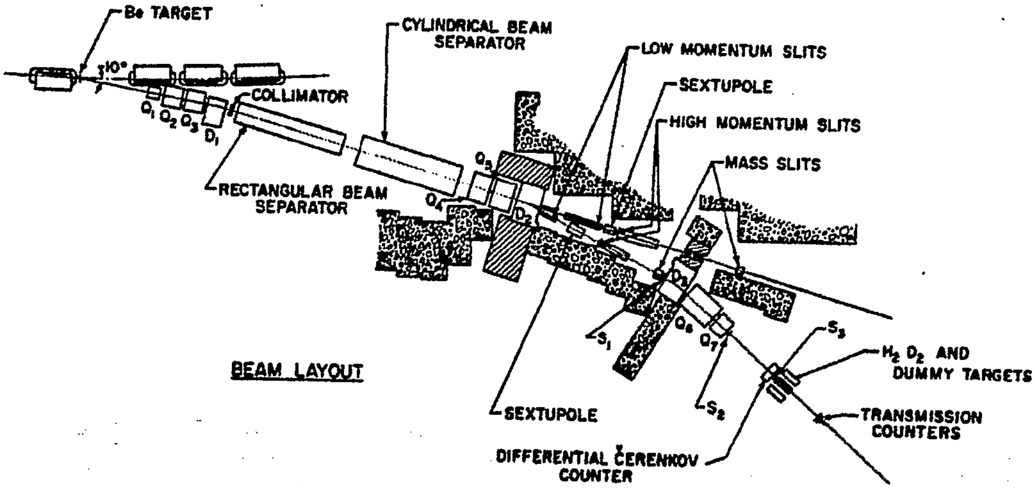


Fig. 2. Layout of a partially separated Brookhaven beam. Q_1-Q_8 are quadrupoles; D_1-D_8 are bending magnets; S1-S3 and $\overline{G}$ are scintillation counters. Note the electrostatic beam separators.

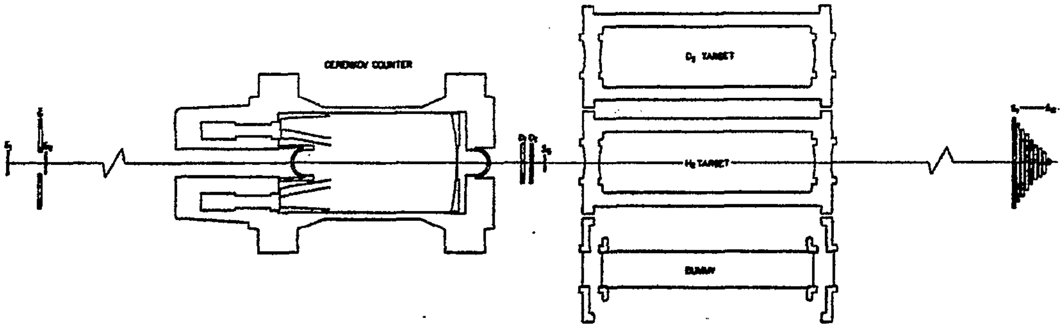


Fig. 3. Layout of the experimental apparatus for the measurement of low energy total cross sections. S_1, S_2, S_3, and $\overline{G}$ are scintillation counters defining the beam. The gas differential Cherenkov counter is shown; it was replaced by a liquid differential Cherenkov counter for measurements at lower momenta. H_2, D_2, and the dummy are the liquid hydrogen, liquid deuterium and the dummy targets, respectively. S_4-S_{12} are the transmission counters.

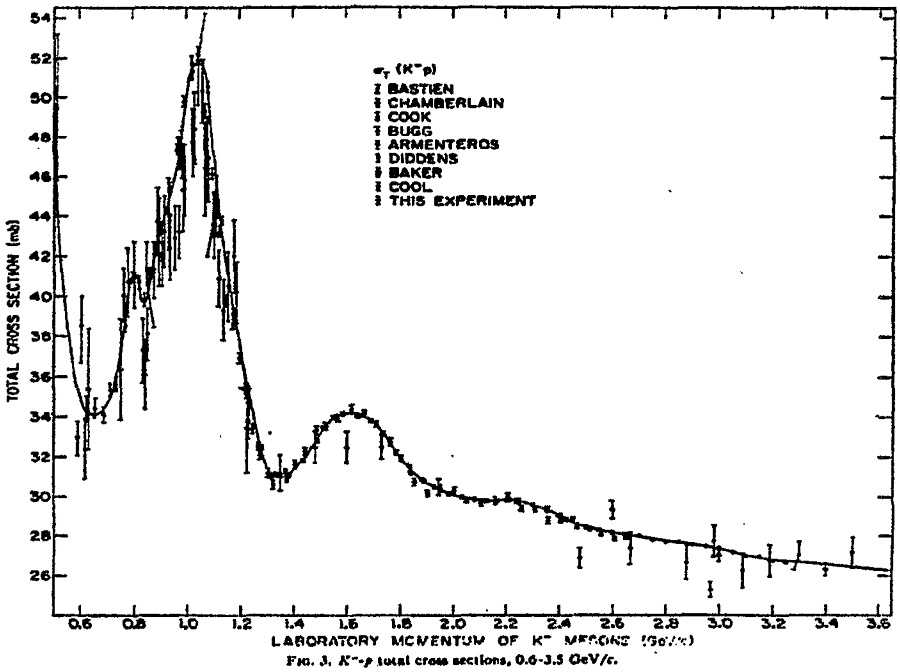


Fig. 4. K^--p total cross sections in the range 0.6-3.5 GeV/c lab. momentum.

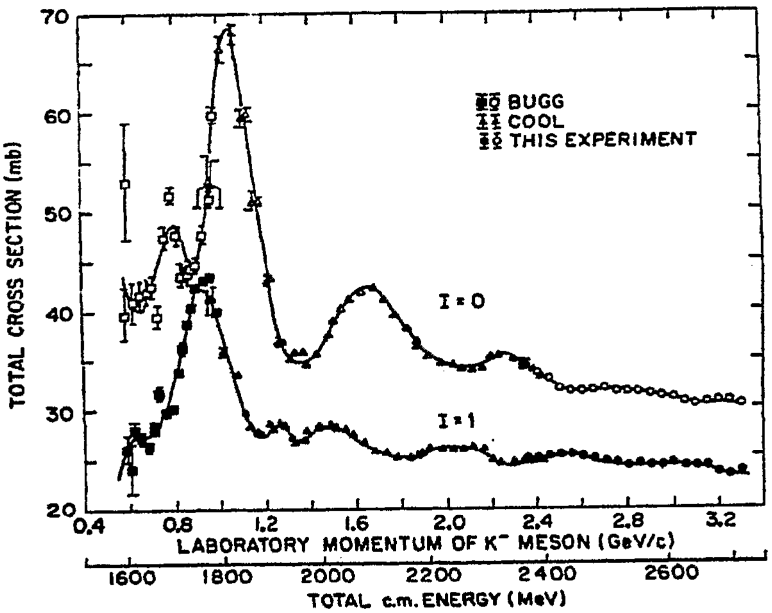


Fig. 5. K^-N total cross sections in the pure I=1 and I=0 states, for the range 0.6-3.3 GeV/c.

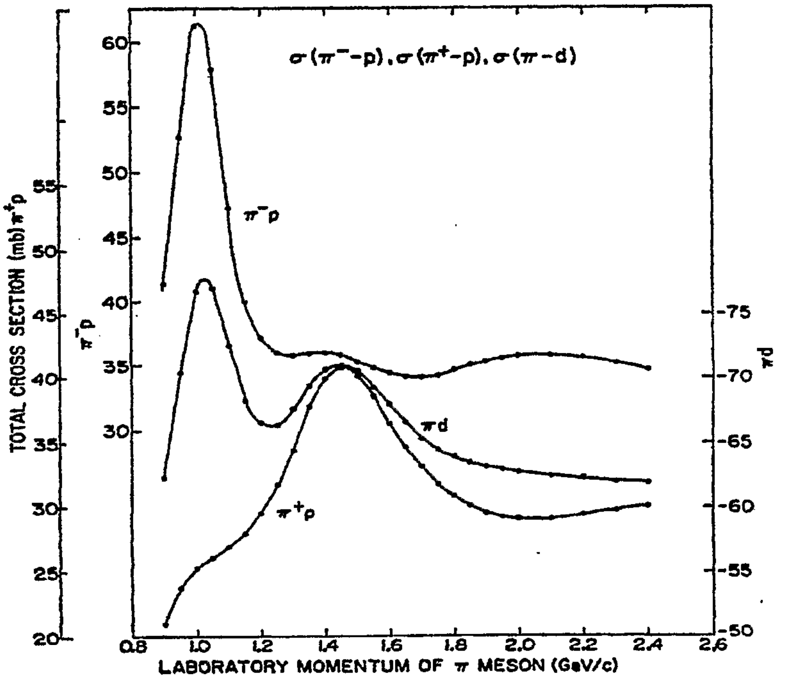


Fig. 6. π^-p, π^+p, and $\pi^\pm d$ total cross sections. For all points shown, the statistical errors are smaller than the size of the data points.

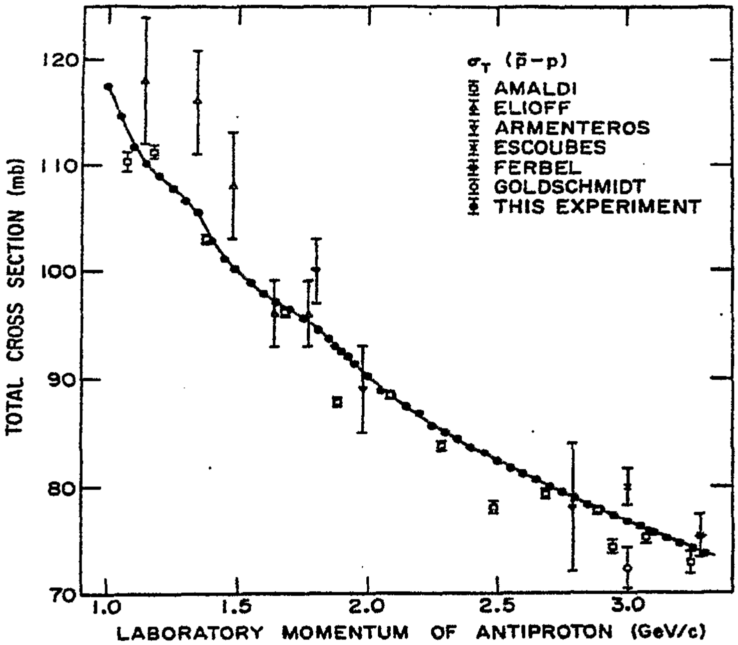


Fig. 7. $\bar{p}p$ total cross sections, in the range 1.0-3.3 GeV/c. For each point, the statistical error is less than the size of the dot.

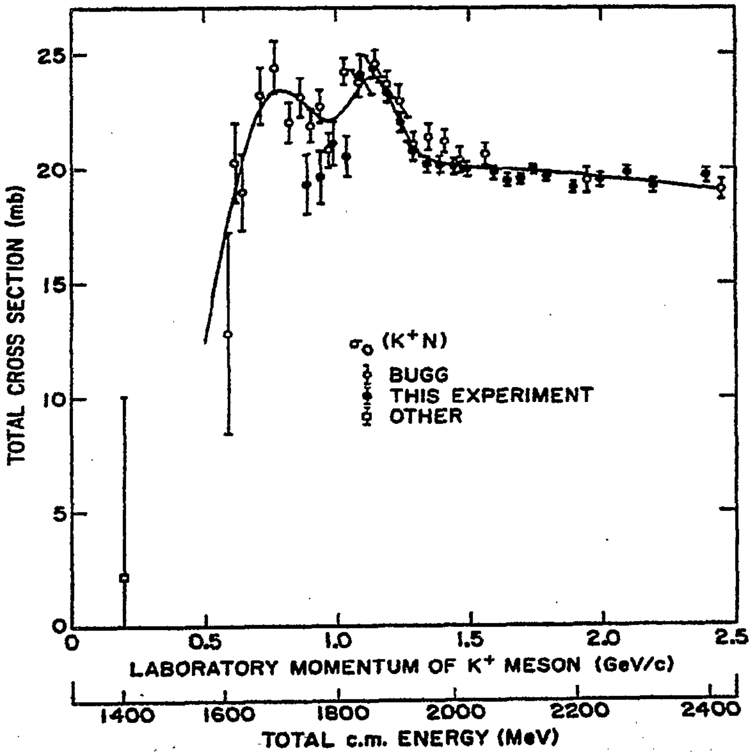


Fig. 8. Total cross section σ_0 for the I=0 isotopic spin state for the K^+N system.

3. Total cross sections at Fermilab

Total cross section measurements at intermediate energies have been performed at BNL [3] and at Serpukhov [13-15]. Then followed measurements at the CERN-ISR at high energies [15, 16] and two sets of measurements at the Fermilab fixed target accelerator [17-22].

Fig. 9 shows the layout of the total cross section measurements at Fermilab. The differences compared to the Brookhaven measurements were mainly due to the much higher energies of the Fermilab beams, thus to the impossibility of using electrostatic separators, to the need of much more selective differential Cherenkov counters, longer targets, etc. Incident particles were defined by scintillation counters and identified by two differential gas Cherenkov counters, allowing cross sections of two different particles to be measured simultaneously. In addition, a threshold gas Cherenkov counter could be used in anticoincidence when required. Typical particle separations are shown in Fig. 10 using two counters made by Ted. Sufficient π^+-K^+ separation was achieved up to 340 GeV/c and at higher momenta using corrected optics [12] Contamination of unwanted particles in the selected beam particles was always below 0.1 % thanks to the marvellous Cherenkov counters designed and built by Ted. In the pion and kaon beams there were small admixtures of muons and electrons (at the level of one part in a thousand and 1 %, respectively). Electrons in the gas Cherenkov counter pion signal were identified by their characteristic signal in a 22-radiation length lead-glass Cherenkov counter placed downstream of the transmission counters. Muons were identified by their ability to pass through 5 m of steel placed downstream of the transmission counters. Other differences concerned the order in the transmission counters (first the large transmission counters at Brookhaven, and the reverse at Fermilab: this is one problem which usually leads to strong debates inside a group!). The transmission counters could be moved on rails so as to subtend at each energy the same t-range. The targets were 3 m long, much longer than in the BNL experiments. The three targets (hydrogen, deuterium and dummy) were surrounded by a common outer jacket of liquid hydrogen for temperature stability. The vapour pressure was continuously monitored and the hydrogen and deuterium densities were determined; their density variations were less than 0.07 %. Target lengths were measured to 0.03 %. Repeated measurements indicated that the cross section measurements were stable to better than 0.2 %.

The data were taken first in the range 50 to 200 GeV/c secondary beam momentum, and later in the range 200 to 370 GeV/c. A compilation of the measured data is presented in Fig. 11. These new higher energy data were presented at the 1974 High Energy International Conference in London. In this occasion a press conference was made and the statements presented there summarize the interest of the measurements and their possible interpretation.

Press Conference

[...]

BROOKHAVEN, FERMILAB AND ROCKEFELLER UNIVERSITY PHYSICISTS OPEN NEW WINDOW ON STRONG NUCLEAR HIGH ENERGY INTERACTIONS

London, July 2, 1974: a new experiment announced today at the 17th International Conference on High Energy Physics held at Imperial College in London, England indicates the

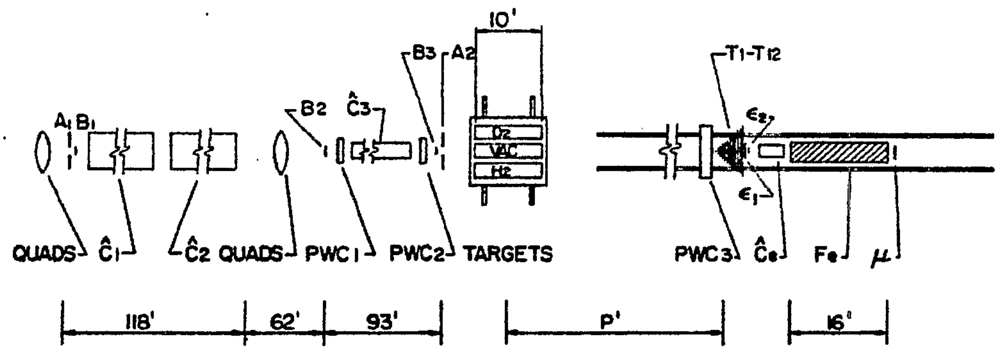


Fig. 9. Layout of the experimental apparatus for the measurement of the high energy total cross sections at Fermilab. C_1, C_2 (C_3) are gas differential (threshold) Cherenkov counters, PWC1-PWC3 are proportional wire chambers B_1-B_3 and A_1-A_2 are scintillation counters. H_2, D_2, VAC are the liquid hydrogen liquid deuterium and dummy targets, T_1-T_{12} are the transmission counters, ε_1-ε_2 are scintillation counters used for efficiency measurements, C_e is a lead glass Cherenkov counter; the iron absorber and the muon (μ) scintillation counter were used for estimating the muon contamination.

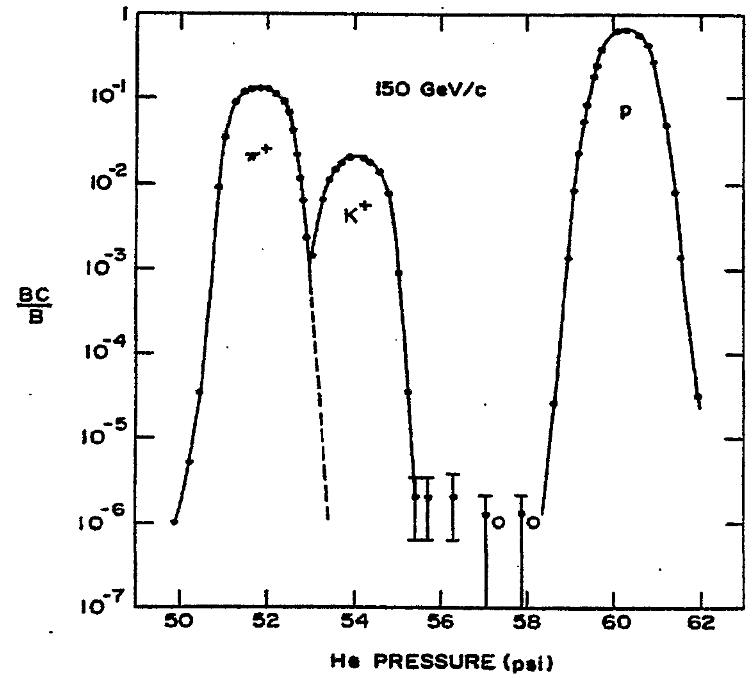


Fig. 10. Relative counting rate versus helium pressure in the gas Cherenkov counters for the beam of unseparated particles of 150 GeV/c momentum.

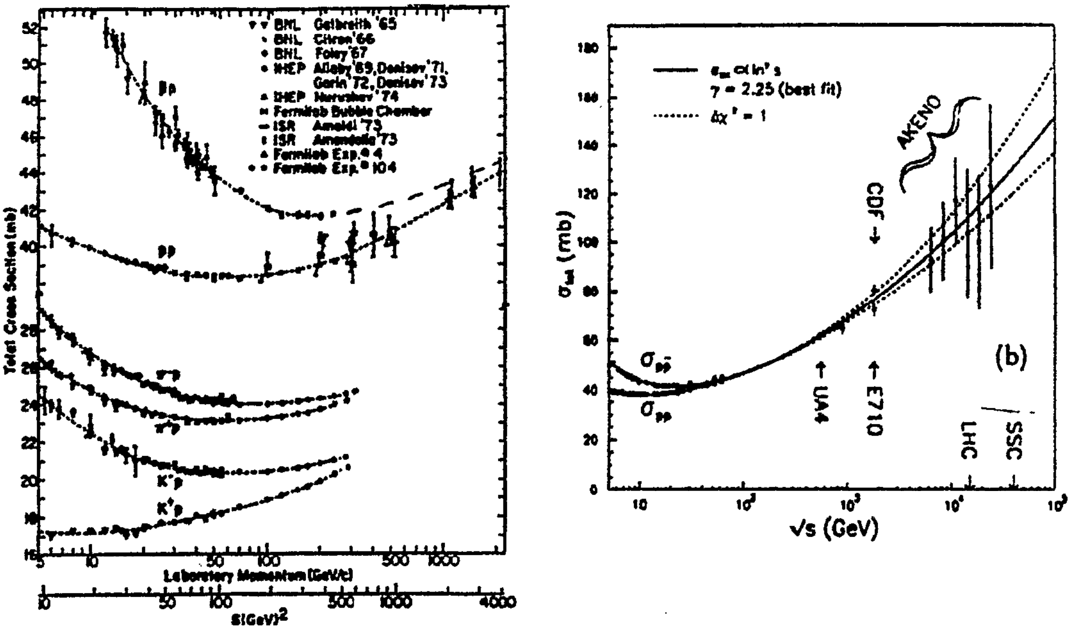


Fig. 11. (a) Compilation of $\bar{p}p$, pp , π^-p, π^+p, K$^-$p and K$^+$p total cross sections plotted versus c.m. energy. (b) the $\bar{p}p$ and the pp total cross sections, including cosmic ray measurements. The solid line is a fit of the σ_{tot} and ρ data with dispersion relations; the region of uncertainty is delimited by dashed lines

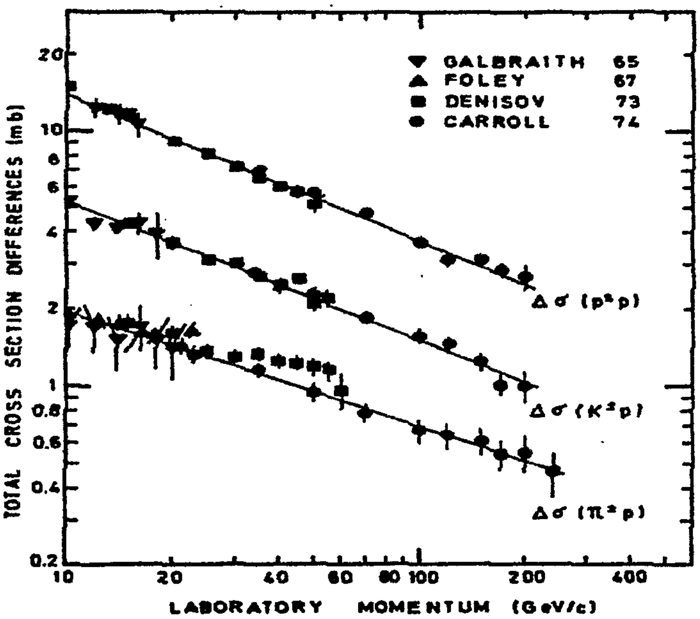
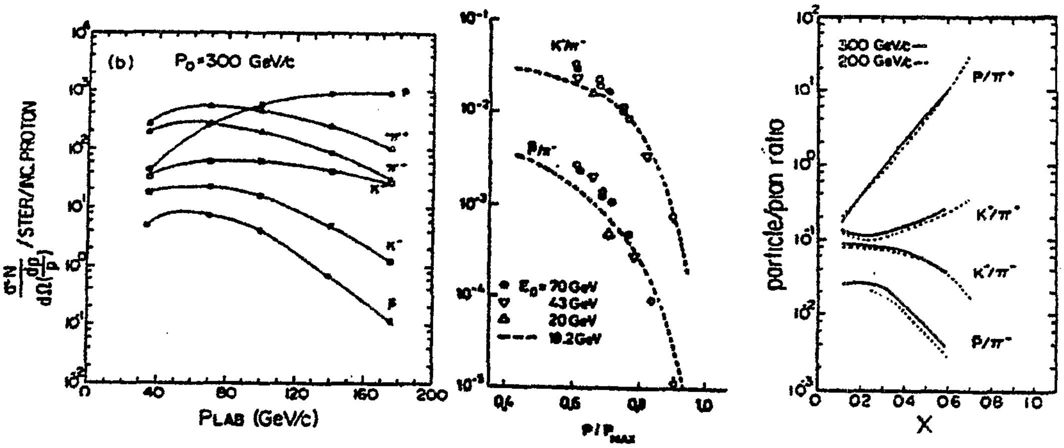


Fig.12. The differences of total cross sections for $\pi^\pm$, K$^\pm$, p and $\bar{p}$ interactions with protons. The solid lines represent fits of the data to a power law dependence.



(a) (b) (c)

Fig.13. (a) Production cross sections of the six long-lived charged hadrons plotted vs lab momentum; (b) (c)particle ratios vs p/p_{max}.

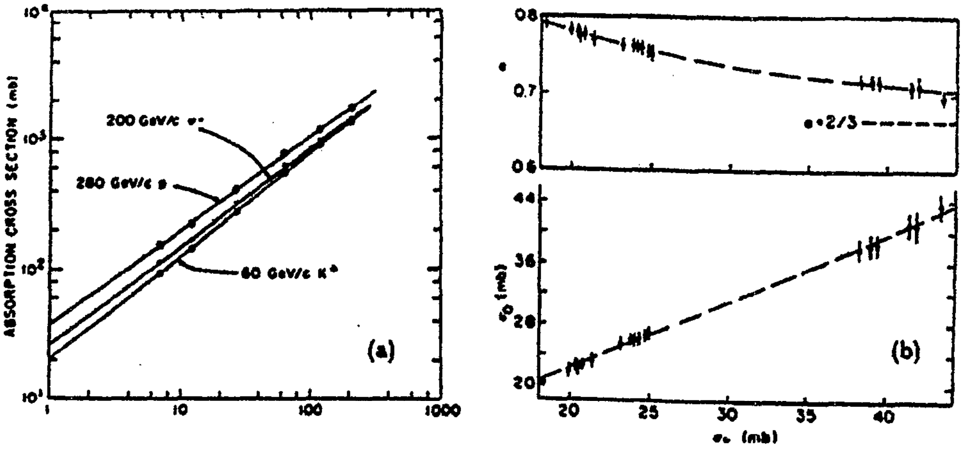


Fig. 14. Absorption cross sections in different nuclei.

surprisingly systematic character of the interaction of the fundamental particles of matter at high energies.

The report describes the results of bombarding protons and neutrons, the basic constituents of atomic nuclei, with six different types of very high energy sub-nuclear particles produced by the new U.S. Fermi National Accelerator Laboratory located near Chicago, Illinois.

The Measurements allow a precise comparison of the interaction probabilities of each of the six different strongly interacting probe particles with the proton and neutron. These interaction probabilitiers are usually referred to as effective areas or "total cross sections" of the proton and neutron.

These precise measurements, with an accuracy of about one part in 500, reveal that the effective size of both the proton and neutron increase for five of the six probes when their energy is increased from 50 to 200 GeV. For the sixth, the antiproton, the rapid decrease in size previously observed below 50 GeV has dramatically slowed and the apparent size becomes essentially constant between 150 and 200 GeV.

The similarities and the intercomparisons of the behaviour of the cross sections with the six probing particle beams indicate that a new simplicity of nature may be revealing itself at very high energies; a situation which has been predicted by some physicists. Since the proton and neutron are the basic blocks of all atomic nuclei, these experiments are a significant advance toward an understanding of the constitution of matter.

The phenomenon of cross sections rising with energy was first suggested in 1971 by scientists working with a beam of positively charged K-mesons at energies up to 55 GeV at the U.S.S.R. Serpukhov Accelerator.

In 1973, scientists working at the European Center for Nuclear Research (CERN) near Geneva, Switzerland announced an increase in proton-proton total cross sections. Although the CERN scientists were limited to the study of proton-proton collisions by the nature of the interacting Storage Ring Accelerator, in which two oppositely directed beams of protons collide with each other, they were able to reach a record equivalent energy of 2,000 GeV.

The new measurements just announced were made with the world's; largest accelerator recently dedicated at Fermilab in which 300 GeV protons strike a stationary nuclear target. Beams of many types of subnuclear particles with energies up to 300 GeV emerge from this target. The six varieties of particle beams which were used included protons, antiprotons, positively and negatively charged pi-mesons and positively and negatively charged K-mesons.

The experiment was carried out by a collaboration between teams of physicists from the Brookhaven National Laboratory (BNL) in Upton, N.Y., the Fermilab in Batavia, Illinois, and The Rockefeller University in New York City.

Details of today's announcement were disclosed at a press conference at the American Institute of Physics. Participating in the conference were: Dr. Thaddeus F. Kycia of BNL; Dr. Winslow F. Baker of Fermilab; and Professor Rodney L. Cool of the Rockefeller University.

Other menbers of the teams and authors of the paper were as follows:

BNL - -Alan S. Carroll, I-Hung Chiang, Kelvin K. Li, Peter O. Mazur, Paul M. Mockett, now at the University of Washington, Seattle, and David C.Rahm.

Fermilab- - David P. Eartly, Georgio Giacomelli, from the Institute of Physics at the University of Padova, Italy, Peter F. M. Koehler, Klaus P. Pretzel, now at the Max Planck Institute of Physics and Astrophysics in Munich, Germany, Roy Rubinstein, and Alan A. Wehmann.

The Rockefeller University - - Orrin D. Fackler

The principal findings announced today are:

1. The increase of the size of a proton with increasing energy appears to be a general and systematic property of strongly interacting nuclear forces. Five of the particles employed were the pi-meson, plus and minus, the K-meson, plus and minus, and the proton itself. The cross sections of protons measured with each of these probes increased with energy between 50 and 200 GeV. The cross section measured with the sixth probe the antiproton, ceased to fall and became constant between 150 and 200 GeV.
   The experiment will be continued up to 400 GeV. When the higher energies are employed in this same experiment, it is possible that all of the cross sections will rise. If this behavior is a universal phenomenon, it will give strong clues as to the fundamental character of the strong nuclear interactions and may assist in reaching a general theory of the strong nuclear forces which has been sought for many years.
2. All of the particle-proton and antiparticle-proton cross section pairs uniformly approach each other approximately inversely proportional to the square root of their energy. The theorem that the difference between a particle cross section and that of its antiparticle on the same target should approach zero at very high energies was enunciated by the Russian theorist, Isaak Ya. Pomeranchuk in 1958.
3. Since it is not possible to have a target of pure neutrons, the other basic ingredient of the atomic nucleus, the deuteron—which is composed of one proton and one neutron—was used as a target. By comparing the proton cross sections and the deuteron cross sections, the neutron cross sections were deduced. For each probe particle, the neutron cross section is very nearly equal to the proton cross section at these ultra high energies.
4. The nuclear forces continue to be charge symmetric. The cross section for a charged pion on a proton is equal to that of the oppositely charged pion on a neutron.

5. This experiment provides the "systematics" of the behavior of an entire class of interactions. The proton and neutron appear to have cross sections nearly equal to each other for all of the probes. The differences between particle and antiparticle pairs seems to be disappearing at extremely high energies. Even the difference in cross section between particles which do not have the same quantum number describing the characteristic of "strangeness" seems to be disappearing.
   [...]

The measurements performed later in the momentum range 200-340 GeV/c confirmed the above statements and proved that also the antiproton-proton total cross section was rising with energy, see Fig. 11. The differences of (antiparticle-proton) – (particle-proton) cross sections are shown in Fig. 12.

The rising of the total cross sections at high energies was a surprise to most physicists. I remember the heated discussions concerning the high energy behaviour of the cross sections; one of these discussions was made at a coffee table by a group of experimentalists and theoreticans: most of the experimentalists favoured a constant cross section, while most theoreticians favoured cross sections becoming smaller. Then arrived Giuseppe Cocconi (one of the driving forces of high energy total and elastic cross section measurements): He listened carefully, then said, "it is all nonsence: I bet you a coffee that total cross sections will rise". This was the first time I, and most experimental colleagues, had heard of this possibility, which looked somewhat ridiculous. Therefore we accepted the bet and a few years later we had to pay it.

The study of total cross sections requires first a study of the beam qualities and of their fluxes. This in turns provides interesting information on the production cross sections of the six long lived charged hadrons, see for instance Fig.13 [22].

Besides the liquid hydrogen, liquid deuterium and dummy targets, one had always available a number of targets of different materials (Li, C, Al, Cu, Sn and Pb). Thus one had the possibility of measuring the absorption cross sections in nuclei, as shown in Fig. 14 [10, 13, 19].

4. The "continuation"

As already stated, the participation in the Brookhaven and Fermilab total cross section experiments created a strong group of friends interested in this line of research. Some of these collaborators made further measurements at different accelerators [18-22].

The logical continuation of the total cross section measurements performed at the fixed target BNL, Serpukhov, and Fermilab accelerators and at the CERN ISR was to measure the total antiproton-proton cross section at the CERN [23] and Fermilab $\bar{p}p$ colliders [24], up to 1.8 TeV c.m. energy. Several members of the previous collaborations measured the antiproton-proton total and elastic cross sections at Fermilab [24]. Clearly, at a collider, one needs a layout considerably different from that used for the transmission measurements performed at fixed target accelerators.

The Fermilab collider results established that the total PN cross section for antiproton-proton interactions keeps increasing with increasing c.m. energies, at least up to 1.8 TeV. Cosmic ray measurements indicate that the total cross sections increase even at higher energies, see Fig. 11b.

The next steps will be measurements at RHIC at BNL and then at the Large Hadron Collider (LHC, the proton-proton collider which is being built at CERN). Maybe some of the collaborators will participate in those experiments

Conclusions

The series of total cross section measurements performed at BNL in the resonance region lead to the discovery of a large number of peaks and structures, most of which correspond to hadronic resonances.

Since the early Serpukhov data, then the CERN data and the Fermilab data we know that all total hadron-hadron cross sections increase with energy; this is also confirmed, even if with low precision, by the highest energy cosmic ray data.

From a theoretical point of view there is not a unique interpretation for this rise, though in many QCD inspired models it may be connected with the increase of the number of minijets and thus to semi-hard gluon interactions.

Most of the high energy elastic and total cross section data have been usually interpreted in terms of Regge Poles, and thus in terms of Pomeron exchange. Even if the Pomeron was introduced long time ago we do not have a consensus on its exact definition and on its detailed substructure. Some authors view it as a "gluon ladder".

Future experiments on hadron-hadron total cross sections remain for the moment centered on the Fermilab Collider, (for $\bar{p}p$)where new measurements will be made in the near future. The experimental future after year 2005 will rely mainly on the LHC proton-proton Collider at CERN. Large area cosmic ray experiments may be able to improve the data in the ultra high energy region.

In any case the collaborations headed by Ted Kycia and Rod Cool produced important results which will remain known in the history of particle physics. "Ted's expertise was in the design, planning, and execution of particle physics experiments, and he had an impressive record of obtaining correct and accurate results. We and many of our colleauges learned much through working with him".

I am greatful to all the collaborators in the various total cross section measurements. I am also greatful to their families for the nice atmosphere during and after work. I thank Ms. Luisa De Angelis for typing the manuscript and Roberto Giacomelli for technical support.

References

1. A. N. Diddens et al. (Structure in the pion-proton cross section between 2 and 3 GeV) Phys. Rev. Lett. 10 (1963) 262; (K^-p total cross section between 2.7 and 5.2 GeV/c) Phys. Rev. 132 (1963) 2721.
2. A. Citron et al (Structure in the pion-proton total cross section between 2.5 and 5.5 GeV/c) Phys. Rev. Lett. 13 (1964) 205.
3. W. F. Baker et al (K^+ and K^-p total cross sections in the momentum range 3-19 GeV/c) Phys. Rev. 129 (1963) 2285; W. Galbraith et al (Total cross sections of p, $\bar{p}$, π and K mesons on p and d in the momentum range 6-22 GeV/c) Phys. Rev. 138 (1965) B913.
4. R. L. Cool, et al. (New structure in K^--p and K^--d total cross sections between 1.0 and 2.45 GeV/c) Phys. Rev. Lett. 16 (1966)1228; (New structure in K^+-p and K^+-d total cross sections between 1.0 and 2.45 GeV/c) Phys. Rev. Lett. 17 (1966) 102.
5. R. J. Abrams, et al. (Structures in pbar p and pbar d total cross sections between 1.0 and 3.3 GeV/c) Phys. Rev. Lett. 18 (1967) 1209; R. J. Abrams, et al. (New structures in K^+ p and K^+ d total cross sections between 1.55 and 3.3 GeV/c) Phys. Rev. Lett. 19 (1967) 259; R. J. Abrams, et al. (New structures

in the K^- p and K^- d total cross sections between 2.4 and 3.3 GeV/c) Phys. Rev. Lett. 19 (1967) 678; R. J. Abrams, et al. (Further structures in K^+ N, I=0 total cross sections) Phys. Lett. 30B (1969) 564.

6. R. L. Cool, et al. (Structure in K^+ N and K^- N total cross sections between 0.9 and 2.4 GeV/c) Phys. Rev. D1 (1970) 1887.

7. R. J. Abrams, et al. (Total cross sections of K^+, K^- and $\bar{p}$ on nucleons up to 3.3 GeV/c) Phys. Rev. D1 (1970) 1917; R. J. Abrams, et al. (Measurement of the pp and pd total cross sections at 3 GeV/c) Phys. Rev. D1 (1970) 2477.

8. A.S. Carroll et al. (Observation of structure in anti-p p and anti-p d total cross sections below 1.1 GeV/c) Phys. Rev. Lett. 32 (1974) 247.

9. R. J. Abrams, et al. (Absorption cross sections of K^+, K^- and $\bar{p}$ on C and Cu in the region 1-3.3 GeV/c) Phys. Rev. D4 (1971) 3235.

10. G. Giacomelli et al. (K^+ d interactions between 0.6 and 1.5 GeV/c) Nucl. Phys. B37 (1972) 577; (Phase-shift analysis of $K^+N \rightarrow K^+N$ scattering in the I=0 state up to 1.5 GeV/c) Nucl. Phys. B71 (1974) 138.

11. R.L. Cool, et al. (Measurement of the magnetic moment and of the decay parameters of the Csiminus hyperon) Phys. Rev. D10 (1974) 792.

K. J. Foley et al. (Elastic scattering of protons, antiprotons, negative pions, and negative kaons at high energies) Phys. Rev. Lett. 15 (1965) 45; Phy. Rev. B138 (1965) 913.

V.E. Barnes et al. (Observation of a Hyperon with strangeness -3) Phys. Rev. Lett. 12 (1964) 209; Phys. Rev. Lett. 34 (1975) 1125.

12. K. K. Li (Hyperon magnetic moments) This symposium;

R. Rubinstein (Cherenkov work) This symposium.

13. J. V. Allaby et al. (Total cross sections of π^-, K^- and $\bar{p}$ on p and d in the range 20-65 GeV/c) Phys. Lett. 30B (1969) 500; S. P. Denisov, et al. (Total cross sections of π^+, K^+ and p on p and d in the momentum range 15-60 GeV/c) Phys. Lett. 36B(1971)415; Yad Fis 14 (1971) 998.

14. F. Binon et al. (Absorption cross sections of 25 GeV/c $\bar{d}$ in Li, C, Al, Cu, Pb) Phys. Lett. 31B (1970) 230.

15. G. Giacomelli (Total cross section measurements) Progress in Nuclear Physics 12 (1970) 77; (Risonanze barioniche) Nuovo. Cimento Suppl. 6 (1968) 517.

16. U. Amaldi et al. (The energy dependence of the pp total cross section for c.m. energies between 23 and 53 GeV) Phys. Lett. 44B (1973) 112.

S. R. Amendolia et al. (Measurements of the total pp cross section at the ISR, Phys. Lett. 44B (1973) 119.

G. Carboni et al. (Precise measurements of $\bar{p}p$ and pp total cross sections at the CERN-ISR) Nucl. Phys. B254 (1985) 697.

G. Giacomelli and M. Jacob (Physics at the CERN-ISR) Phys. Rep. 55 (1979) 1.

17. W.F. Baker, et al. (Measurement of π^+, π^-, K^+, K^- , p and pbar production by 200 and 300 GeV/c protons) Nucl. Phys. B5l (1974) 303.

18. A. S. Carroll, et al (Total cross sections of p and $\bar{p}$ on protons and deuterons between 50 and 200 GeV/c) Phys. Rev. Lett. 33 (1974) 928; A. S. Carroll, et al (Total cross sections of π^+, π^-, K^+ and K^- on p and d between 50 and 200 GeV/c) Phys. Rev. Lett. 33 (1974) 932.

19. A. S. Carroll, et al (Total cross sections of π^+, π^-, K^+, K^-, p and $\bar{p}$ from 23 to 280 GeV/c) Phys. Lett. 61B (1976) 303.

20. A. S. Carroll, et al (Absorption cross sections of pi$^+$, pi$^-$, K^+, K^-, p and $\bar{p}$ on nuclei between 60 and 280 GeV/c) Phys. Lett. 80B (1979) 319.

21. A. S. Carroll, et al (Total cross sections of pi^{+}, pi^{-}, K^{+},K^{-}, p and $\bar{p}$ on p and d between 200 and 370 GeV/c) Phys. Lett. 80B (1979) 423.
22. G. Giacomelli (Total cross sections and elastic scattering at high energies) Phys. Rep. 23C (1976) 123.
23. M. Bozzo et al. (Measurement of the $\bar{p}p$ total and elastic cross sections at the CERN SPS collider) Phys. Lett. B147 (1984) 352.
24. N.A. Amos, et al. (Measurement of the $\bar{p}p$ total cross section at $\sqrt{s}$=1.8 TeV) Phys. Rev. Lett. 63 (1989)2784; (Antiproton-proton elastic scattering at $\sqrt{s}$=1.8 TeV from -t=0.034 to 0.65 (GeV/c)**2) Phys. Lett. B247 (1990) 127; (A luminosity-independent measurement of the $\bar{p}p$ total cross section at $\sqrt{s}$=1.8 TeV) Phys. Lett. B243 (1990) 158.
25. W. F. Baker et al. (Production of $\pi^{\pm}$, K$^{\pm}$, p and $\bar{p}$ by 400 GeV/c protons) Fermilab – 78/79-EXP (1978).

Ted Kycia and Cerenkov Counters

Roy Rubinstein
Fermilab
Kycia Memorial Symposium, BNL
19 May 2000

I want to thank Brookhaven for providing this opportunity to honor Ted Kycia, a person whom I respected very much, and worked with for about 15 years. I can date quite closely when I first started to work with him. All of us above a certain age can remember where we were on the 22nd of November 1963 when we heard of the death of President Kennedy. I was a Cornell RA in the trailer on the AGS floor setting up the fast logic for an experiment with Ted due to start in a few days; this was the Galbraith et al. total cross section experiment mentioned by Giorgio Giacomelli in the previous talk.

I want to discuss here a particle physics technology in which Ted was pre-eminent but for which he was little known outside of a small circle.

Ted Kycia and Cerenkov Counters

Cerenkov effect discovered 1930s

Use in particle physics started 1950s
(Reviews late 50s)

1960s: New energy range of AGS, PS

Ted started building gas Cerenkov counters ~1960
(also solid, liquid)

1970s: Fermilab, SPS

Study hadron interactions (e.g. total cross sections) with different incident particles π, k, p

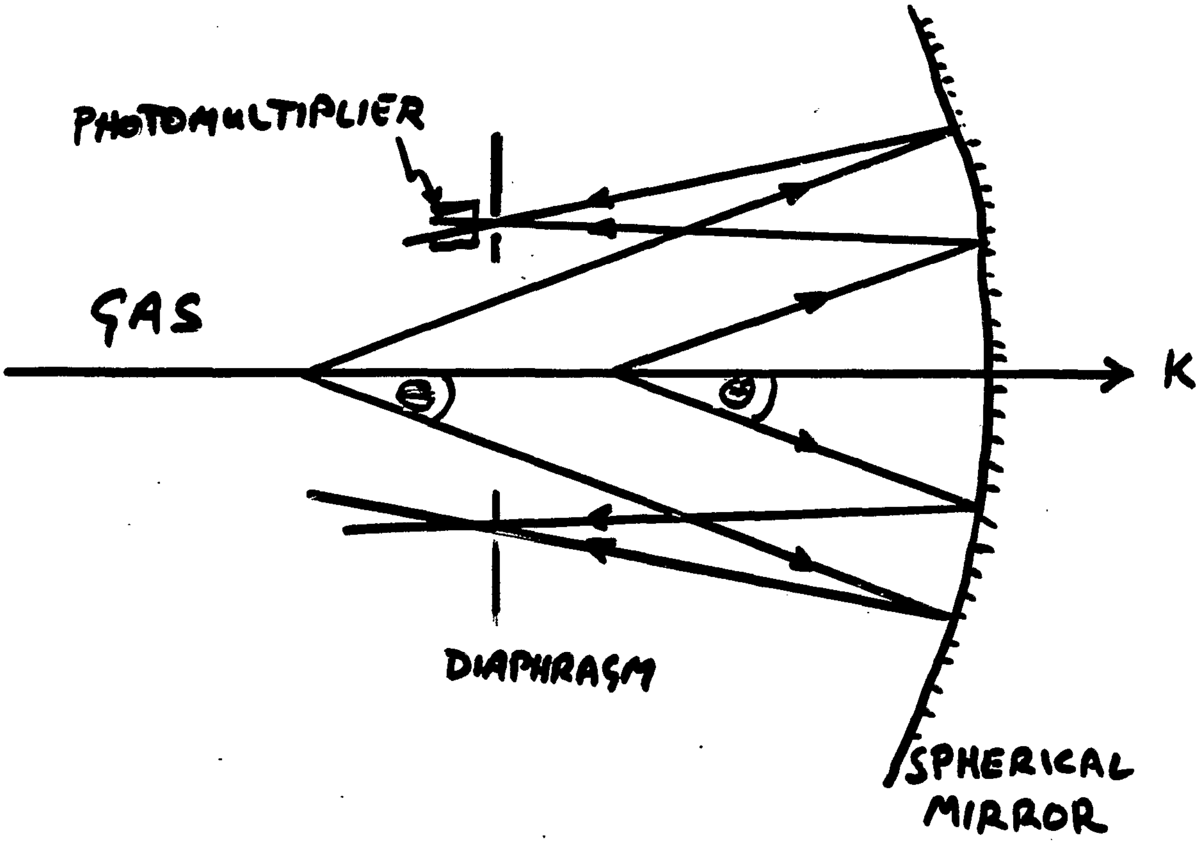
Secondary beam is a mixture of π, k, p of same momentum

Measurement of β of a beam particle gives its type

Use Cerenkov effect to measure β (generally π k separation most challenging)

$$\cos\theta = \frac{1}{n\beta} \qquad \left(\beta > \frac{1}{n}\right)$$

(Fix θ, and vary gas pressure to vary n)



K LIGHT

Ted made 2 design decisions that made his counters the best in the world, and built a series of counters

BUT

Apart from

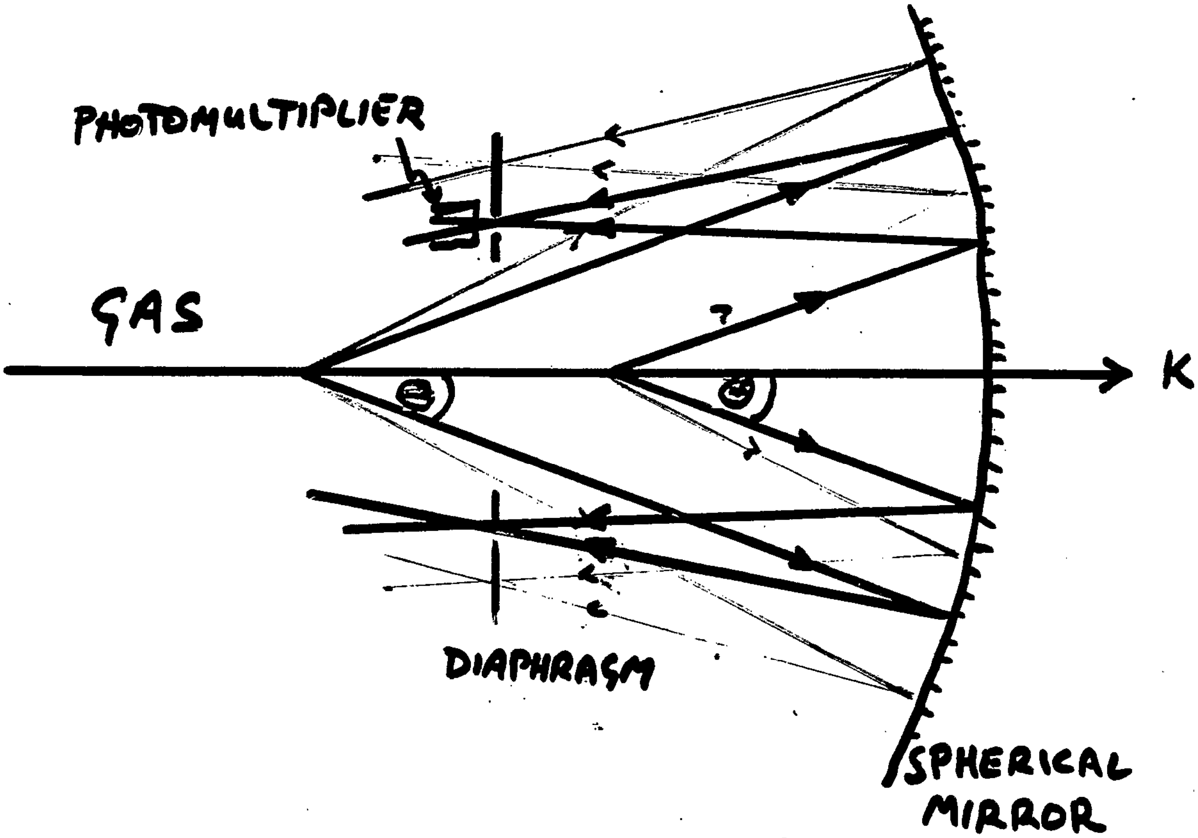
T. F. Kycia and E. W. Jenkins, Nuclear Electronics, Vol. 1, p. 63 (1962)

Ted never published his Cerenkov counter work

(always T. F. Kycia – to be published)

Competition was Robert Meunier (CERN)

Meunier published and also wrote review articles, and generally is quoted in any article on Cerenkov counters.



K LIGHT

π LIGHT

Due to $\triangle p$ beam
$\Delta\theta$ dispersion ($n = n(\lambda)$)
$\Delta\theta$ beam optics (use parallel section)
Multiple scattering in gas, windows, etc.

π and K light can partially overlap at the focal plane

Ted put veto photomultipliers at the π light focus

Veto: might lower efficiency of K
detection a little
would reduce π contamination of K
signal

Efficiency vs purity can be varied
aperture of K diaphragm
threshold for π signal, etc.

Ted may not have been first to use vetos in this way, but all of his counters had them, and very few counters of other people did

Because of the vetos, Ted achieved higher purity signals

T.F. KYCIA + E.W. JENKIN
1961/2

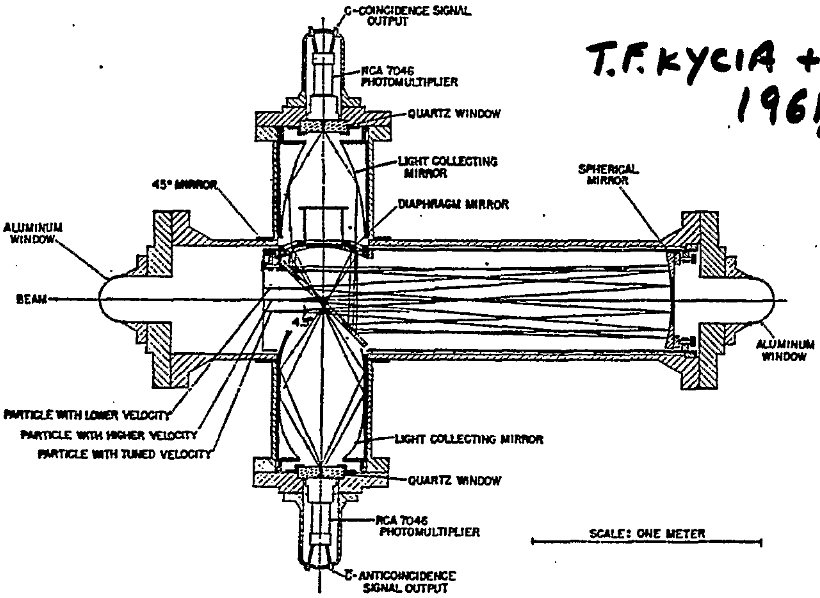


FIG. 3. Čerenkov counter optical system.

about a fixed angle of 4.5° is focused by a spherical mirror into a ring image at an annular slit. The Čerenkov light which passes through this defining aperture is focused upon a 5-in.-diam photomultiplier tube (RCA 7046). The defining annular slit itself is cut into an ellipsoidal mirror. Light which arrives outside the slit is refocused by this mirror onto another 5-in.-diam photomultiplier tube. The signal-to-noise ratio is improved by requiring, with tunnel-diode discriminators, a large pulse from the light passing through the slit (the coincidence channel C) and only a small pulse from the light which appears outside it (the anticoincidence channel $\bar{C}$). Typically the background due to knock-on electrons, off-axis and off-momentum particles, and other sources is reduced by more than an order of magnitude in this way.

The counter is filled with CO_2 gas and can be operated at pressures as high as 1000 psig. The CO_2 radiator is 3 m in length and 18 cm in useful diameter. It yields at least 25 photoelectrons in the coincidence channel. A range of relative velocities $\beta=v/c$ from 0.98 to 1.0 is covered by varying the gas pressure and thus the index of refraction according to the relation $\cos\theta=1/n\beta$, where n is the index of refraction and θ is the Čerenkov angle which is fixed at 4.5°.

The counter is designed to resolve particles whose relative velocities differ by as little as $\Delta\beta=2\times10^{-4}$ at momenta greater than 18 BeV/c. An example of a resolution curve at a momentum of 18 BeV/c is shown in Fig. 4; the velocity difference between the K^+ and [illegible] peaks correspond to $\Delta\beta=3.6\times10^{-4}$. In the momentum range of a few BeV/c, multiple scattering in the counter windows and gas appreciably broadens the ring image. The width of the annular slit can be changed to accommodate the full image size.

C. Electronics

Figure 5 is a block diagram of the electronics. The transistorized coincidence circuits, discriminators (DISC), and fanouts were designed by Sugarman *et al.*[18] The discriminator makes use of 20-mA tunnel diodes (Z 61–22), and its operation is stable for input pulses from 2 to 20 mA.

The counters ($S_4S_5S_6S_7$) were circular plastic scintillators 0.5 in. thick of various diameters. They were viewed by RCA 6810 A photomultiplier tubes. The high voltage was supplied at each tube base by a radio-frequency oscillator, transformer, and rectifier.[18] The outgoing pulses were limited at the tube base to ~6 mA.

The coincidences ($S_1S_2S_3$) and ($S_1S_2S_3C\bar{C}$) were recorded. ($S_1S_2S_3$) gives the total number of charged particles; ($S_1S_2S_3C\bar{C}$) gives the number of particles of the selected mass value (e.g., K mesons). The final counters $S_4S_5S_6$ were of graduated sizes with S_4 the smallest, S_6 the largest. Their purpose was to obtain the variation of the total cross section measured at different small angle cutoffs in order to extrapolate to zero angle. For this purpose the coincidences ($S_1S_2S_3C\bar{C}S_4$), ($S_1S_2S_3C\bar{C}S_5$), and ($S_1S_2S_3C\bar{C}S_6$) were recorded. Since, according to the optical model, the width of the diffraction peak is inversely proportional to the momentum, the sizes of counters S_4, S_5, and S_6 were selected as appropriate to the momentum.

During the experiment the internal targeting conditions were sometimes erratic which gave large variations

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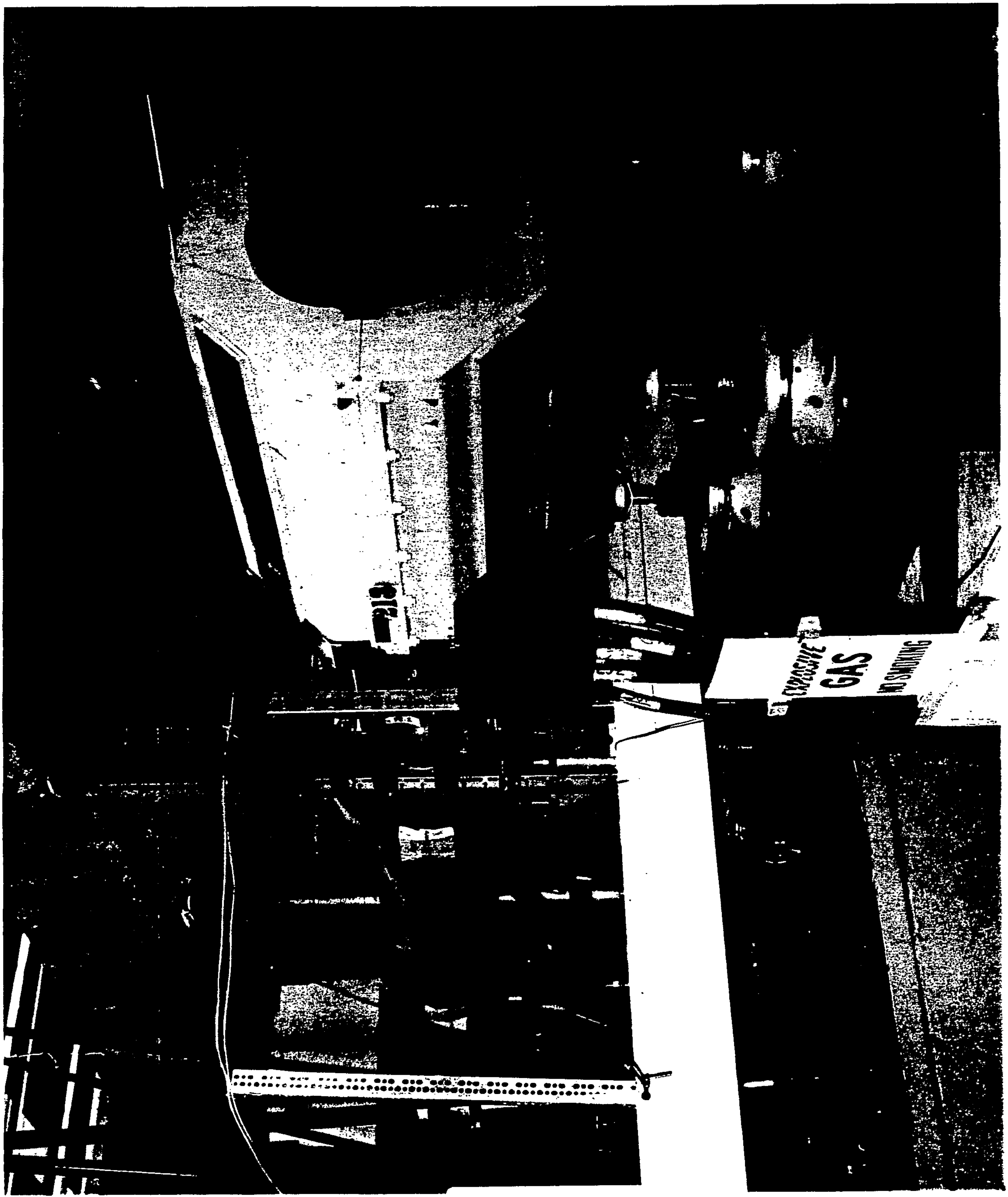
[18] R. Sugarman, W. A. Higinbotham, F. C. Merritt, and A. H. Yonda, Brookhaven National Laboratory Report BNL-5390 (unpublished); R. M. Sugarman and W. A. Higinbotham, *Proceedings of the International Conference on Instrumentation for High-Energy Physics* (Interscience Publishers, Inc., New York, 1961), p. 54.

1964



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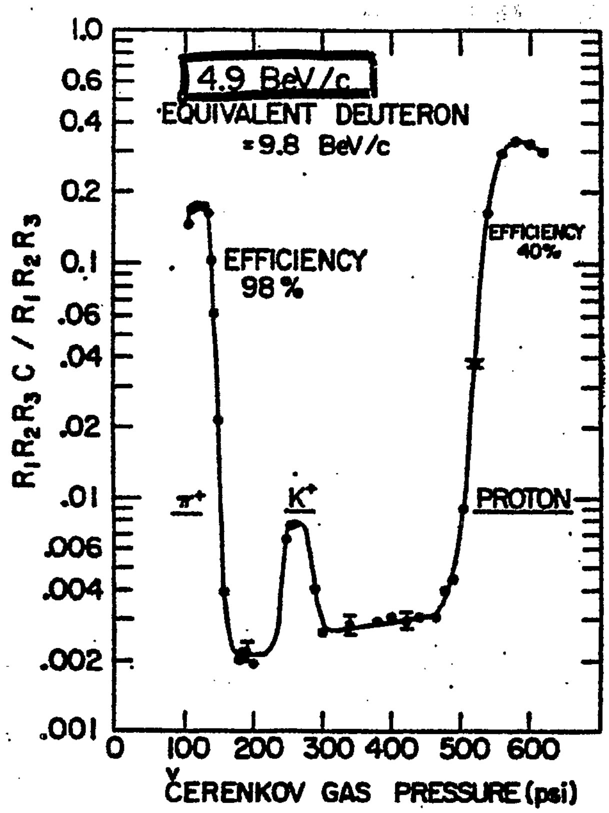


FIG. 3. Čerenkov counter pressure curve for the 11.6-BeV/c measurement.

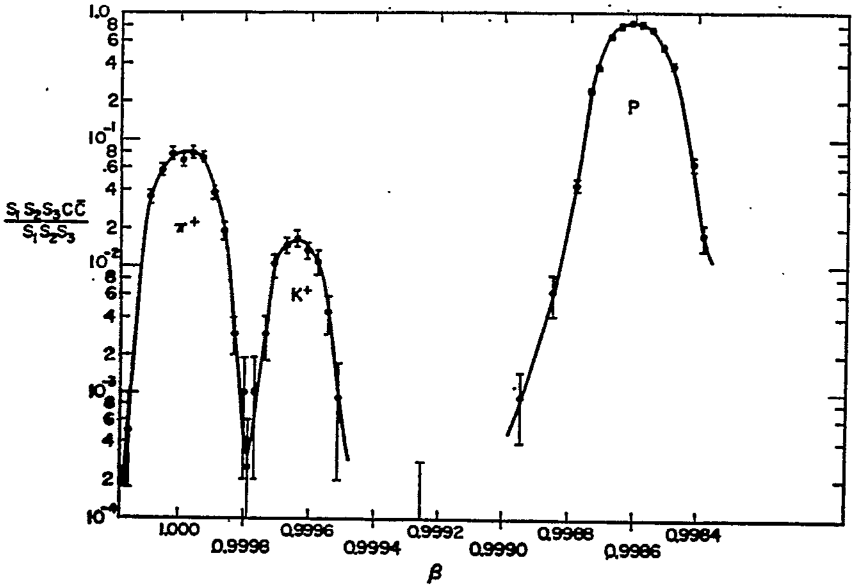
4½° COUNTER

NO VETO

1963

the fraction of protons removed from the beam. In the worst case, the 11.6-BeV/c experiment, proton loss amounted to 43% at a CO_2 pressure of 605 lb/in^2, or 30 g/cm^2 of CO_2 in the beam. The proton loss was determined by measuring R_{123}/R_{12} as a function of the gas pressure, and was checked with the result expected from known proton-nuclear total cross sections.

We would expect the effective deuteron loss factor to be significantly worse since the cross section for deuterons on carbon and oxygen is larger than for



4½° COUNTER

FIG. 4. Performance of Čerenk counter at 18 BeV/c. This cu was taken by varying the gas pr sure and measuring the fractio the beam counted by the Čeren counter.

in the instantaneous counting rates. For this reason, an additional coincidence channel was provided to record ($S_1S_2S_3C\bar{C}$) (S_6 delayed) where the delay inserted in the S_6 channel was 217 nsec which corresponded to the time difference between successive rf beam bunches within the accelerator. In this way the accidental coincidence rate could be continuously monitored and an accurate correction made.

An auxiliary 1-in.-diam counter S_7 was placed just behind S_6. It could be moved by remote control horizontally or vertically in a plane perpendicular to the beam axis. Coincidences ($S_1S_2S_3C\bar{C}S_7$) were then used for beam alignment and for measuring the size of focal spot of the beam. Similarly, the coincid ($S_1S_2S_3C\bar{C}S_iS_7$) was used to check periodically efficiency of counter S_i for $i=4$, 5, and 6. The me efficiency of the counters and their associated elec circuits was greater than 99%.

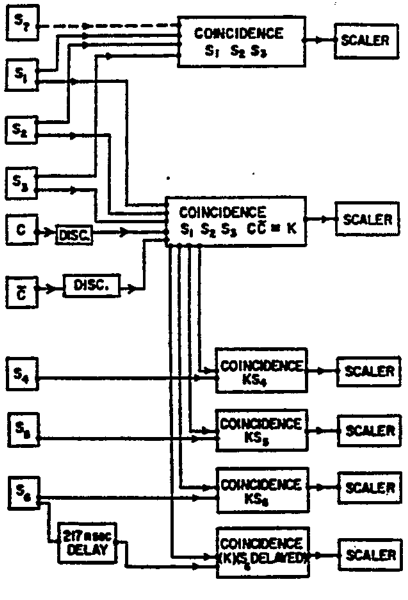


FIG. 5. Block diagram of the electronics.

D. Hydrogen Target

The hydrogen target was 120 in. long and 11 diameter. The windows at each end of the targ 1.42 g cm^{-2} Al; the hydrogen was 21.3 g cm^{-2}. A d target was used for target-empty runs.

III. EXPERIMENTAL PROCEDURE

The mean momentum values were obtained fr accurately measured integral field excitation cur magnet D and the geometry of the appara values were checked by measuring the velocity of particles with the Čerenkov counter C. The va $\Delta p/p$ were obtained from calculations using th sions of the pertinent aperture stops.

The magnet currents required in the qu lenses were calculated[16] in advance for a suita tion of momenta. Final adjustments of the cu quadrupoles Q_1 and Q_2 were made by maxim efficiency of the counter C at a few momenta. T these currents could be set satisfactorily by sc the measured magnet excitation curves.[19] The justment of Q_3 and Q_4 was made at a few measuring directly the size of the focal spot wi S_7 (see Sec. II C). Thereafter, a satisfactory was found to be an adjustment of current

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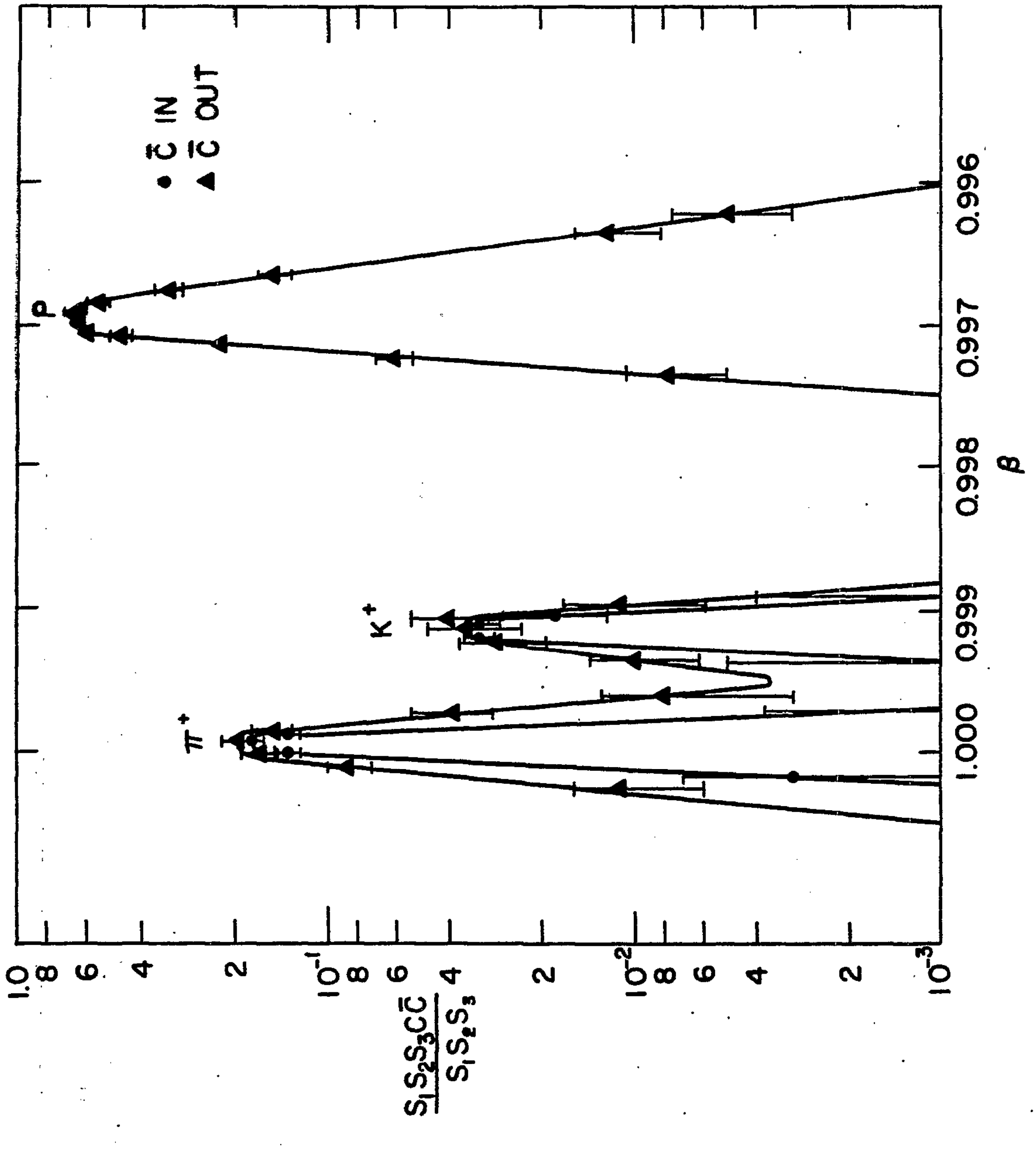
[19] G. T. Danby, Brookhaven National Laborato Department Internal Report GTD-2 (unpublished).

TABL

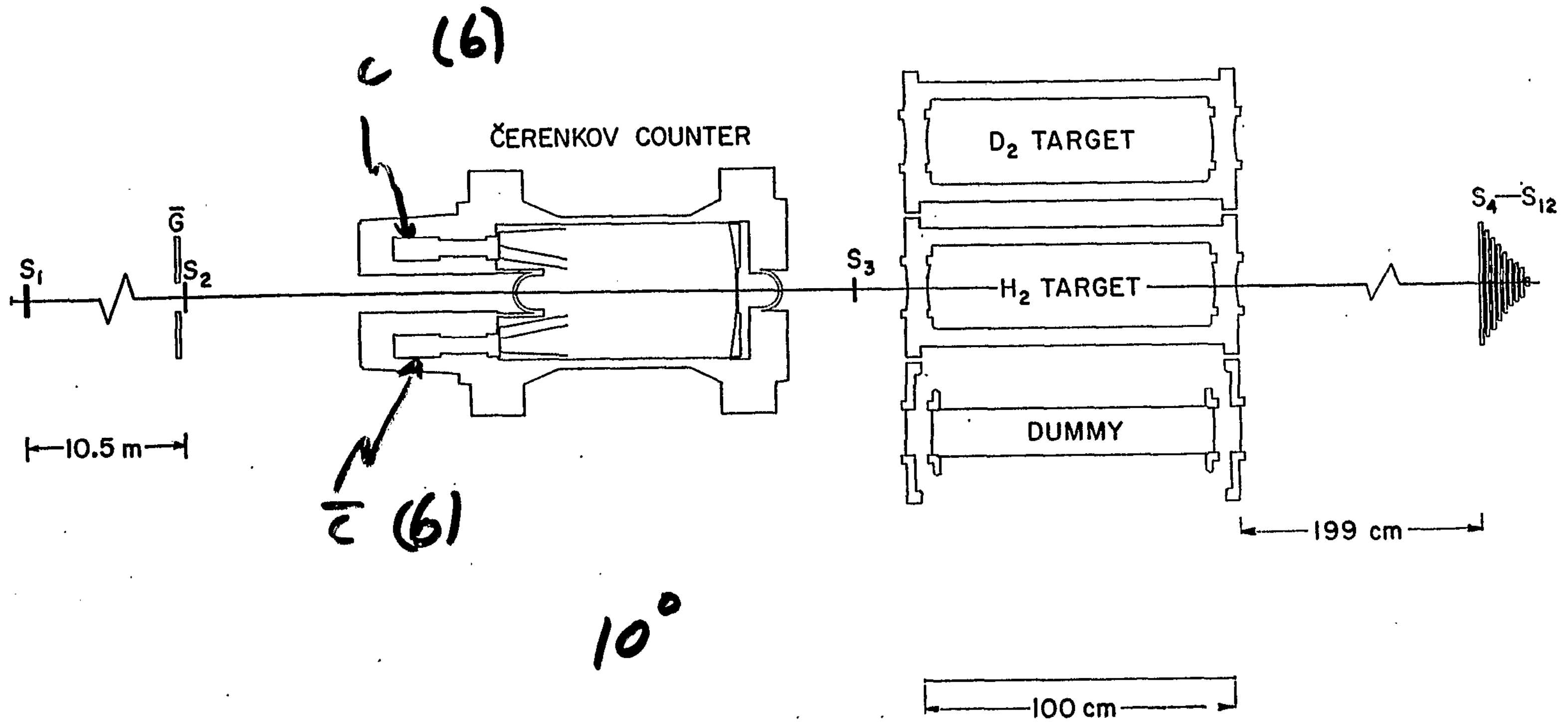
Momentum (BeV/c)
3.25
4.0
5.5
7.0
8.5
10.0
10.9
11.5
12.5
13.4
15.0
16.9
19.0

Corrected addi

11'

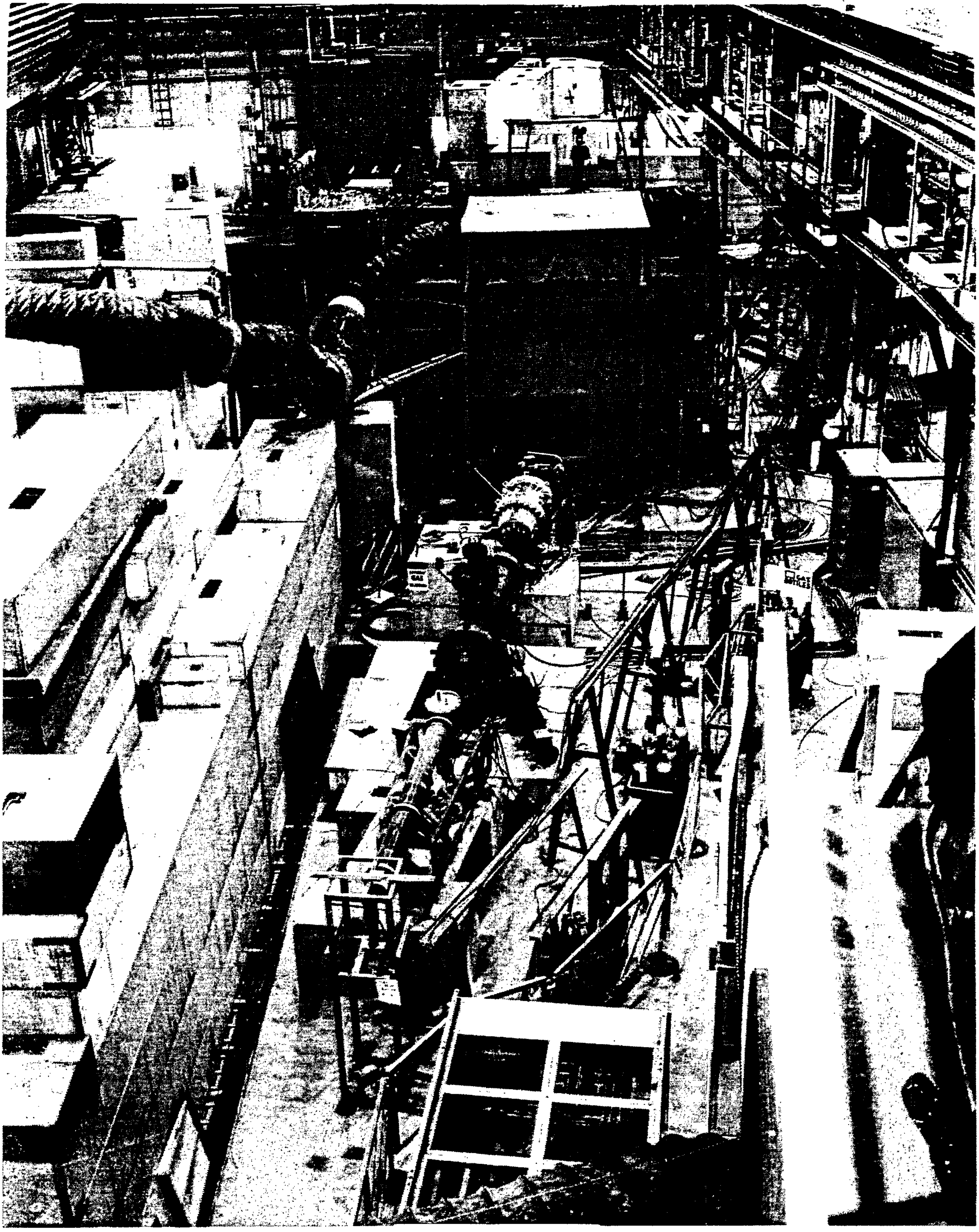

● C̄ IN
▲ C̄ OUT
π⁺
K⁺
P
β
1.000
0.999
0.998
0.997
0.996
$\frac{S_1S_2S_3C\bar{C}}{S_1S_2S_3}$
1.0
8
6
4
2
10^{-1}
8
6
4
2
10^{-2}
8
6
4
2
10^{-3}

LOW MOMENTUM
~ 2000 Psi
CONICAL REFLECTORS
+ DIAPHRAGM



10°

FIG. 2. Layout of the experimental apparatus. S_1, S_2, S_3, and $\bar{G}$ are scintillation counters defining the beam. The gas differential Čerenkov counter is shown; it was replaced by a liquid differential Čerenkov counter for some measurements at lower momenta. H_2, D_2, and the dummy are the liquid hydrogen, liquid deuterium, and dummy targets, respectively. S_4–S_{12} are the transmission counters.

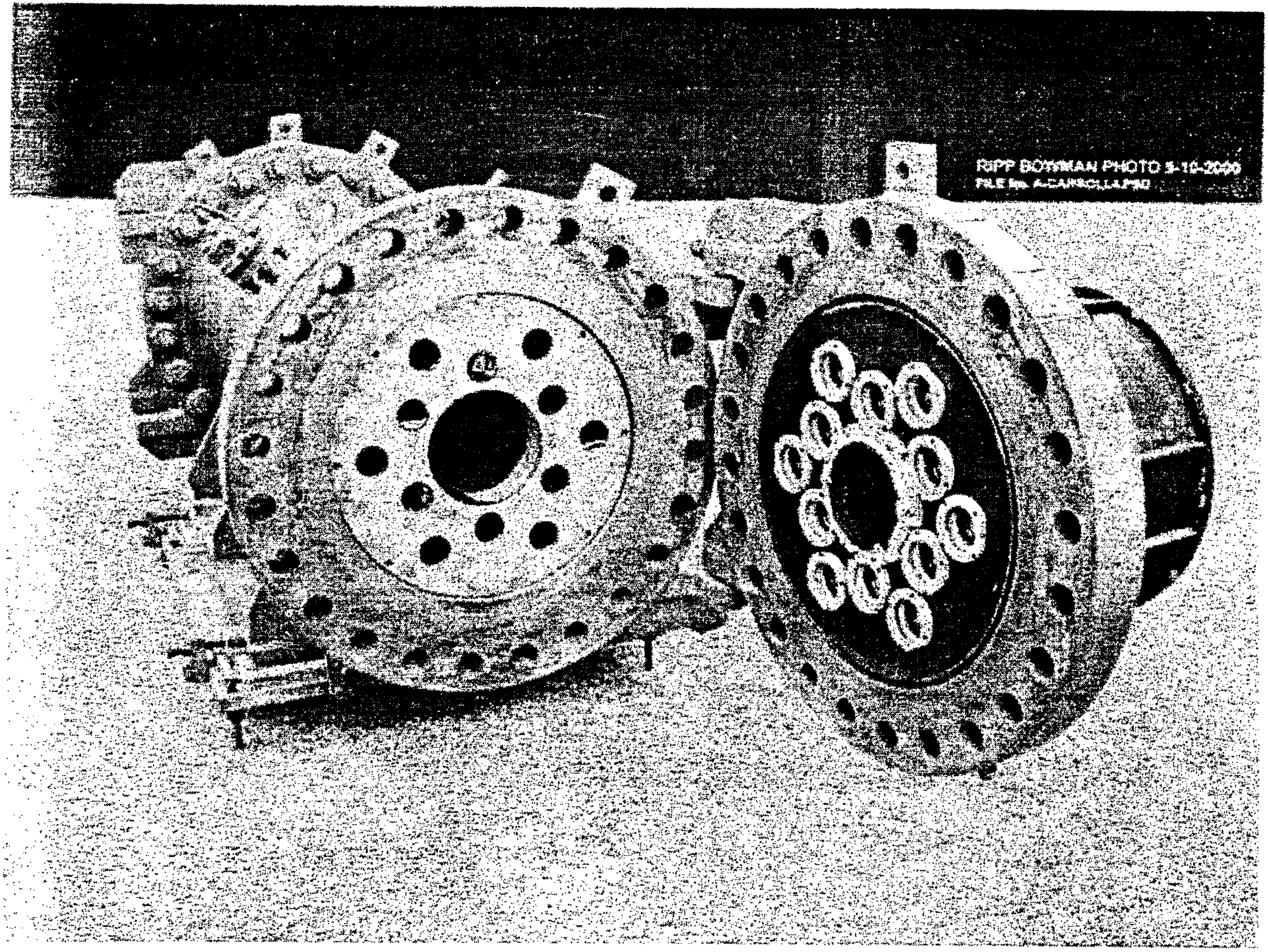


1967

Ted stayed with the 6 coincidence, 6 veto design, with optics as in the 10° counter.

A counter for a different momentum range would have a different Cerenkov angle

In late 1960s, Ted built 2 more counters for the AGS, to replace the original 4 ½° counter (4 ½°, 2 metres)



RIPP BOWMAN PHOTO 5-10-2000
FILE No. [illegible]

1970s – Fermilab, SPS

Ted built counters for Fermilab
Meunier built counters for Fermilab and CERN

Two different philosophies

$$\cos\theta = \frac{1}{n\beta}$$

$$N = AL\sin^2\theta$$

$$\Delta\theta \ \textit{dispersion} \approx K\theta \quad \begin{pmatrix} \textit{cerenkov light spectrum} \\ n = n(\lambda) \end{pmatrix}$$

Ted: **small Cerenkov angle**
$\therefore$ long length; small dispersion

Meunier: **Large Cerenkov angle**
$\therefore$ short length; must correct for dispersion (complex optics)
(no vetos)

Ted (Fermilab M1 beam)

	16 metres	15 mr
	32 metres	7.5 mr
Combine:	48 metres	5 mr

Meunier (Fermilab M6 beam)

5 metres	25 mr

Ted's counters required more beam length

Meunier's counters required a more parallel beam, and were more complex optically

BNL AUI
BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC. UPTON, L.I., N.Y. 11973

TELEPHONE: (516) 345-3706

May 21, 1976

Dr. Lincoln Reed
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

Dear Linc,

The function of the High Resolution Gas Differential Cerenkov Counter was to identify secondary particles in the M_1 beam line in the FNAL Meson Laboratory. The M_1 beam line and the Cerenkov counter were designed to be compatible. In particular, the angular divergence of the beam in the "parallel section" dictated the maximum Cerenkov angle for adequate separation at the, then, maximum momentum of 180 GeV/c. The Cerenkov angle was chosen to be 11.5 milliradians for which a radiator length of 55 feet was required. We wanted to have two Cerenkov counters for identifying two types of particles in the "parallel section" so the length of the parallel section became 120 feet long.

Just before the Cerenkov counter design began, it became very clear that the maximum momentum of the particles in that beam will greatly exceed 200 GeV/c. The situation was further complicated by the fact that Klaus Pretzl increased the maximum angular divergence in the "parallel section" from ± 0.2 to ± 0.28 milliradians.

If the two Cerenkov counters were to be combined into one and the Cerenkov angle reduced by a factor of two, there would be insufficient light output (which varies inversely with the square of the Cerenkov angle). I, therefore, changed the Cerenkov angle to 15.66 milliradians for one counter which then gives us 7.61 milliradians when the counters are bolted together. Only the spherical mirror needed to be changed inside the counter.

Enclosed you will find a Xerox copy of a table showing the contribution to the resolution $\Delta\beta/\beta$ from the effect of dispersion in helium for MODE 1 (for separate counters where $\theta_c = 15.66$ mr) and MODE 2 (for joined counters where $\theta_c = 7.61$ mr). Notice that the difference between the two contributions varies as the inverse square of the Cerenkov angle. Therefore the effect of dispersion for my 7.61 mr combination is a factor of 10 smaller than for Meunier's DISC counter with its $\theta_c = 24.5$ mr. The need for chromatic correction therefore vanishes. In any kind of a practical beam with high intensities the main thing to worry about is the angular divergence, also shown in the table. It doesn't vary with momentum and is the main source of the width of the peaks on the pressure curve, and hence the resolution. It's clear that the $\theta_c = 7.61$ mr is adequate for separating K mesons from π mesons even at 450 GeV/c if the angular divergence is reduced by a factor of three from what currently exists in the M_1 beam line. The Cerenkov angle need not be reduced to reduce the effect of dispersion at current Fermi Lab energies. It would need to be reduced only if the beam angular divergence is not to be reduced. Another advantage of my design over Meunier's is that I can tolerate a factor of 10 higher $\Delta\theta_H \times \Delta\theta_V$ in the beam for the same resolution. In other words, he needs a much more parallel beam.

So as far as β resolution goes for separating K mesons from π mesons, for $\theta_c = 7.61$ mr it is only a function of beam angular divergence. For $\theta_c = 15.66$ mr it is a function of angular divergence up to ≈ 300 GeV at which point the dispersion effect enters in.

The effect of momentum spread in the beam and multiple scattering on the resolution can be ignored.

The Cerenkov counter pressure vessel and quartz photomultiplier windows were designed to operate at a maximum pressure of 300 p.s.i. I decided on that high pressure mainly in order to have a rigid structure that would not be affected by temperature and pressure changes. High pressures usually are required at low momenta where high resolution is not necessary and so one can switch to a gas such as CO_2.

There are 6 photomultiplier tubes on each of the coincidence and anti-coincidence rings. Enclosed is the optics diagram of the Cerenkov counter at the photomultiplier tube end as well as the diagram for a single counter. Adjascent pairs of the 6 coincidence photomultipliers are added with resistive mixers, amplified, and a three-fold coincidence required. The 6 anti-coincidence outputs are added with resistive mixers, amplified, and put in anti-coincidence with the three-fold coincidence.

Twelve RCA C 31000 M photomultipliers and twelve RCA 8575 photomultipliers were to be used on the two counters, the former on the coincidence channel and the latter on the anticoincidence channel. We couldn't get delivery on the C31000 M's and so the original running was all done with RCA 8575's. Enclosed are copies of pressure curves taken at 100, 150 and 200 GeV/c, all taken with RCA 8575's. The resolution was adequate and the efficiency exceeded 90%.

When I bolted the two counters together we scrounged up six C 31000 M's at Fermilab and put them on the coincidence side, with RCA 8575's on the anti-coincidence side and took the enclosed pressure curve at 280 GeV/c. The primary proton momentum was 300 GeV/c.

The counting rates are limited by the photomultiplier base design and discriminator. We could operate at 10^6/pulse. Val Fitch is running with one of my old counters at the AGS on antiprotons. The $\bar{p}$ level is at a level of

10^5 - 10^6/pulse and π^- level at 10^7 - 10^8/pulse. Under circumstances such as these the anti-coincidence channel could not be used. The background between peaks could be increased by a factor of 10. This should almost never be a problem at Fermilab because the rates π mesons are not at that level at the highest momenta where high resolutions are required. I should point out that the resolutions at 100, 150 and 200 GeV/c would now be better than shown on the pressure curves with the C 31000 M's, all twelve of which are presently in the counters.

Each counter weighs about 5000 pounds. You might notice that there is a long extension pipe on the upstream end of the Cerenkov counter just to give it a longer radiator length. In tandem use the counter weighs about twice as much. The two extension pipes are bolted together on the upstream end of the counter.

Some of the other numbers that you may wish to have are:

Focal lengths of spherical mirrors; 409.4 inches and 842.82 inches.

Inside radius of pressure vessel; 9.625 inches.

Pressure vessel wall thickness; 0.375 inches.

I should stop at this point and if you have any more questions I shall respond to them. Regards,

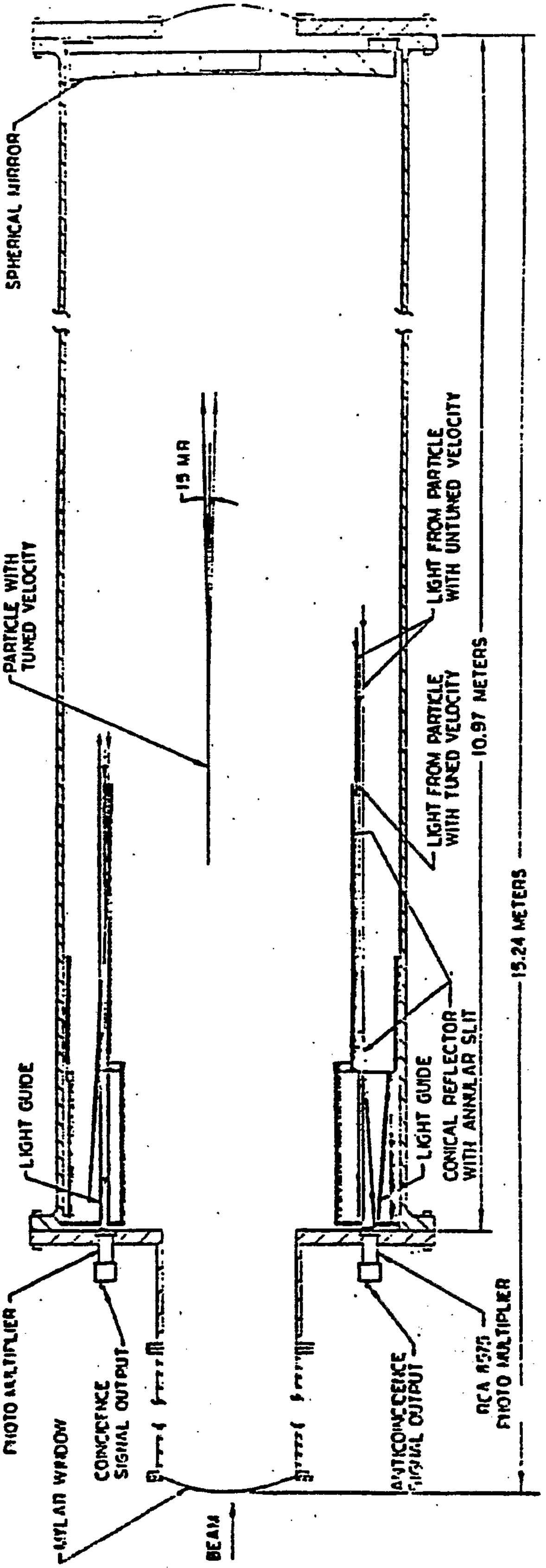
Sincerely yours,

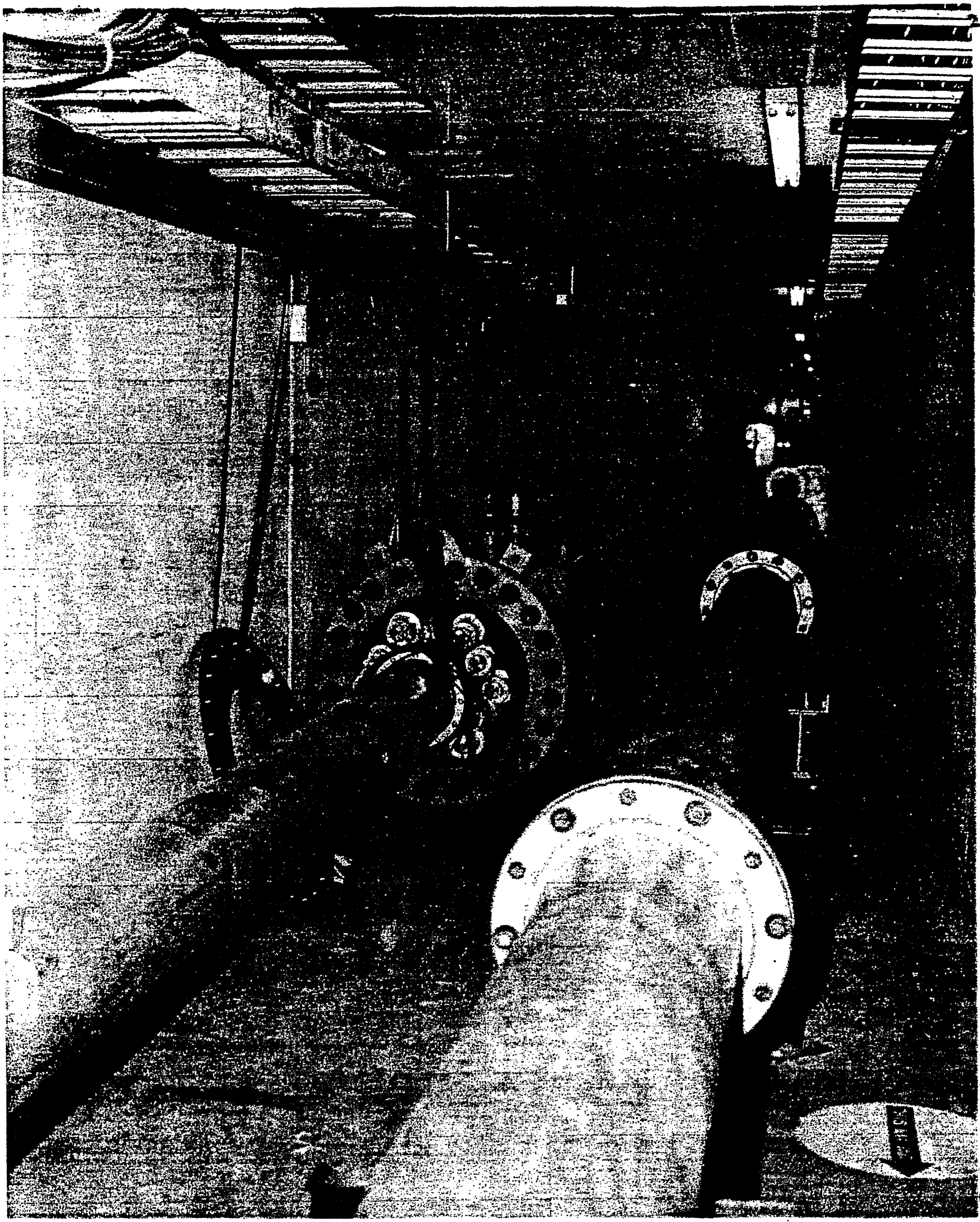
Ted

T. F. Kycia

Encls.

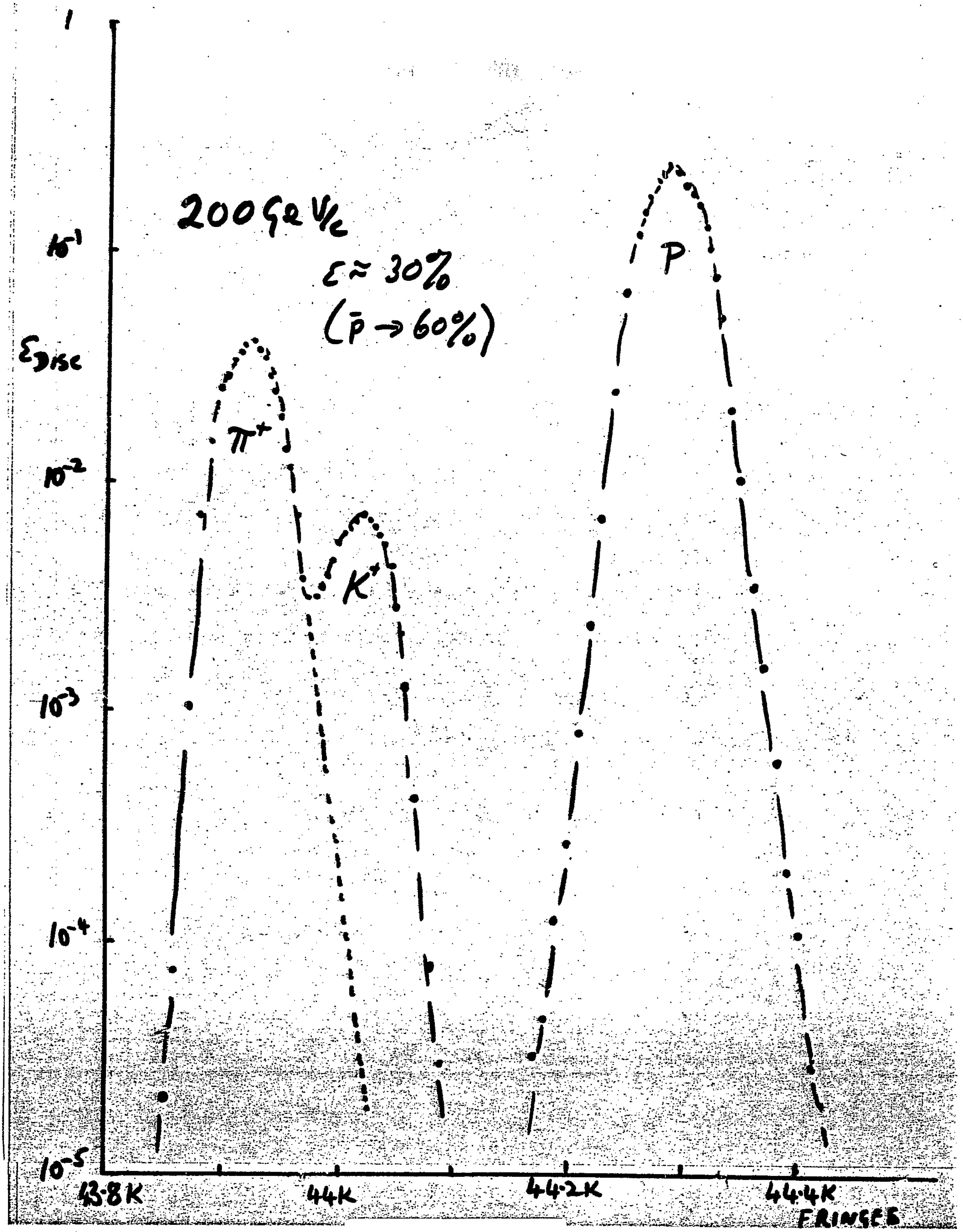
DIFFERENTIAL CERENKOV COUNTER





14-377-11

1981
MEUNIER COUNTER



48metres

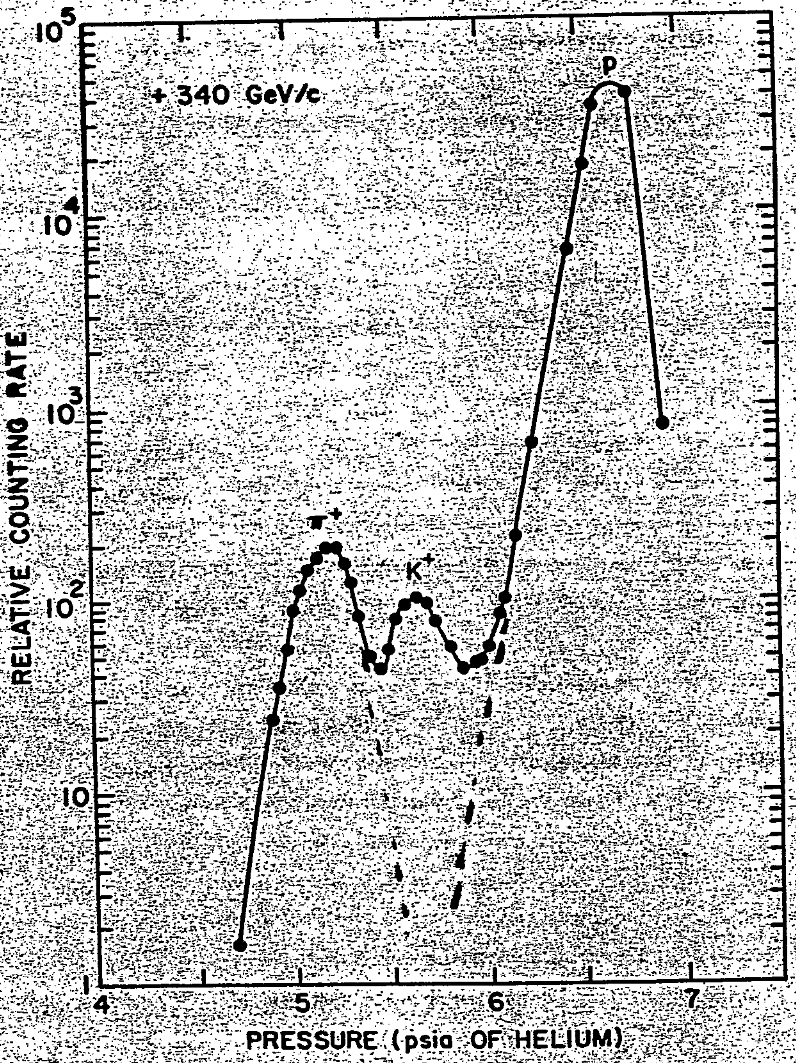
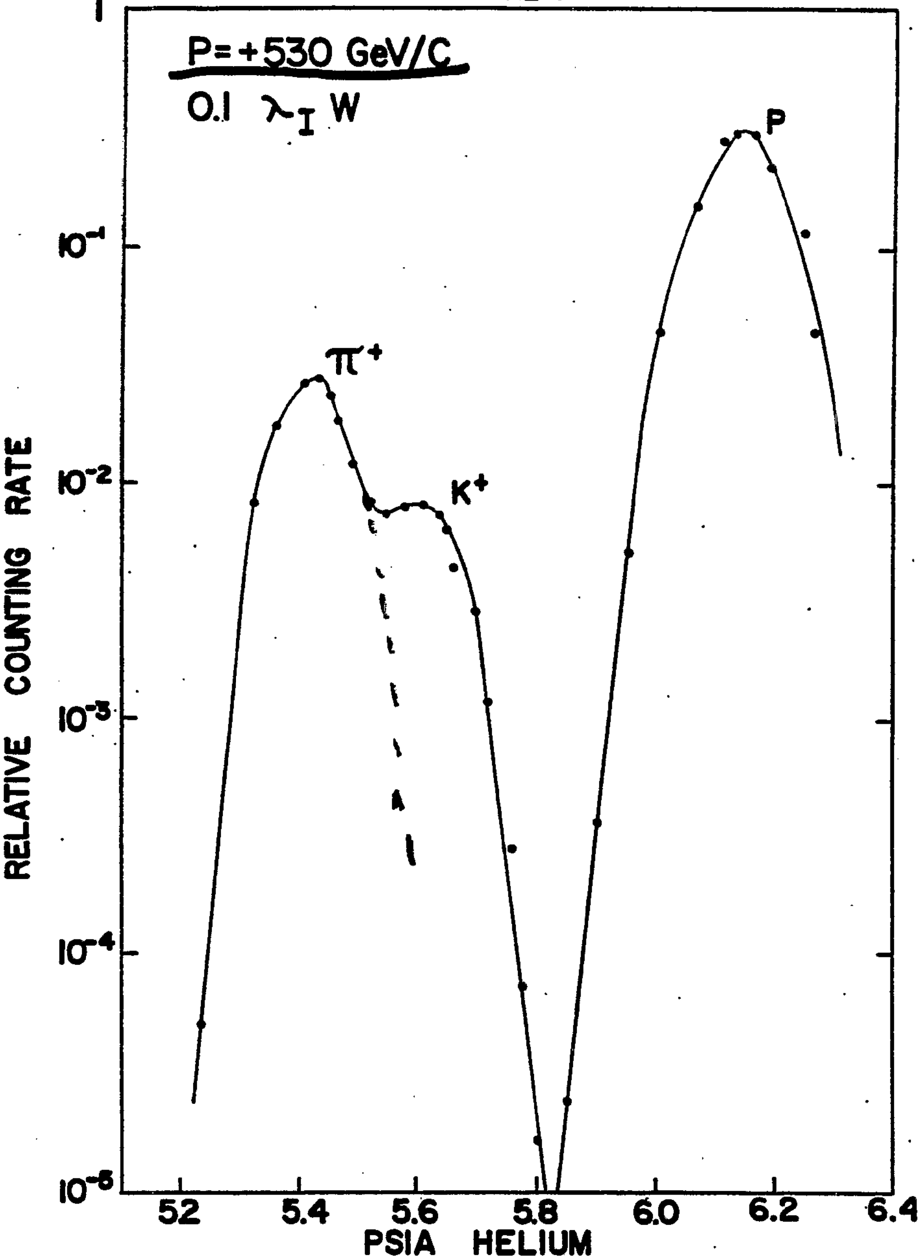


Fig. 1. Pressure curve obtained with the gas differential Cerenkov counter at +340 GeV/c.

~1978

48metres

FIGURE 1



1988

Summary

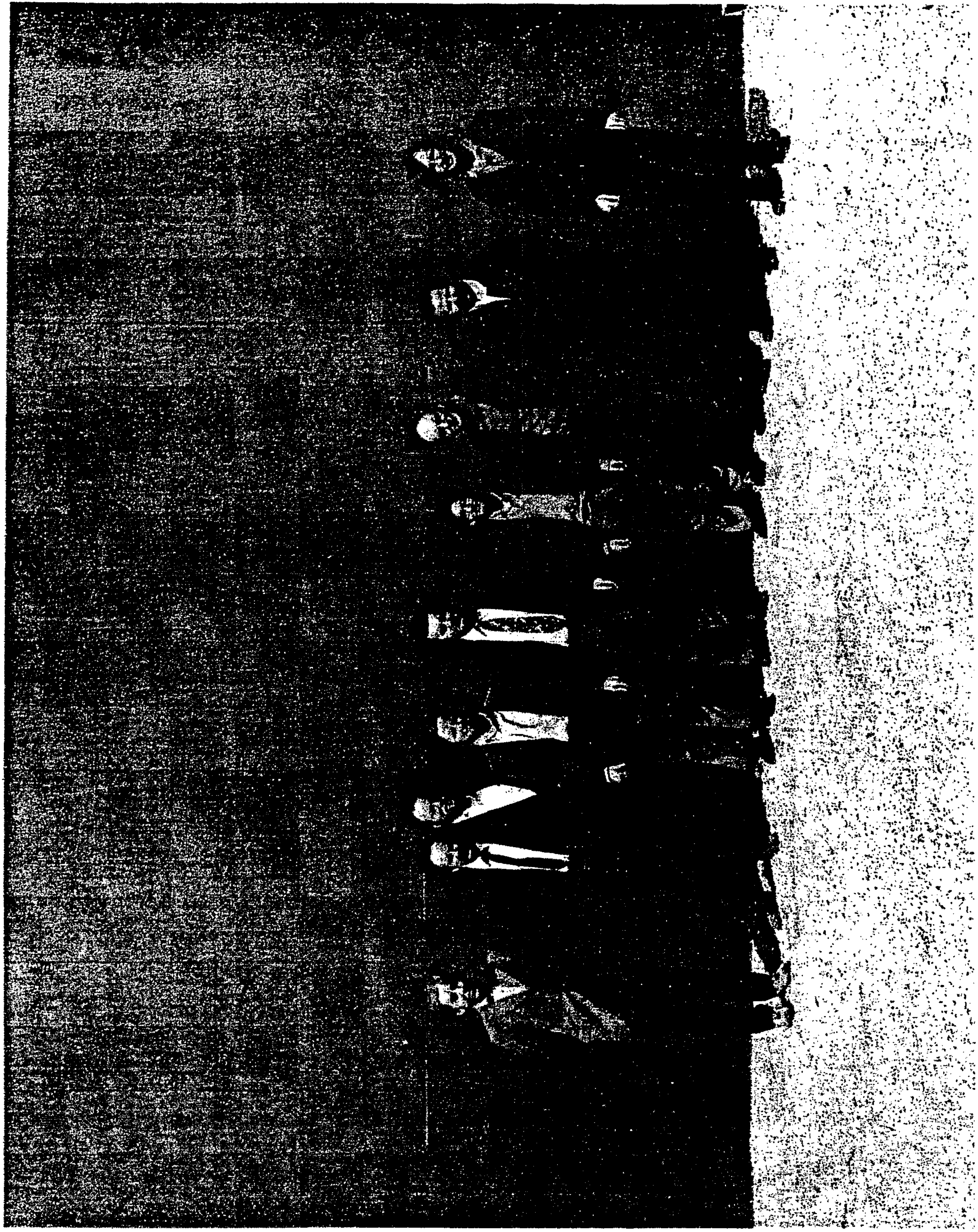
Ted pushed the use of veto photomultipliers and small Cerenkov angles, unlike most other people

He did not publish or publicize his counters, so their excellent performance only known to a limited number of colleagues and afficionados

But

He built the world's best beam Cerenkov counters

1-377-492



A Brief History of the Our Search for CP Violation in $K^{\pm} \rightarrow \pi^{\pm} \pi^{0} \gamma$ and Other Interesting K Decays

P.M. Mockett
Kycia Symposium
Brookhaven National Lab
19 May 2000

- My colleagues on this experiment along with Ted Kycia were R. J. Abrams, A. S. Carroll, K. K. Li, J. Menes, D. N. Michael and R. Rubinstein.

- Special thanks for their assistance were given to C. Anderson, J. Fuhrmann, G. Munoz, H. Sauter, F. Seir and O. Thomas.

- We also elicited the help of the BNL bubble chamber group headed by R. Shutt and N. Samios.

Decay Modes Studied

Direct Term and CP Violation (Physical Review Letters)

$$K^{\pm} \to \pi^{\pm} \pi^{0} \gamma \to \pi^{\pm} 3\gamma$$

Test of K Decay Models (Physical Review D)

$$K^{\pm} \to \pi^{\pm} 2\gamma$$

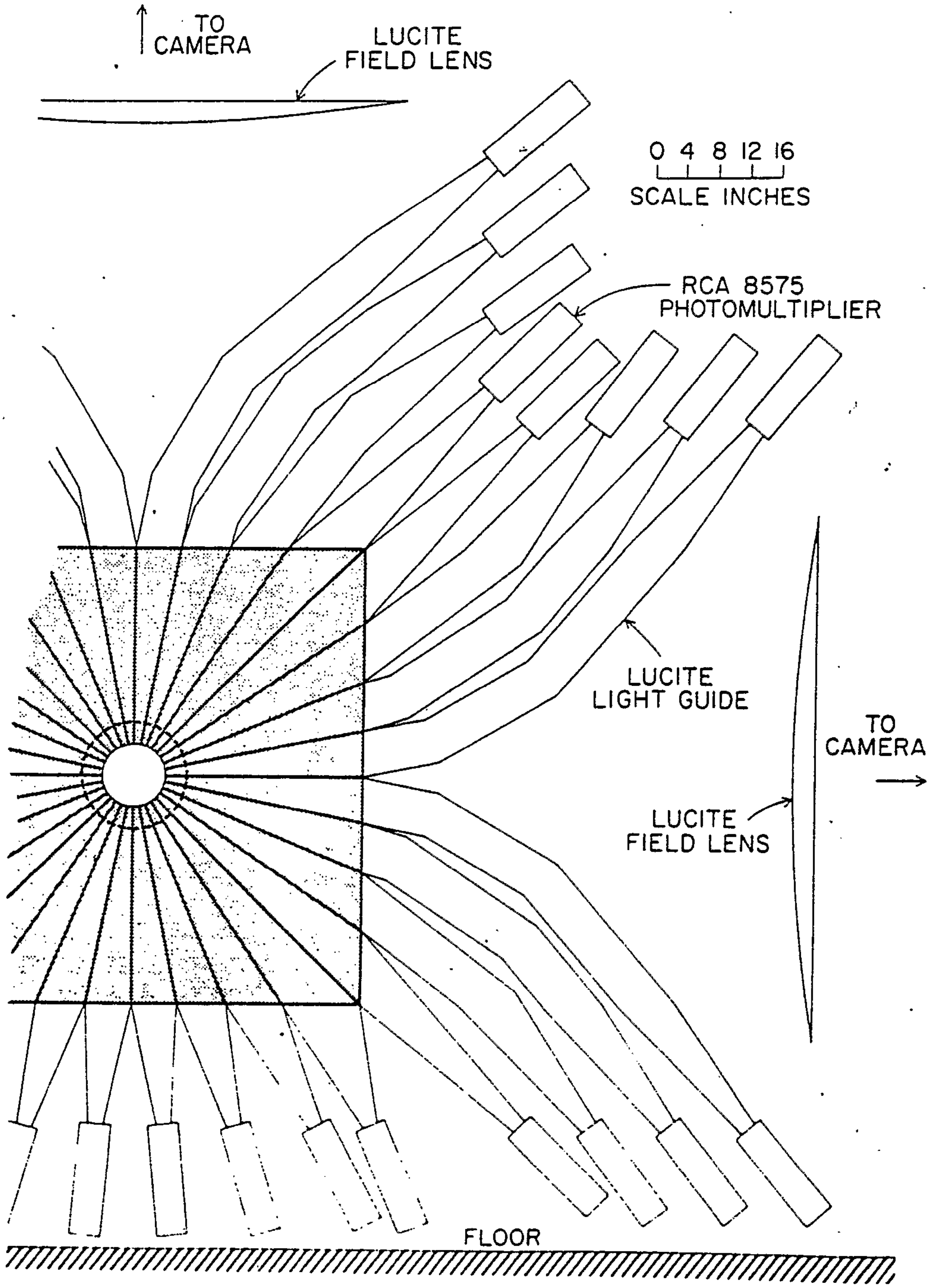
Search For the Rare Decay (Physics Letters)

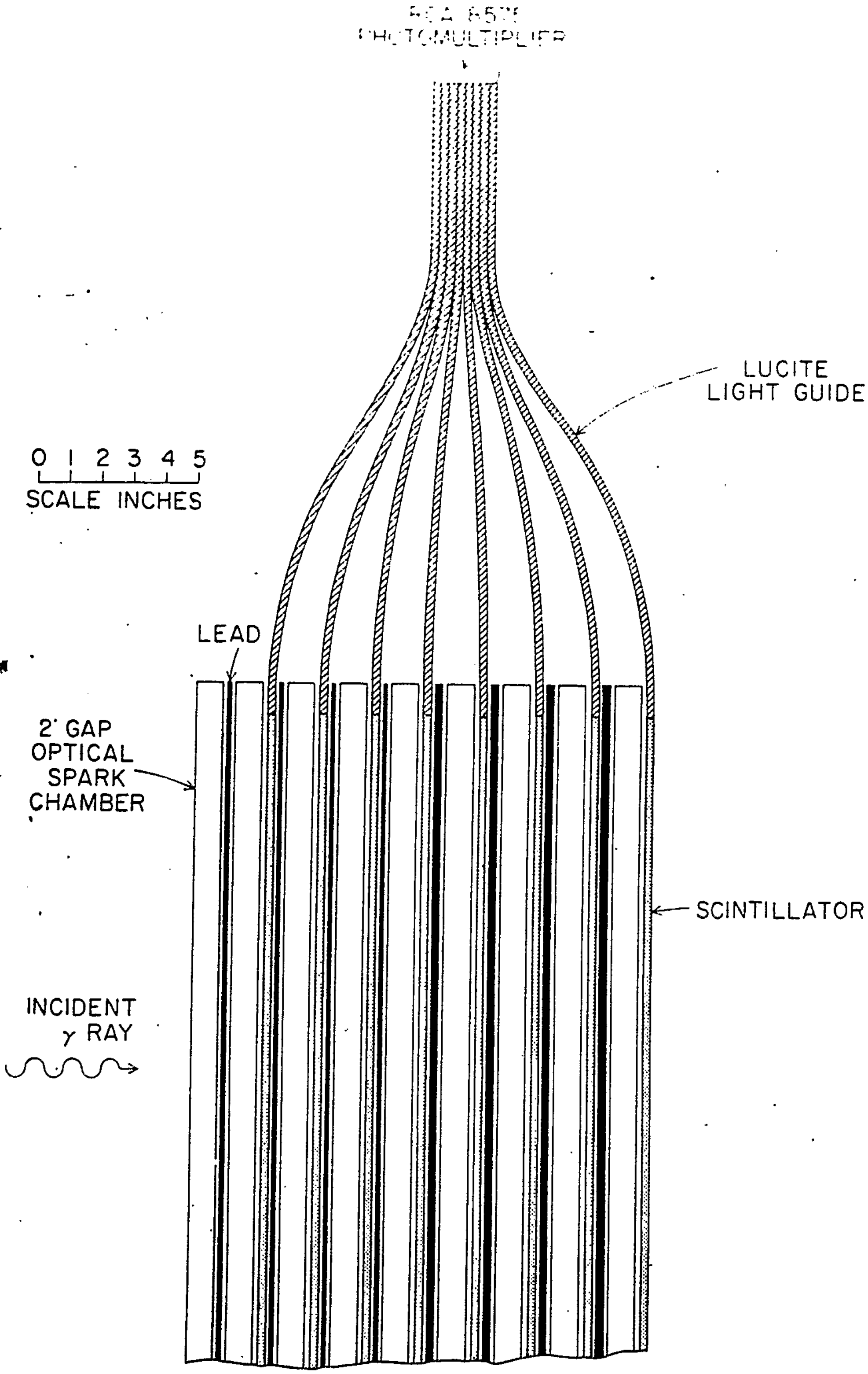
$$K^{\pm} \to \pi^{\pm} \pi^{0} \to \pi^{\pm} 4\gamma$$

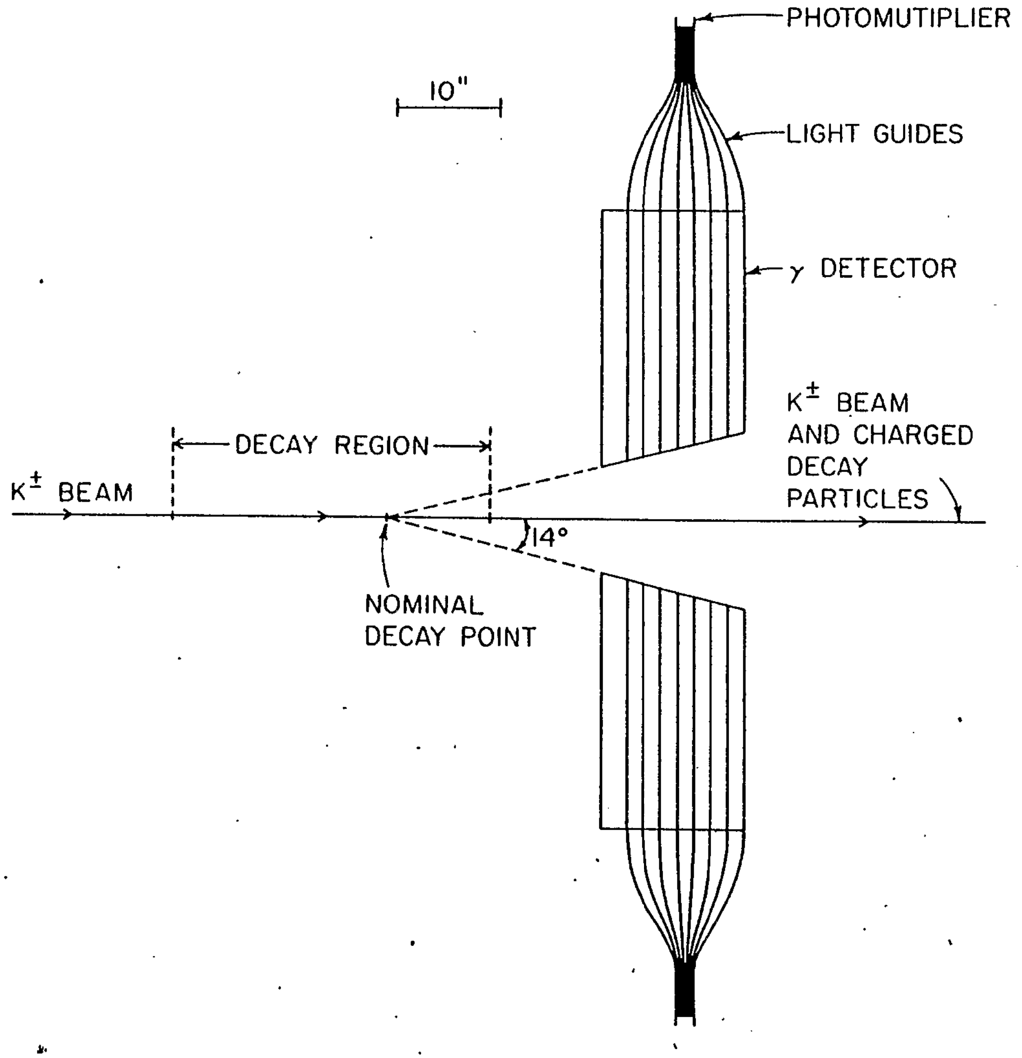
Kaon Form Factors (Physical Review D)

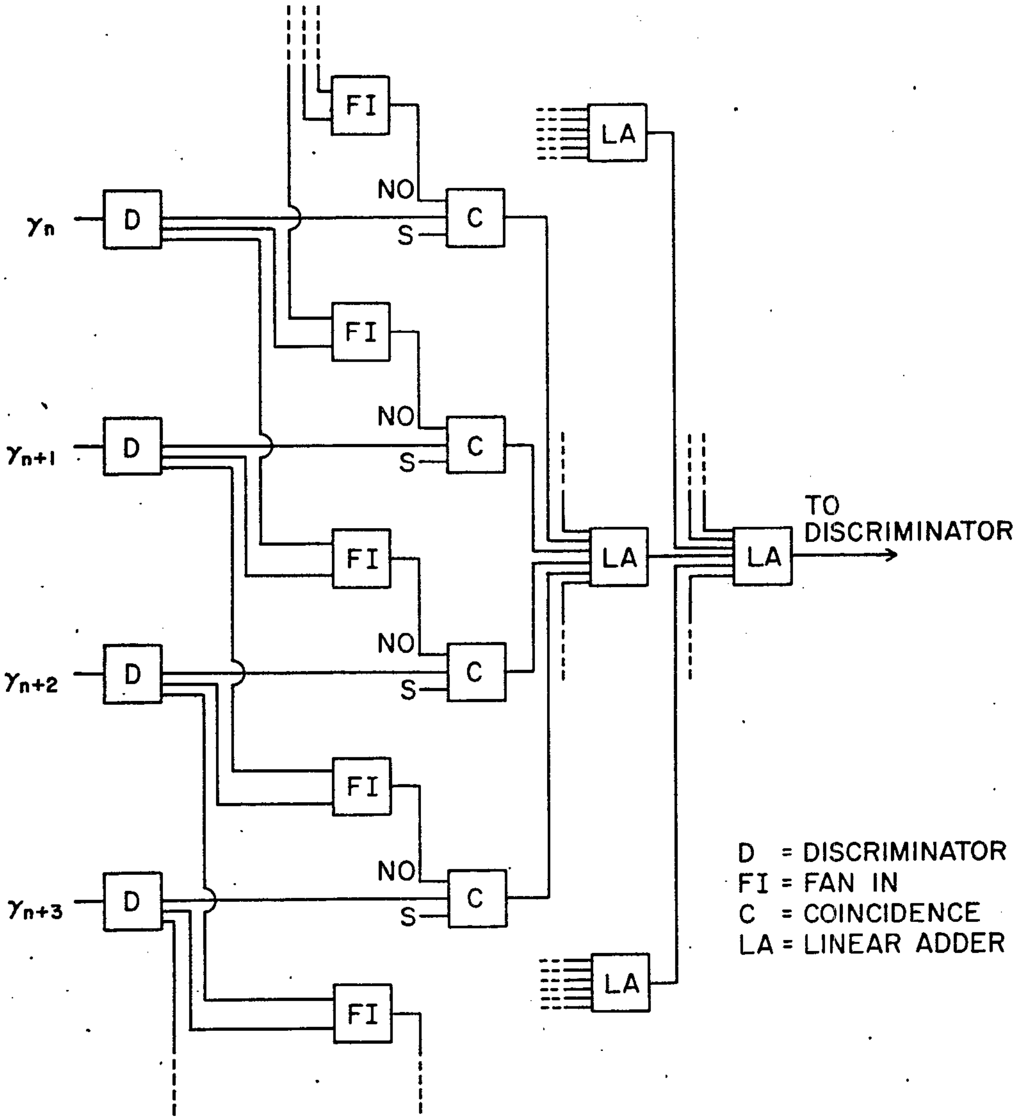
$$K^{+} \to \mu^{+} \pi^{0} \nu \to \mu^{+} \nu\, 2\gamma$$

Detector Description (Nuclear Instruments)

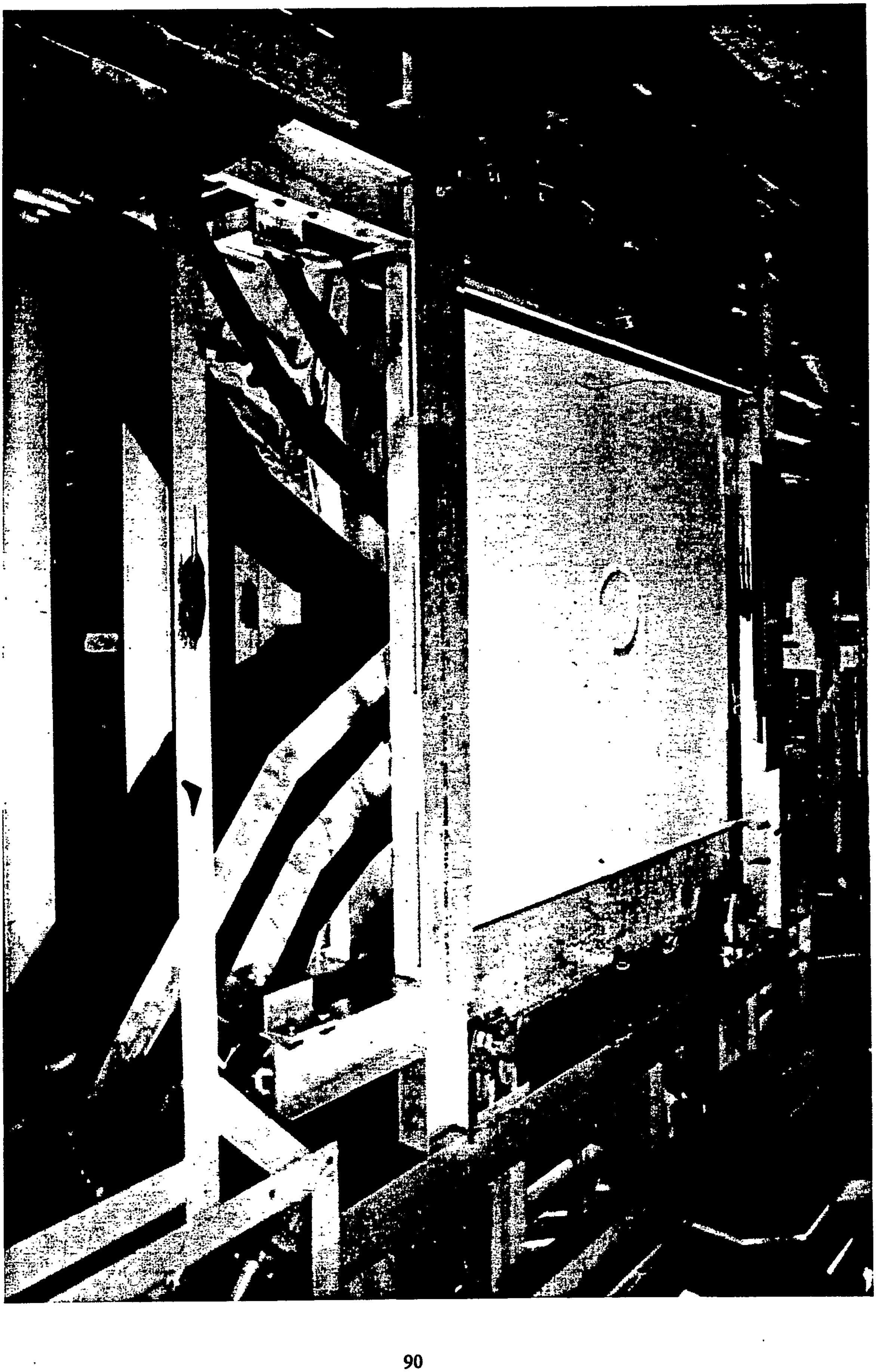

TO CAMERA
LUCITE FIELD LENS
0 4 8 12 16
SCALE INCHES
RCA 8575 PHOTOMULTIPLIER
LUCITE LIGHT GUIDE
TO CAMERA
LUCITE FIELD LENS
FLOOR

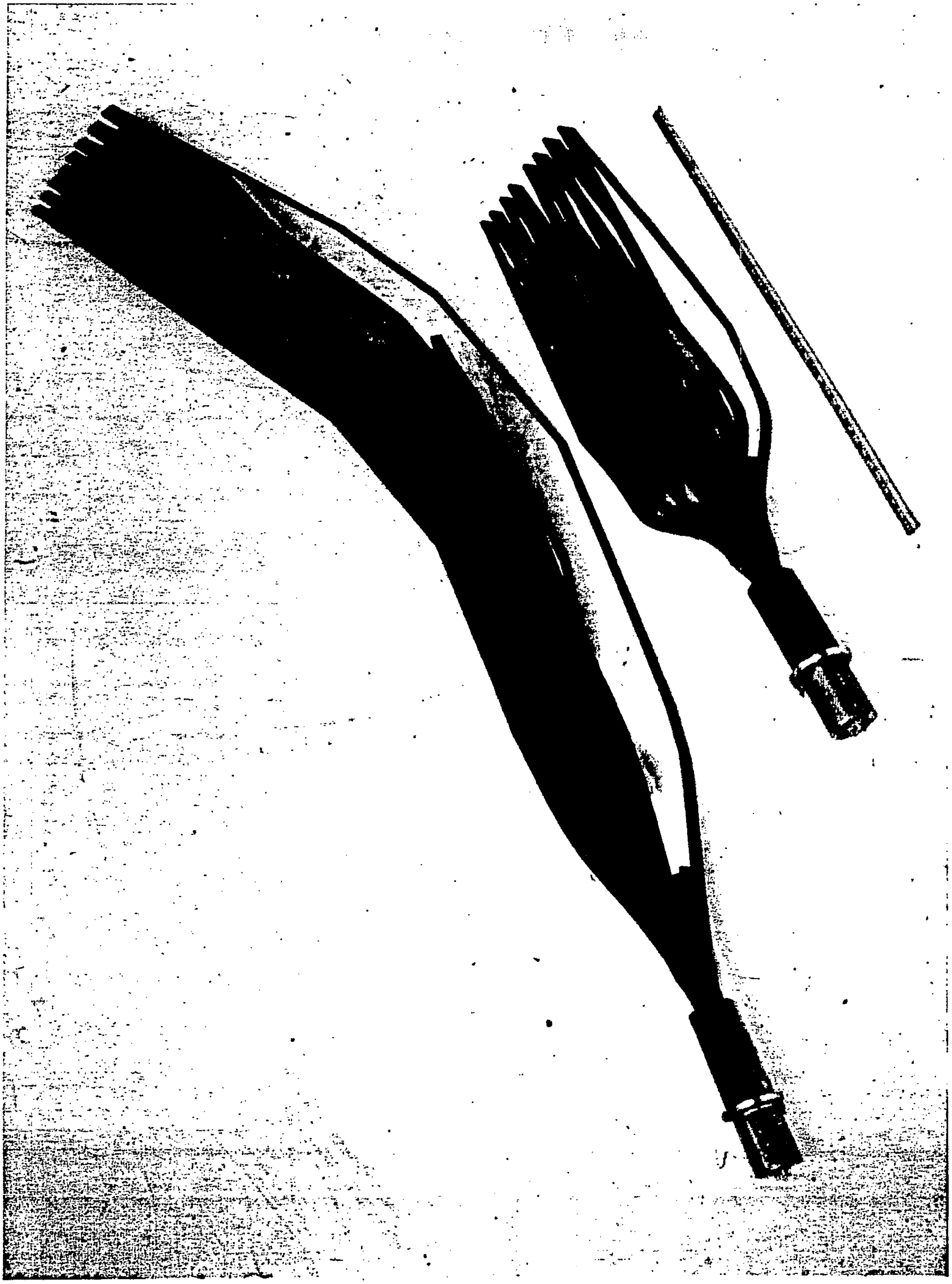

RCA 8575
PHOTOMULTIPLIER
LUCITE
LIGHT GUIDE
0 1 2 3 4 5
SCALE INCHES
LEAD
2" GAP
OPTICAL
SPARK
CHAMBER
SCINTILLATOR
INCIDENT
γ RAY

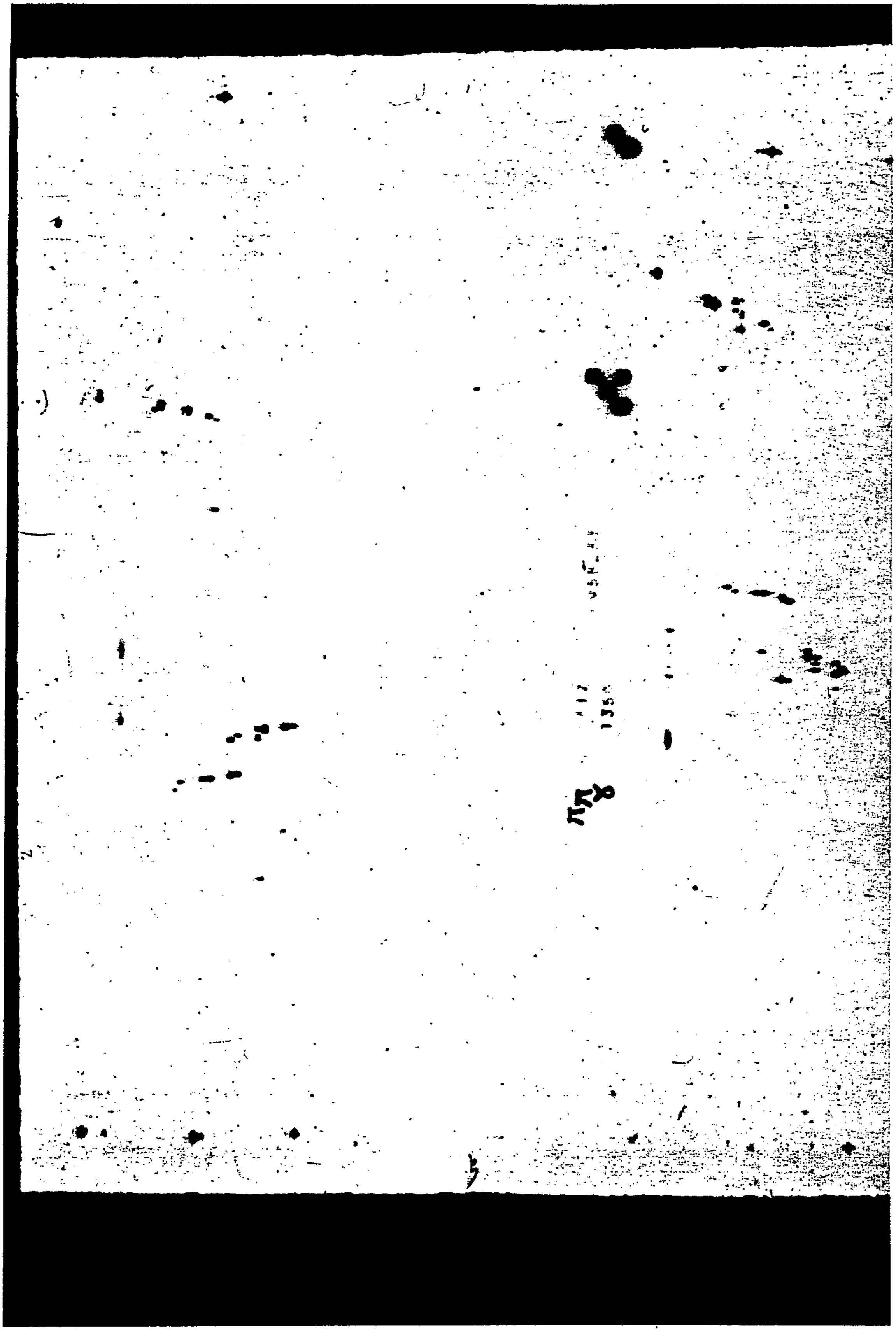
PHOTOMUTIPLIER
10"
LIGHT GUIDES
γ DETECTOR
K± BEAM AND CHARGED DECAY PARTICLES
DECAY REGION
K± BEAM
14°
NOMINAL DECAY POINT

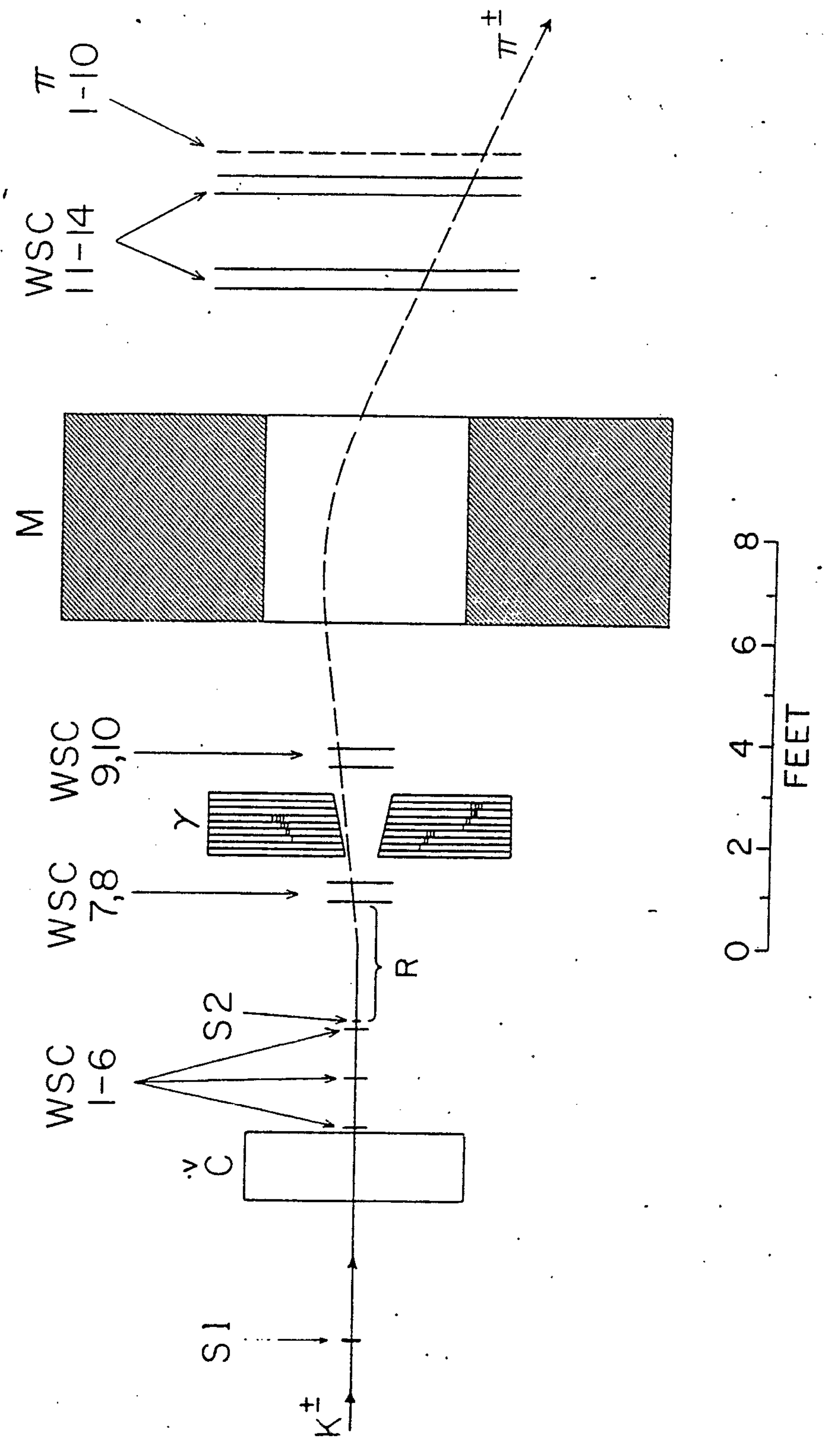


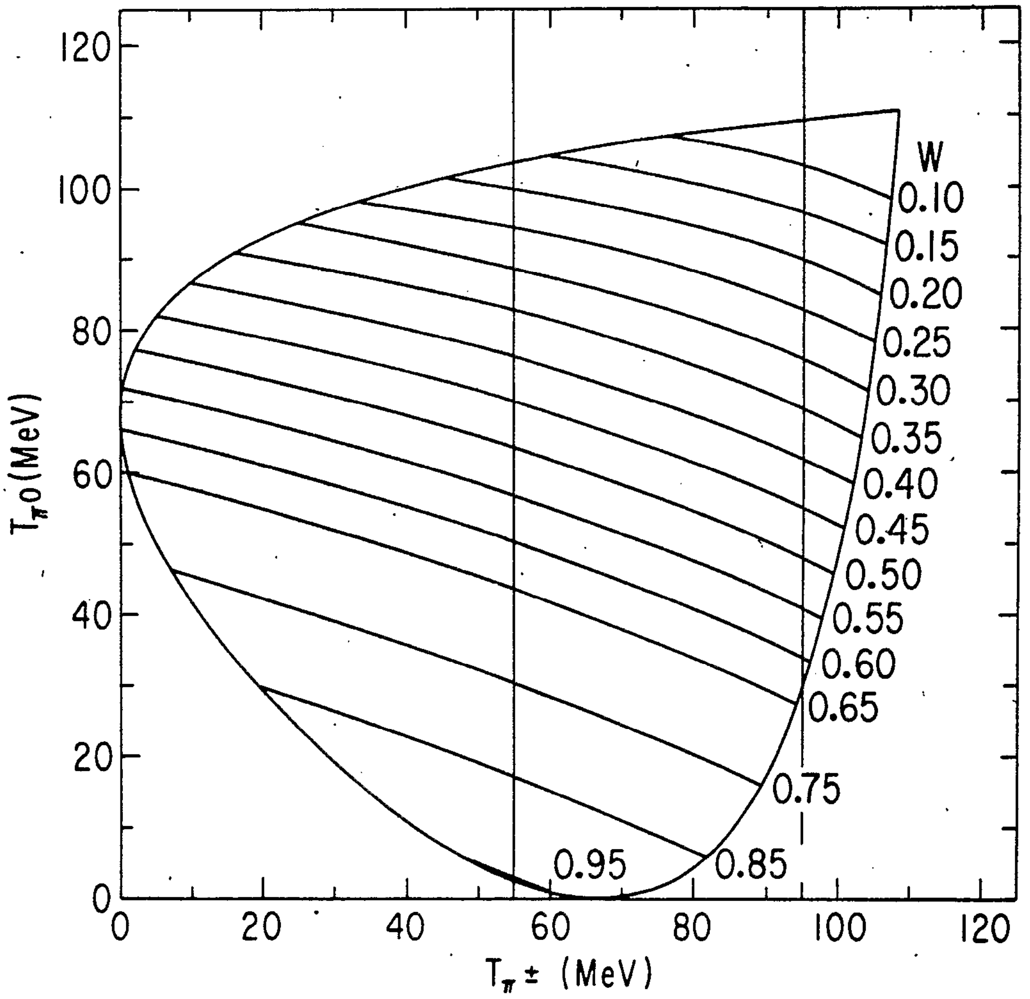
D = DISCRIMINATOR
FI = FAN IN
C = COINCIDENCE
LA = LINEAR ADDER



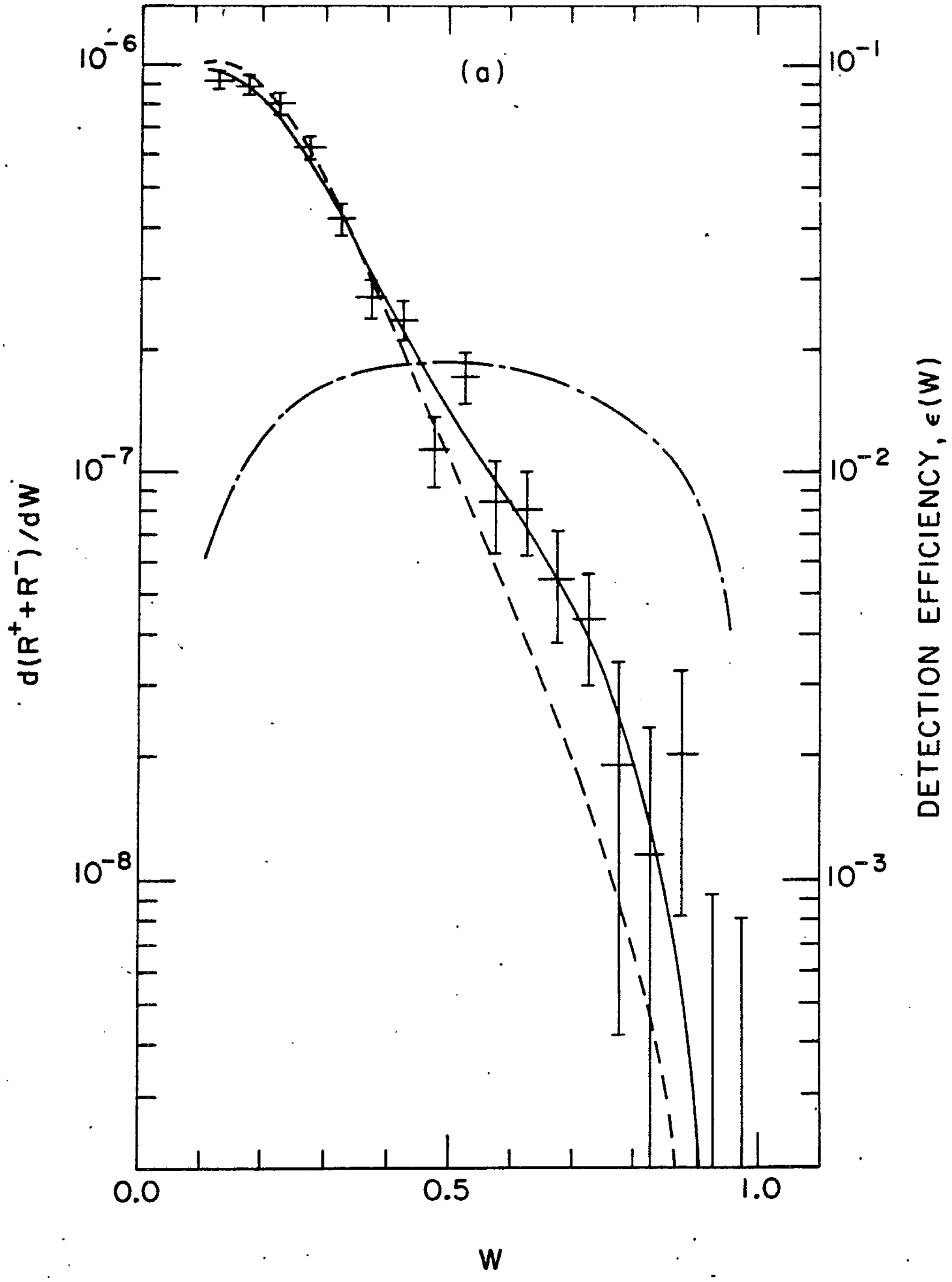


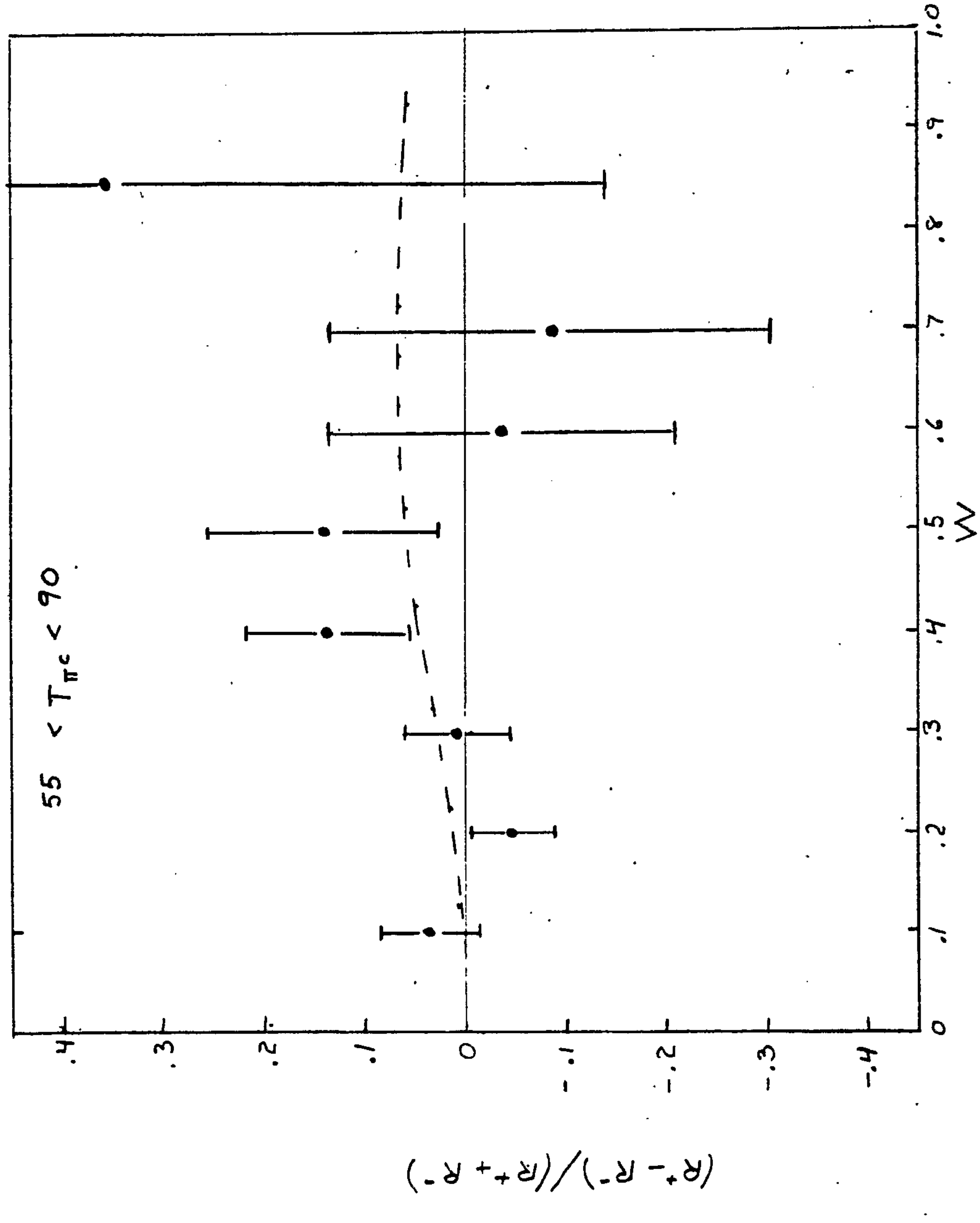



K±
S1
Č
WSC 1-6
S2
R
WSC 7,8
Y
WSC 9,10
M
WSC 11-14
π 1-10
π±
0
2
4
6
8
FEET

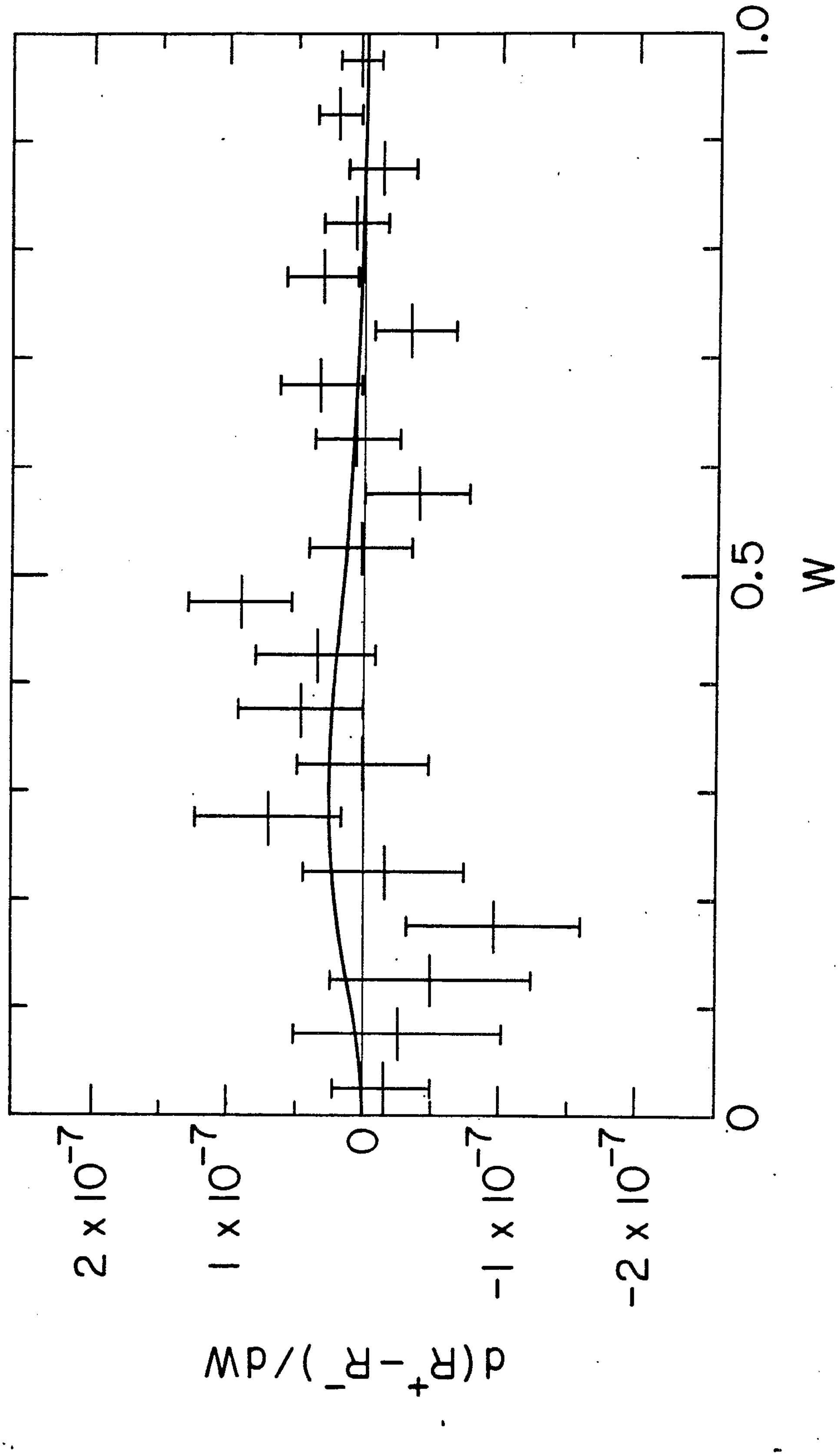


W
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.75
0.85
0.95
T$_{\pi}$0 (MeV)
T$_{\pi}$± (MeV)
0
20
40
60
80
100
120


(a)
10^{-6}
10^{-7}
10^{-8}
10^{-1}
10^{-2}
10^{-3}
$d(R^+ + R^-)/dW$
DETECTION EFFICIENCY, $\epsilon(W)$
0.0
0.5
1.0
W



55 < T_πc < 90
W
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
(R⁺ − R⁻)/(R⁺ + R⁻)
.4
.3
.2
.1
0
−.1
−.2
−.3
−.4


2 x 10^{-7}
1 x 10^{-7}
0
−1 x 10^{-7}
−2 x 10^{-7}
d(R$^+$−R$^-$)/dW
0
0.5
1.0
W

Conclusions

Ted was an adventurer:

Ted had a broad ready smile:

Ted could have been a brain surgeon:

It was an exciting, challenging and fun period:

AGS E631 - Study of K_L Radiative Decays

Laurence Littenberg - BNL

Ted Kycia Memorial Symposium - 19 May 2000

#631

Proposal to Study Radiative Decays of K_L^0

W.C. Carithers, C. Lam, P. Muhlemann and B. Wormington

University of Rochester

A.S. Carroll, I-H. Chiang, T.F. Kycia, K.K. Li, P.O. Mazur
and R. Rubinstein

Brookhaven National Laboratory

#631

Proposal to Study Radiative Decays of K_L^o

J-P. de Brion
W.C. Carithers, ~~C. Lam, P. Muhlemann and B. Wormington~~

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an~~d R. Rubinstein~~

Brookhaven National Laboratory

Proposal to Study Radiative Decays of K_L^o

I. Introduction

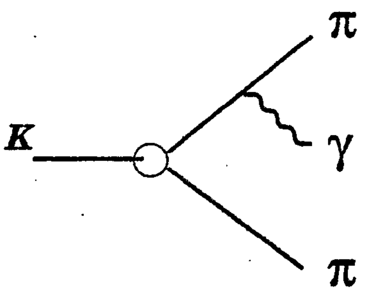
Hadronic structure is best studied with a probe that is theoretically well understood so that one can separate the structure of the probe from the structure it is probing. Most of our information on hadronic structure has thus come from weak and electromagnetic probes. The weak current has been used as a probe of K meson structure in semi-leptonic decays. A very large number of experiments have been performed to determine the form factors associated with these decays.[1]

By contrast, very little is known experimentally about the electromagnetic except structure of the kaon. Since all K decays involve $|\Delta Y| = 1$ transitions, the $K_L \to K^{\pm}e^{\mp}\nu$ weak interaction necessarily enters so that radiative K decays involve both weak and electromagnetic currents.

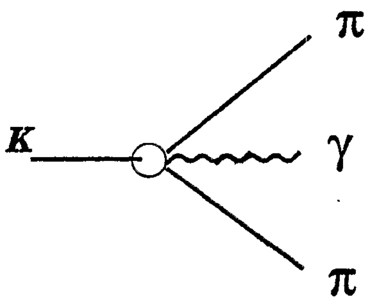
The scale for all radiative K_L^o decays is set by the rate for $K_L^o \to \gamma\gamma$. This branching ratio is known to be $(4.9 \pm 0.4) \times 10^{-4}$ from several measurements. Interestingly the $K_L^o \to \gamma\gamma$ decay and the $K^{\pm} \to \pi^{\pm}\pi^{o}\gamma$ experiment of Abrams et al.,[2] are the only radiative kaon decay experiments which indicate other than inner bremsstrahlung. Since the $\gamma\gamma$ decay is a 2-body final state it contains only the scale factor. The $K^{\pm} \to \pi^{\pm}\pi^{o}\gamma$ experiment was able to demonstrate the existence of direct emission without probing its detailed structure.

We propose a broad based study of possible kaon structure by measuring radiative decay modes of the K_L^o. All of these measurements will be done simultaneously in apparatus capable of high data rates and sensitive to branching ratios as low as 5×10^{-9}. These decays include $e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\pi^+\pi^-\gamma$ and ~~$e^{\pm}\pi^{\mp}\nu\gamma$~~. Furthermore, a large sample of $\pi^+\pi^-\pi^o$ decays would also be recorded. $e^+e^-\pi^o$, $\mu^+\mu^-\pi^o$, $\pi^{\pm}\pi^{o}e^{\mp}\nu$

$K \to \pi\pi\gamma$

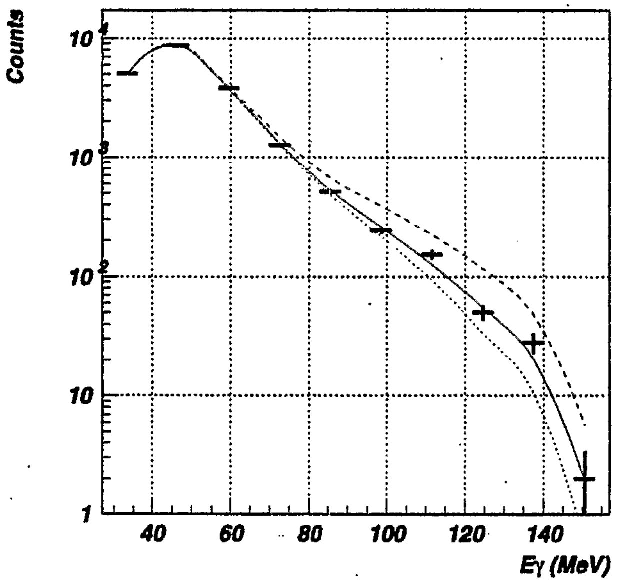


Inner Bremsstrahlung, proportional to $K \to \pi\pi$

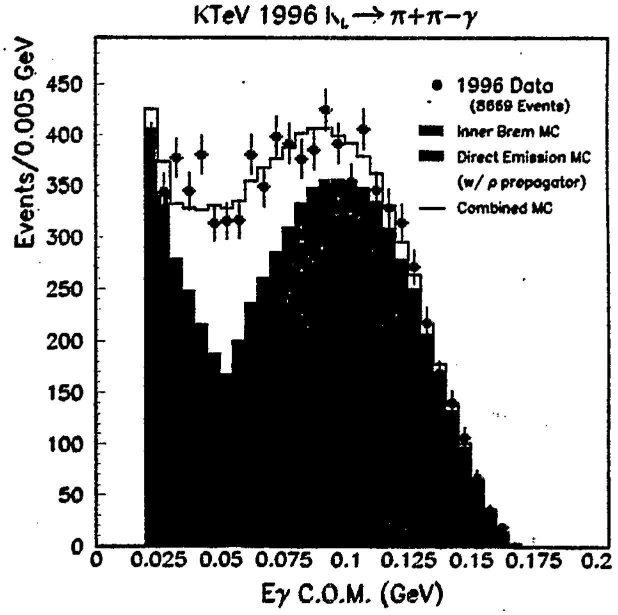


Direct Emission, the interesting part

The direct emission is expected to be roughly comparable for charged and neutral kaons, but the IB varies greatly. For charged kaons the IB is very large so the direct emission is only a few percent of the whole and very hard to pick out.

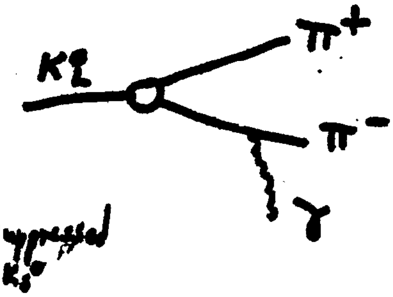


For K_L IB is suppressed by CP-invariance so the direct emission is relatively much larger and easier to extract. There's also a possibility of seeing direct CP-violation through the interference of the IB and direct emission, although this is not expected in the Standard Model.



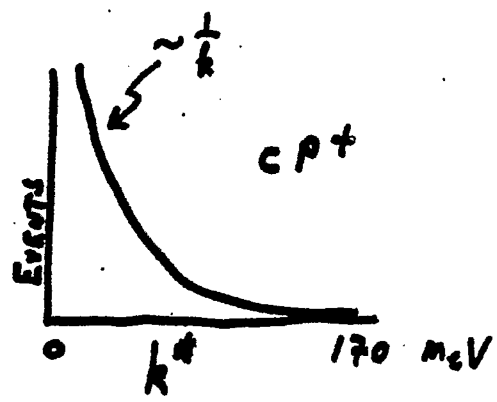
$K_L^0 \to \pi^+ \pi^- \gamma$

Inner Bremstrahlung



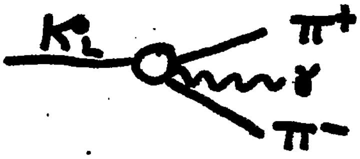
QED

CP suppressed unlike K_S^0

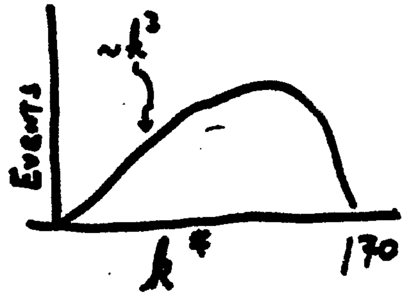


CP+

Direct Emission



M1 (CP-) ?

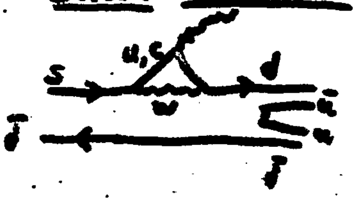


D.E. Phenomenologically handled by multipole expansion.

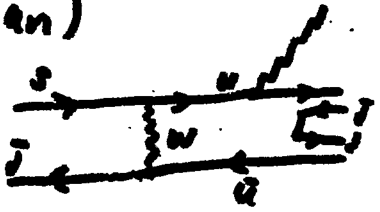
Higher order terms should be suppressed by > 10x.

CP violation not expected (i.e. no E1, M2 etc)

Short distance calc (Malakian)



G.I.M suppressed



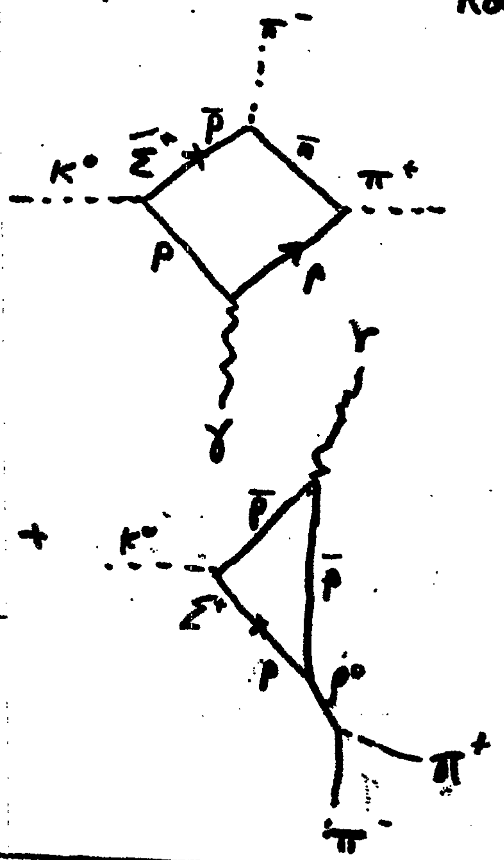
Penguin contrib small

Result b.r. $\sim 7 \times 10^{-7}$, way too small

$\pi\pi\gamma$ Theories

Baryon loop

ROCKMORE, SMITH, WONG



etc

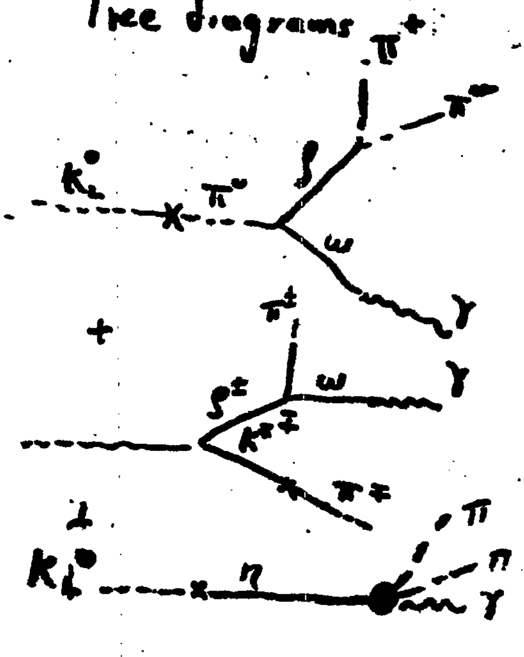
$K_L \to \pi^+\pi^-\gamma$
$K^+ \to \pi^+\pi^0\gamma$ } right

$K_L \to \gamma\gamma$ low by factor 3 or so

etc.

Tree diagrams

MOSHE, SINGER



$K_L \to \gamma\gamma$
$K^+ \to \pi^+\pi^0\gamma$ } right

$K_L \to \pi^+\pi^-\gamma$ high by O.M.

enhanced by $\left(\frac{1}{m_K^2 - m_\eta^2}\right)^2$

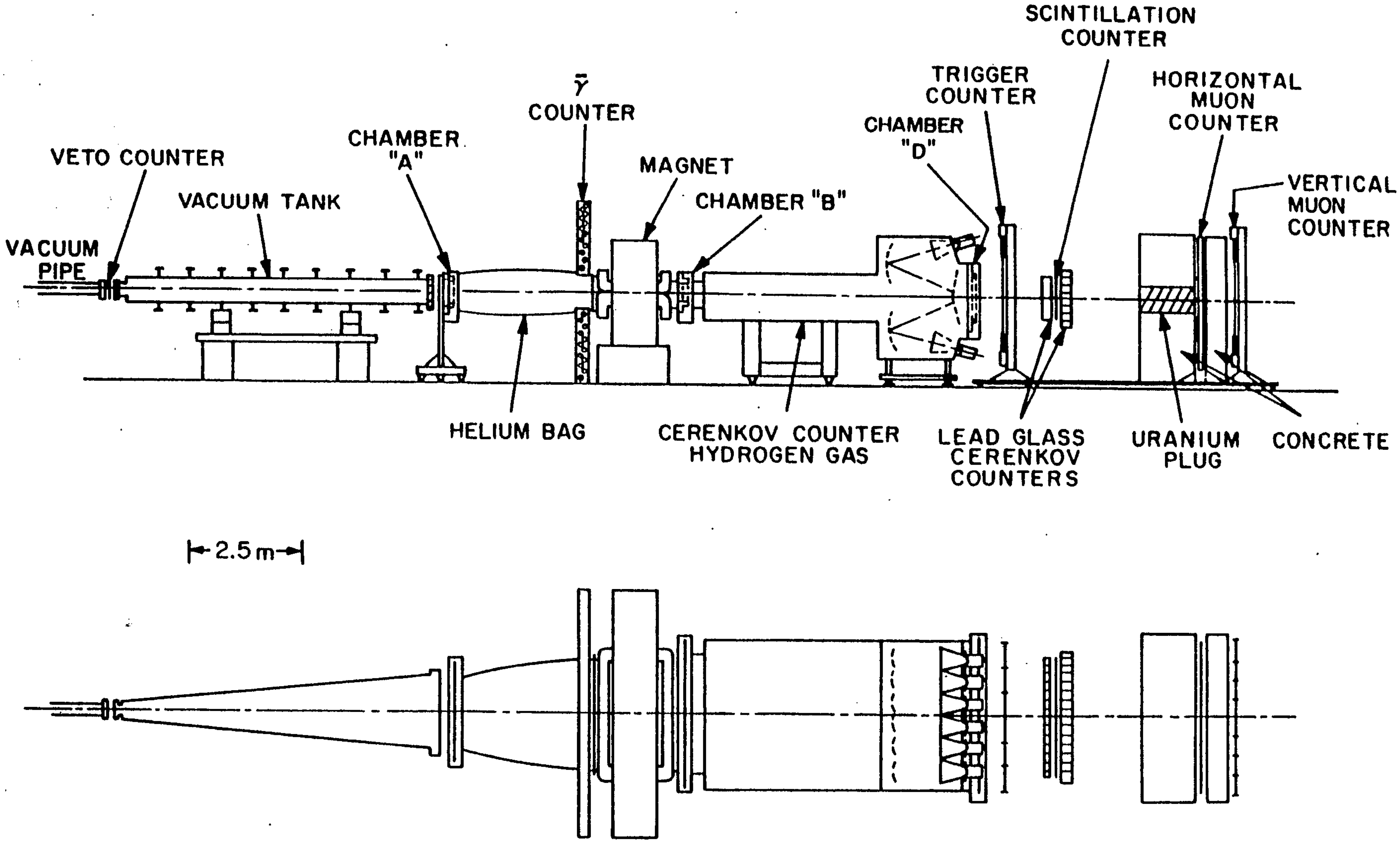


Fig. 15. Experimental arrangement for AGS Experiment #631.

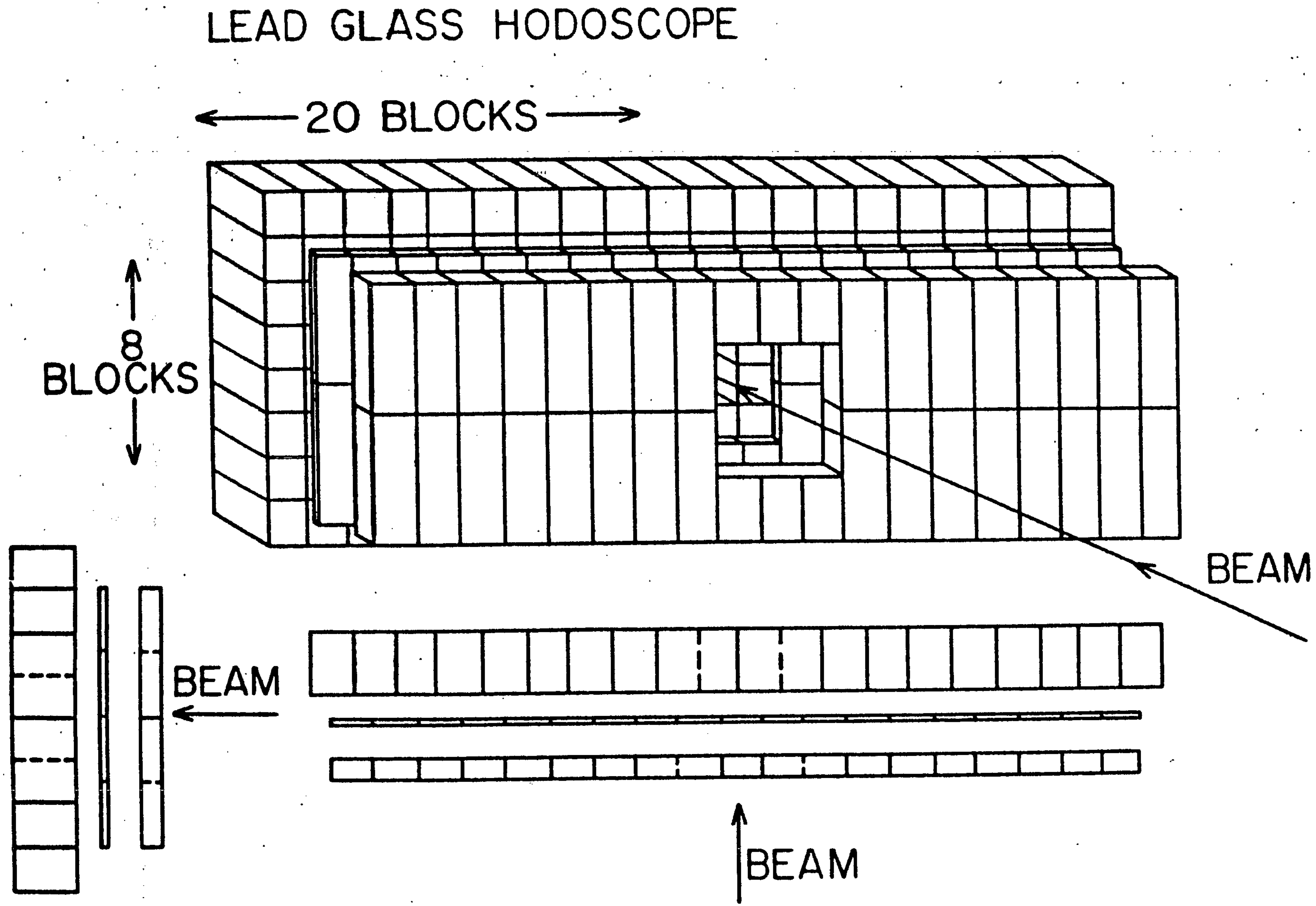


Fig. 1. Lead glass array in offset, side elevation and plan views.

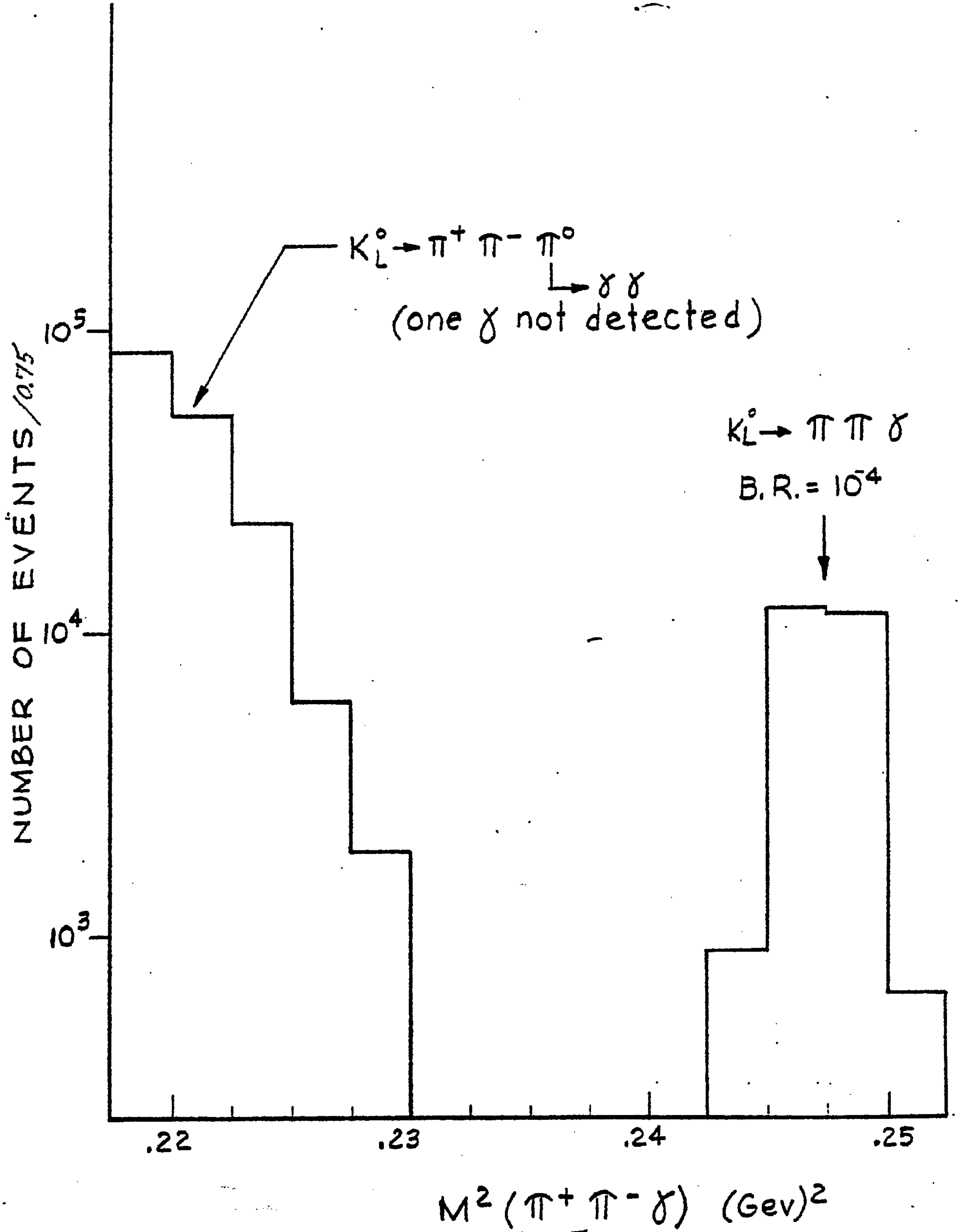
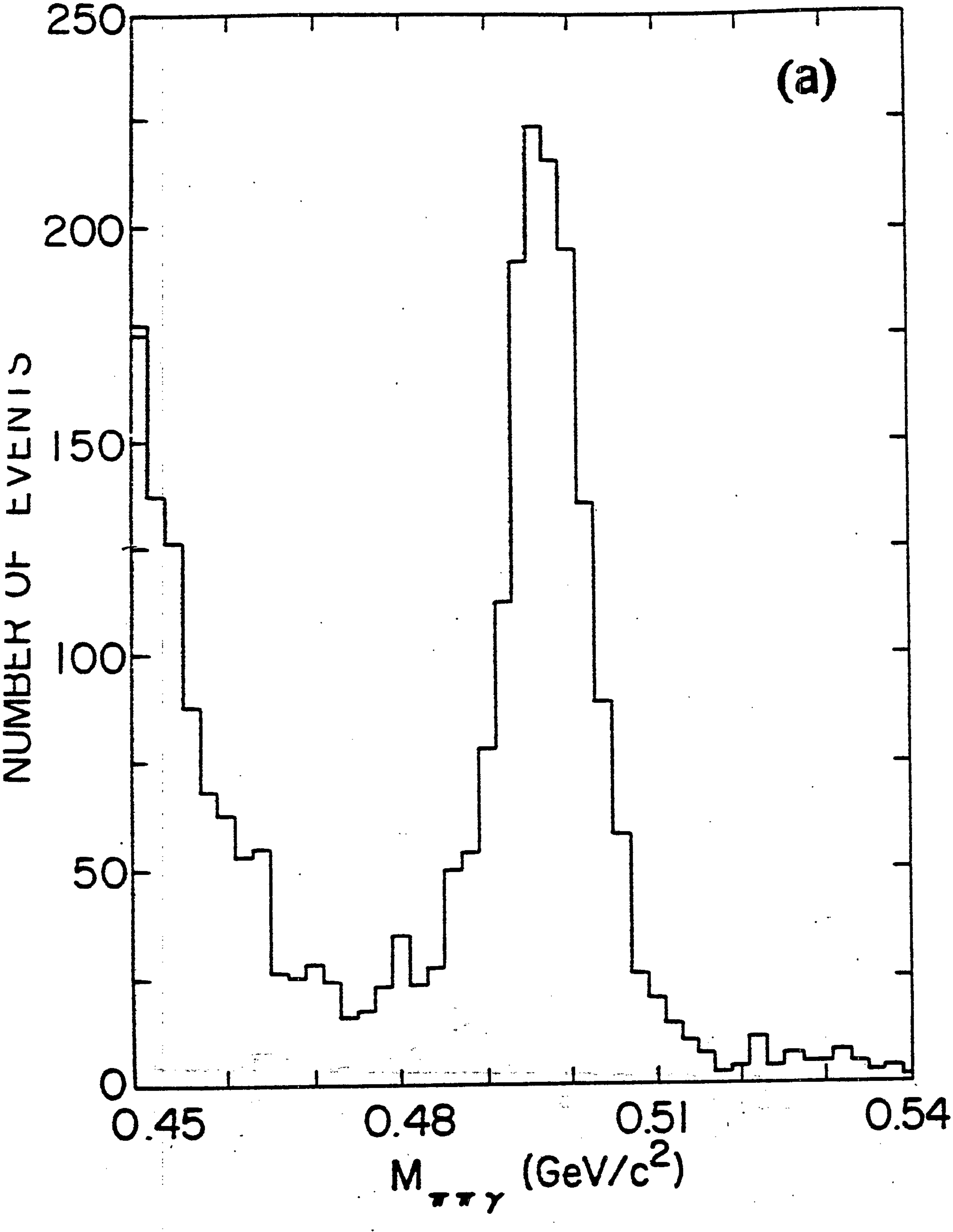
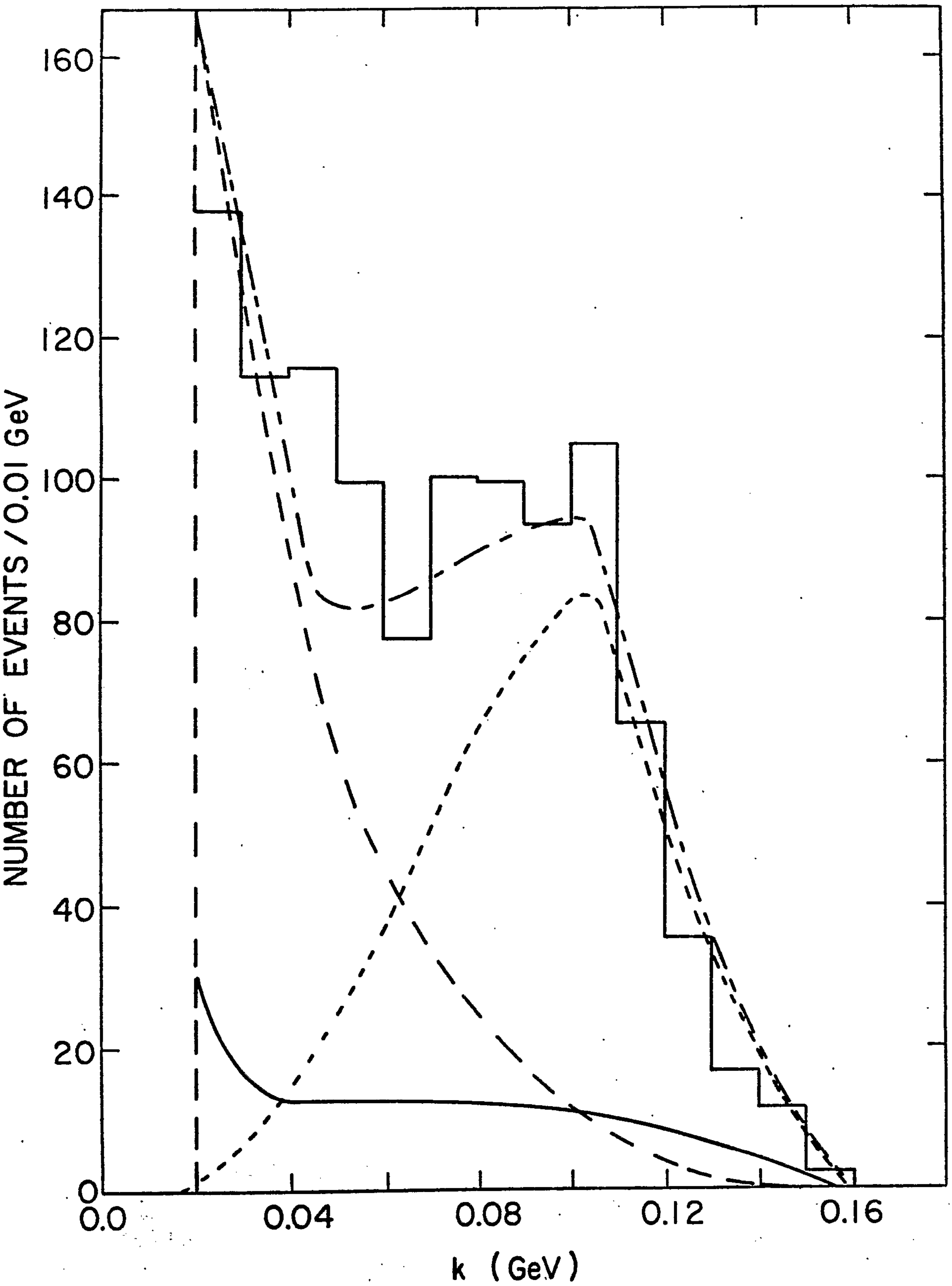
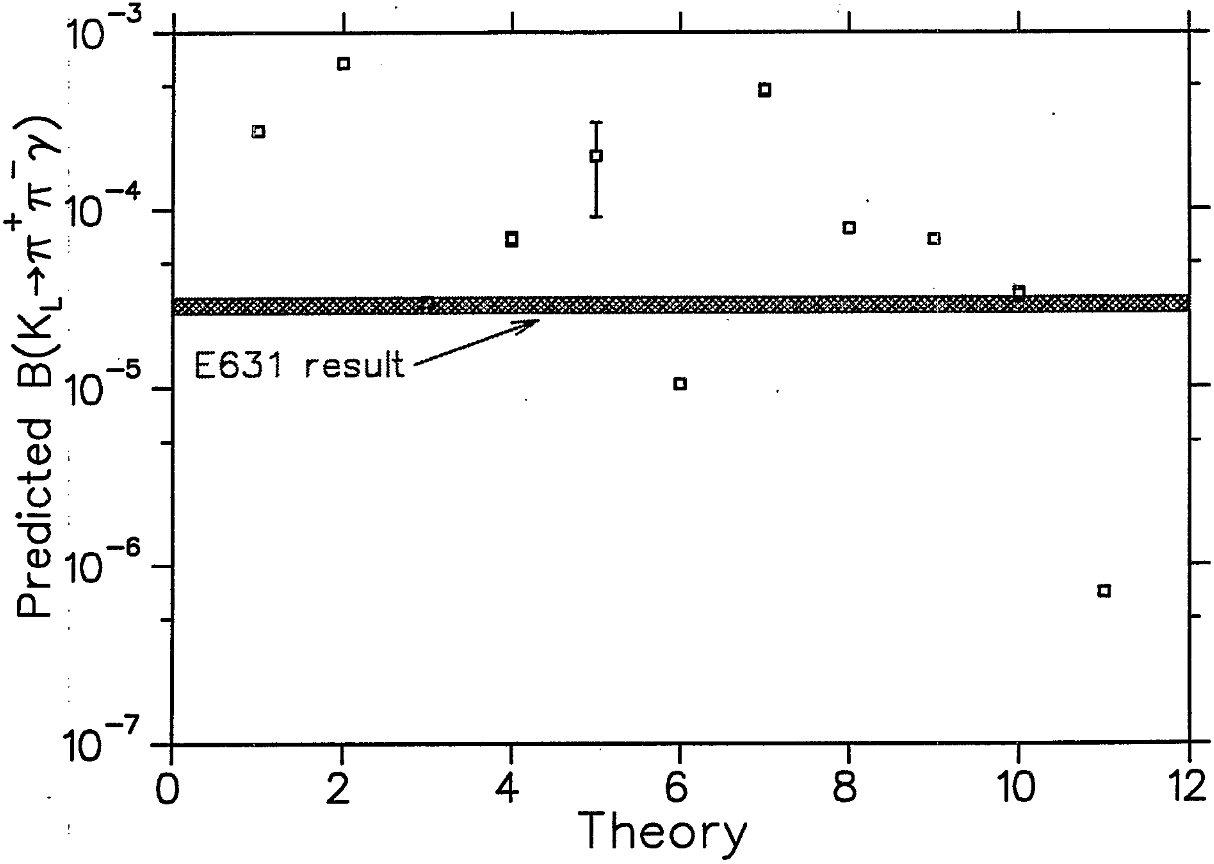

NUMBER OF EVENTS/0.75
10⁵
10⁴
10³
.22
.23
.24
.25
M² (π⁺ π⁻ γ) (Gev)²
K°L → π⁺ π⁻ π°
→ γ γ
(one γ not detected)
K°L → π π γ
B. R. = 10⁻⁴

FIGURE 5

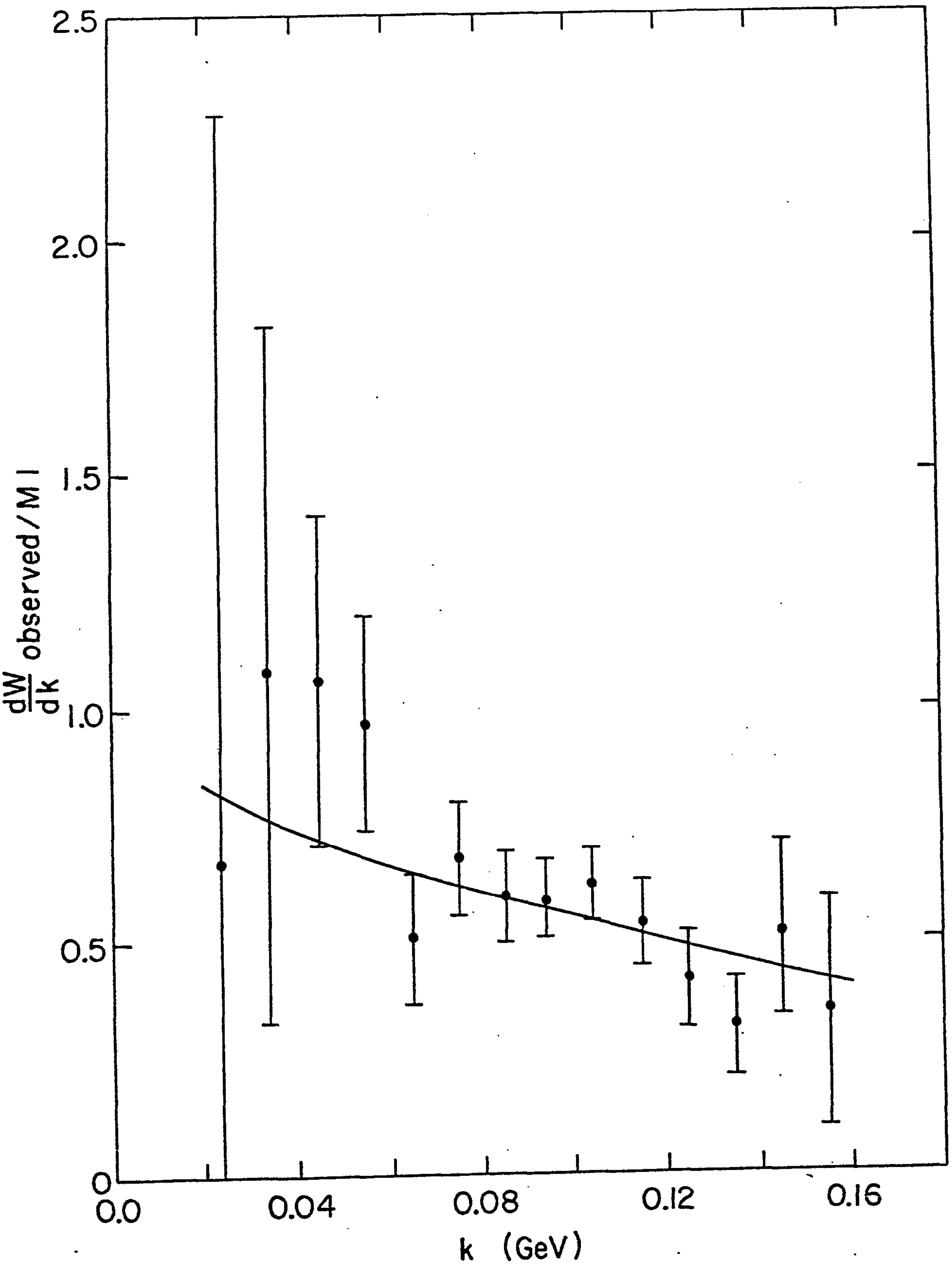


(a)
NUMBER OF EVENTS
250
200
150
100
50
0
0.45
0.48
0.51
0.54
$M_{\pi\pi\gamma}$ (GeV/c^2)


NUMBER OF EVENTS / 0.01 GeV
160
140
120
100
80
60
40
20
0
0.0
0.04
0.08
0.12
0.16
k (GeV)



Predicted $B(K_L \rightarrow \pi^+ \pi^- \gamma)$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
E631 result
0
2
4
6
8
10
12
Theory


2.5
2.0
1.5
1.0
0.5
0
$\frac{dW}{dk}$ observed / M1
0.0
0.04
0.08
0.12
0.16
k (GeV)

$K^{L}_{o} \rightarrow$	EVENTS OBSERVED PREVIOUSLY	B.R. OR UPPER LIMIT	THEOR. PREDICTIONS
$\pi^+\pi^-\gamma$	24	$6 \pm 2 \times 10^{-5}$	$10^{-5} - 6 \times 10^{-4}$
$e^+e^-\gamma$	NONE	$< 2.8 \times 10^{-5}$	$2-8 \times 10^{-6}$
$\mu^+\mu^-\gamma$	NONE	$< 7.8 \times 10^{-5}$	$1.5 \times 10^{-7} - 6 \times 10^{-4}$
$e^+e^-\pi^0$	NONE	NONE	$10^{-13} - 10^{-6}$
$\mu^+\mu^-\pi^0$	NONE	$< 5.7 \times 10^{-5}$	$10^{-13} - 10^{-6}$
$\pi^\pm\pi^0 e^\mp \nu$	NONE	$< 2.2 \times 10^{-3}$	$5-16 \times 10^{-5}$

$K_L \rightarrow$	EVENTS OBSERVED PREVIOUSLY	B.R. OR UPPER LIMIT	THEOR. PREDICTIONS	THIS EXP
$\pi^+\pi^-\gamma$	24	$6\pm2\times10^{-5}$	$10^{-5}-6\times10^{-4}$	$2.9\pm.3\times10^{-5}$ (1070 evts)
$e^+e^-\gamma$	NONE	$<2.8\times10^{-5}$	$2-8\times10^{-6}$	$17.4\pm8.7\times10^{-6}$
$\mu^+\mu^-\gamma$	NONE	$<7.8\times10^{-5}$	$1.5\times10^{-7}-6\times10^{-4}$	$2.8\pm2.8\times10^{-7}$
$e^+e^-\pi^0$	NONE	NONE	$10^{-13}-10^{-6}$	$<2.3\times10^{-6}$
$\mu^+\mu^-\pi^0$	NONE	$<5.7\times10^{-5}$	$10^{-13}-10^{-6}$	$<1.2\times10^{-6}$
$\pi^\pm\pi^0e^\mp\nu$	NONE	$<2.2\times10^{-3}$	$5-16\times10^{-5}$	$6.2\pm2.0\times10^{-5}$ (16 evts)

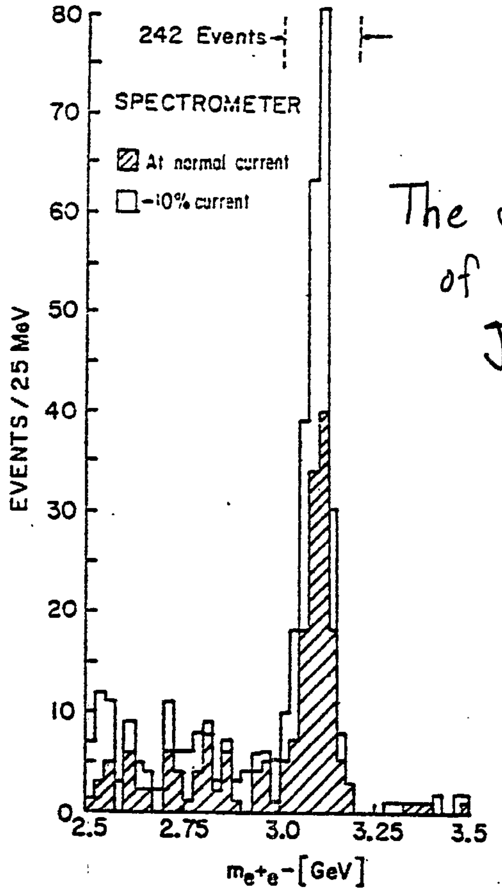


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

The discovery of the J/ψ

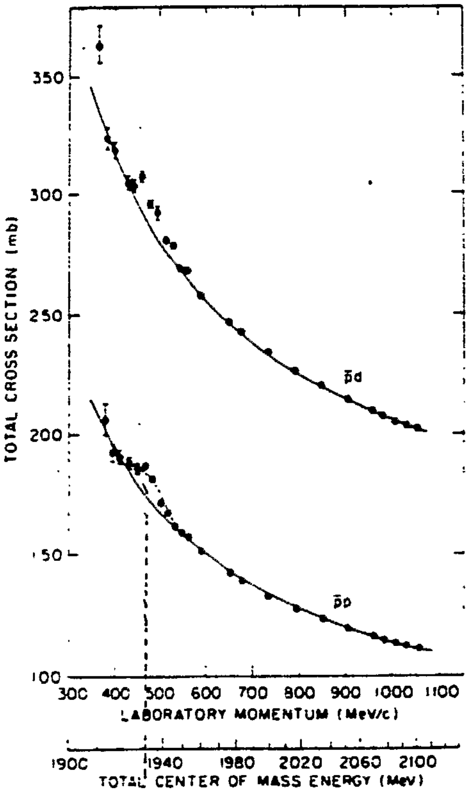
Led to

PROPOSAL 656

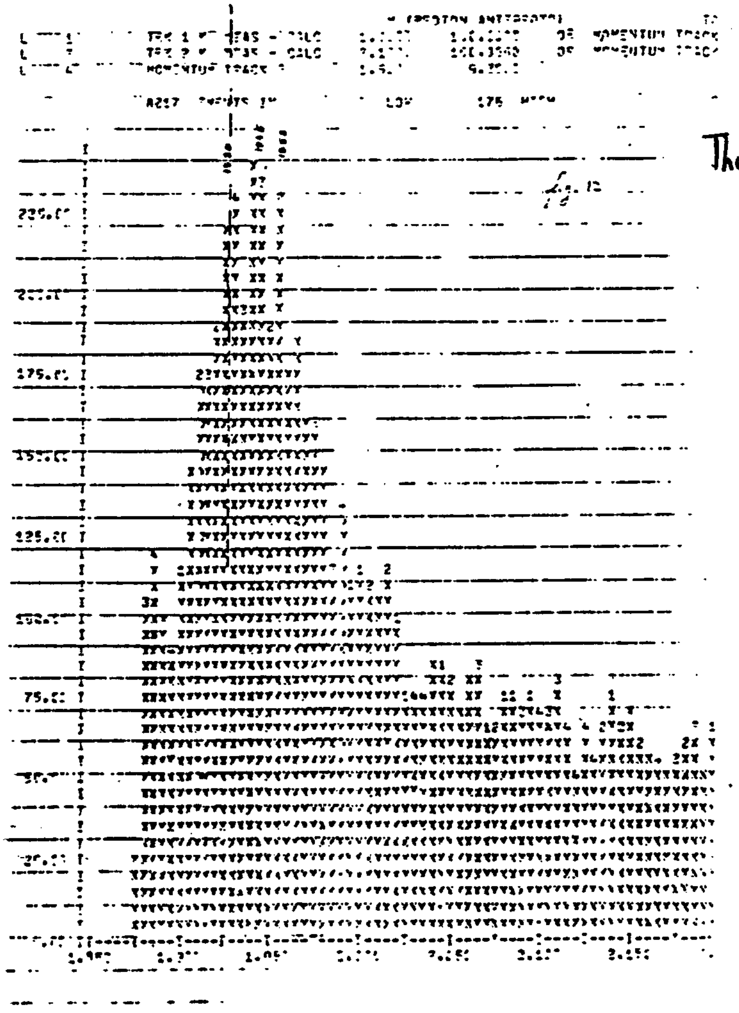
Search for Narrow $\bar{p}p$ and $\bar{p}p\gamma$ States

A.S. Carroll, I-H. Chiang, T.F. Kycia, K.K. Li, L. Littenberg
and P.O. Mazur
Brookhaven National Laboratory

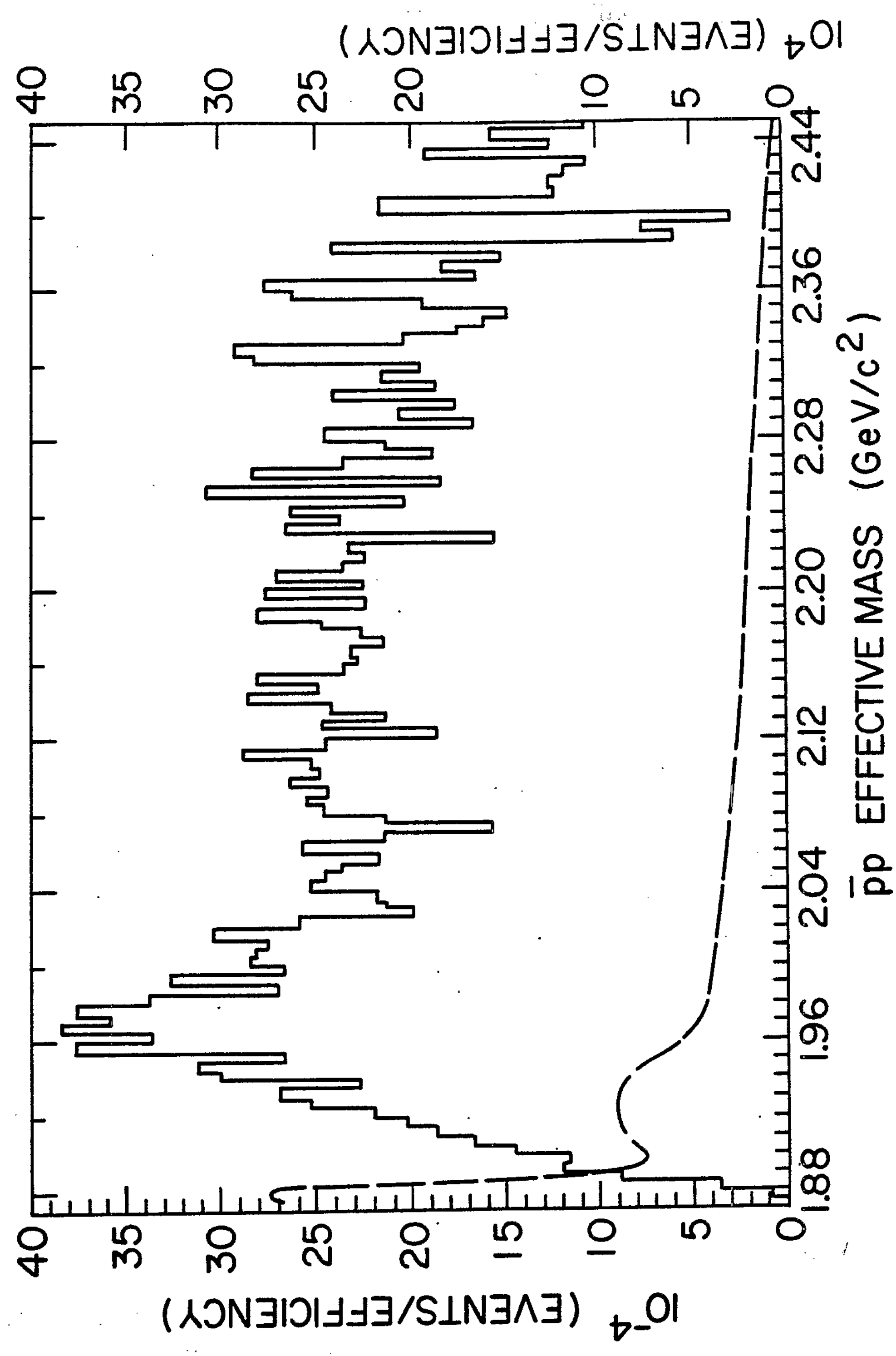
W.C. Carithers and J.P.de Brion
University of Rochester



Structure observed in formation



There in production?


p̄p EFFECTIVE MASS (GeV/c²)
1.88
1.96
2.04
2.12
2.20
2.28
2.36
2.44
10⁻⁴ (EVENTS/EFFICIENCY)
10⁴ (EVENTS/EFFICIENCY)
0
5
10
15
20
25
30
35
40

Conclusions

E631 was an extremely successful experiment.

- Three new decay modes of the K_L were discovered:
  - $K_L \to e^+e^-\gamma$
  - $K_L \to \mu^+\mu^-\gamma$
  - $K_L \to \pi^\pm\pi^0e^\mp\nu$
- $B\left(K_L \to \pi^+\pi^-\gamma\right)$ was accurately measured for the 1st time
- A new dynamical effect was seen in the $K_L \to \pi^+\pi^-\gamma$.
  - This is still a challenge to theory.
- The first ever limit was put on $K_L \to \pi^0e^+e^-$.
- Attention was focussed on $K_L \to \pi^0\ell^+\ell^-$ in CP-violation.

Ted pioneered lead glass calorimeters.

- this work was crucial to the success of E631.
- also contributed to wide spread use of this technique.

E656 put limits on new particle production in $n + Be \to \bar{p}pX$.

But the lesson I retained was of Ted's scientific integrity.

E703

First Search for the H Six-Quark State

Ted Kycia Memorial Symposium

19 May 2000

Alan Carroll

TIME LINE FOR E703

1 NOV 1976	Bob Jaffe submits a paper to PRL, "Perhaps a Stable Dihyperon"
? NOV 1976	Ted Kycia acquires a copy of a preprint
9 DEC 1976	Ted Kycia and Val Fitch submit Proposal 703, "Search for Six Quark States"
31 JAN 1977	Jaffe paper published in PRL
1 FEB 1977	Experiment 703 Approved for two weeks running with sole use of AGS at ~5 GeV/c in B1 Line
23 JUN 1977	Test of 5 GeV/c low intensity extraction
26 JUN 1977	Test of E703 with secondary beam
7-21 AUG 1977	E703 runs with 5 GeV/c protons
18-29 Sept 1977	E703 runs with 5 GeV/c protons
~26 JUL 1978	Paper submitted to PRL, "Search for Six Quark States"
18 SEP 1978	"Search for Six Quark States" published.

Search for Six-Quark States

A. S. Carroll, I-H. Chiang, R. A. Johnson, T. F. Kycia, K. K. Li,
L. S. Littenberg, and M. D. Marx
Brookhaven National Laboratory, Upton, New York 11973

and

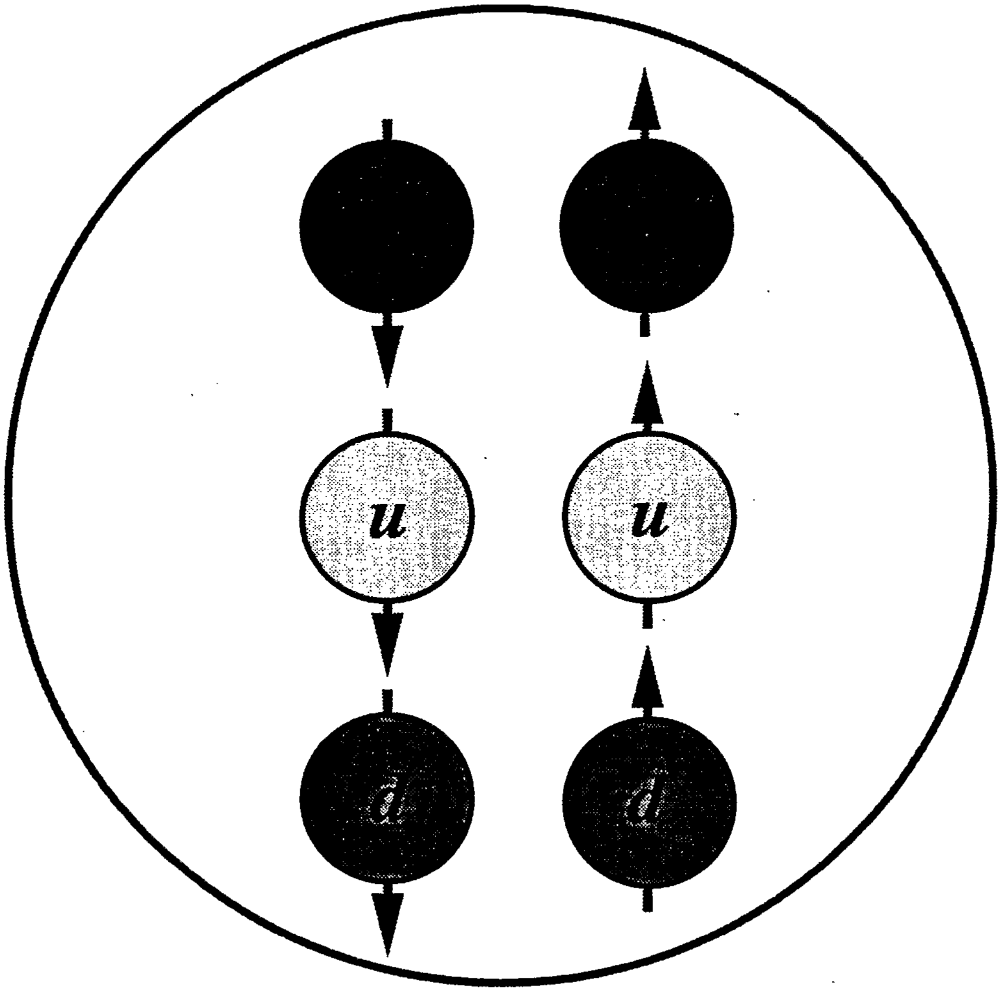
R. Cester, R. C. Webb, and M. S. Witherell
Princeton University, Princeton, New Jersey 08540

(Received 26 July 1978)

We have searched the missing-mass spectrum of the reaction $pp \rightarrow K^+K^+X$ for a narrow six-quark resonance in the mass range 2.0–2.5 GeV/c^2. No narrow structure was observed. Upper limits for the production cross section of such a state depend upon mass and vary from 30 to 130 nb.

As the evidence for the colored quark structure of hadrons mounts, the apparent absence of exotic quark combinations becomes more and more puzzling. Nothing in current theory excludes $qq\bar{q}\bar{q}$, six-quark, or even larger states from existing as long as they are color singlets. In recent papers, Jaffe has used the Massachusetts Institute of Technology bag model[1] to calculate the masses of dimeson[2] and dibaryon[3] states. An unexpected prediction emerged from the calculations: There should exist a neutral six-quark, strangeness $= -2$ state *below* $\Lambda\Lambda$ threshold that is stable to all but weak decays. Though this result comes from a specific model, Lipkin has argued that the general features of quantum chromodynamics and the known baryon mass splittings imply that the six-quark state with charge zero, spin zero, and strangeness $= -2$ would have the greatest binding potential.[4] No prior experiment could exclude the existence of

The H^0 Dibaryon – The Simplest Strangelet



Properties:

1. *Spin = 0*
2. *Isospin = 0*
3. *Strangeness = −2*
4. *Quark Structure = Q^6, all in relative S state*

Uniqueness – *The H dibaryon is the only dibaryon predicted to be stable with respect to strong decay*

The contribution to our S-wave hadron's mass from lowest order gluon exchange is proportional to

$$\Delta \equiv -\sum_{i>j} \vec{\sigma}_i \cdot \vec{\sigma}_j \vec{\lambda}_i \cdot \vec{\lambda}_j M(m_iR, m_jR) \tag{1}$$

where $\vec{\sigma}_i$ ($\vec{\lambda}_i$) is the spin (color) vector of the i-th quark normalized to 3(2). $M(m_iR,\ m_jR)$ measures the interaction strength. In the bag model it is a simple

For color singlet hadrons containing only quarks (no antiquarks)

$$\Delta = \left(8N - \frac{1}{2} C_6 + \frac{4}{3} J(J+1)\right) \overline{M} \tag{2}$$

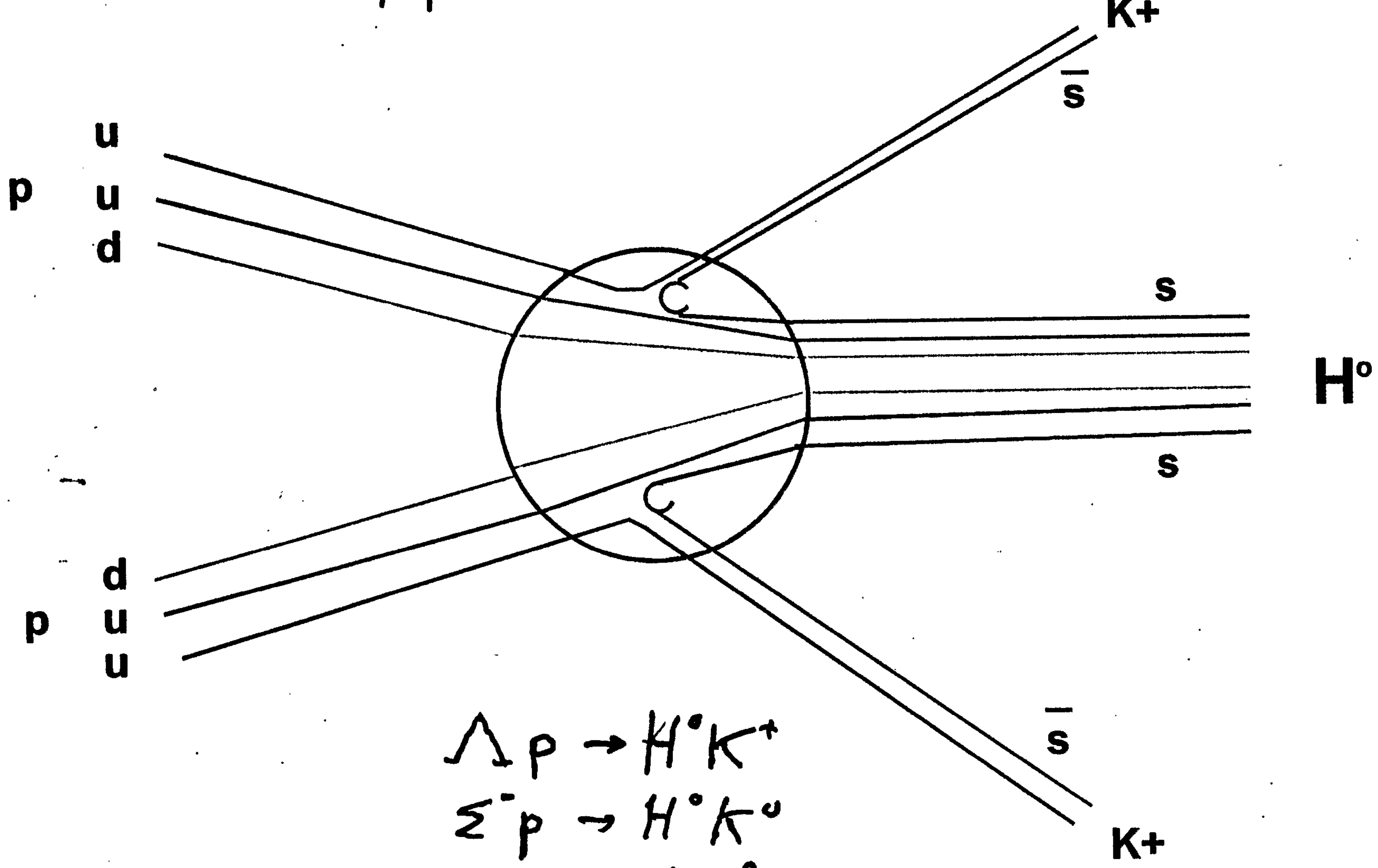
where N is the total number of quarks, J is their angular momentum, and C_6 is their "colorspin"—the quadratic Casimir of SU(6) for the colorspin representation

$$M = \frac{4}{3} (4\pi B)^{1/4} \left[2.043N - z_0 + \alpha_c \Delta\right]^{3/4} \tag{3}$$

where $B^{1/4} = 146$ MeV, $z_0 = 1.84$ and $\alpha_c = g^2/4\pi = 0.55$ are fixed in the $Q\overline{Q}$ and Q^3 sectors of the model.[3]

$SU(6)_{cs}$ Representation	C_6	J	$SU(3)_f$ Representation	Mass in the limit $m_s = 0$
490	144	0	$\underline{1}$	1760
896	120	1, 2	$\underline{8}$	1986
280	96	1	$\underline{10}$	2165
175	96	1	$\overline{\underline{10}}$	2165
189	80	0, 2	$\underline{27}$	2242
35	48	1	$\underline{35}$	2507
1	0	0	$\underline{28}$	2799

$pp \rightarrow H^\circ K^+ K^+$



$\Lambda p \rightarrow H^\circ K^+$

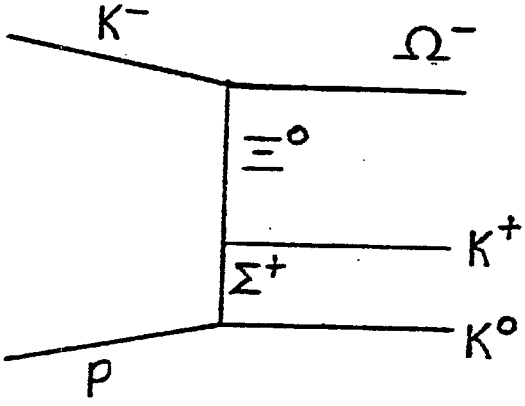
$\Sigma^- p \rightarrow H^\circ K^\circ$

$\Xi^- p \rightarrow H \pi^\circ$

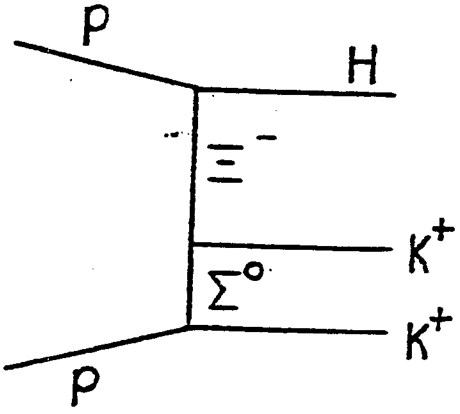
$K^- d \rightarrow H K^\circ$

$K_1\, d \rightarrow H\ K^+$

$A A \rightarrow H^\circ X$

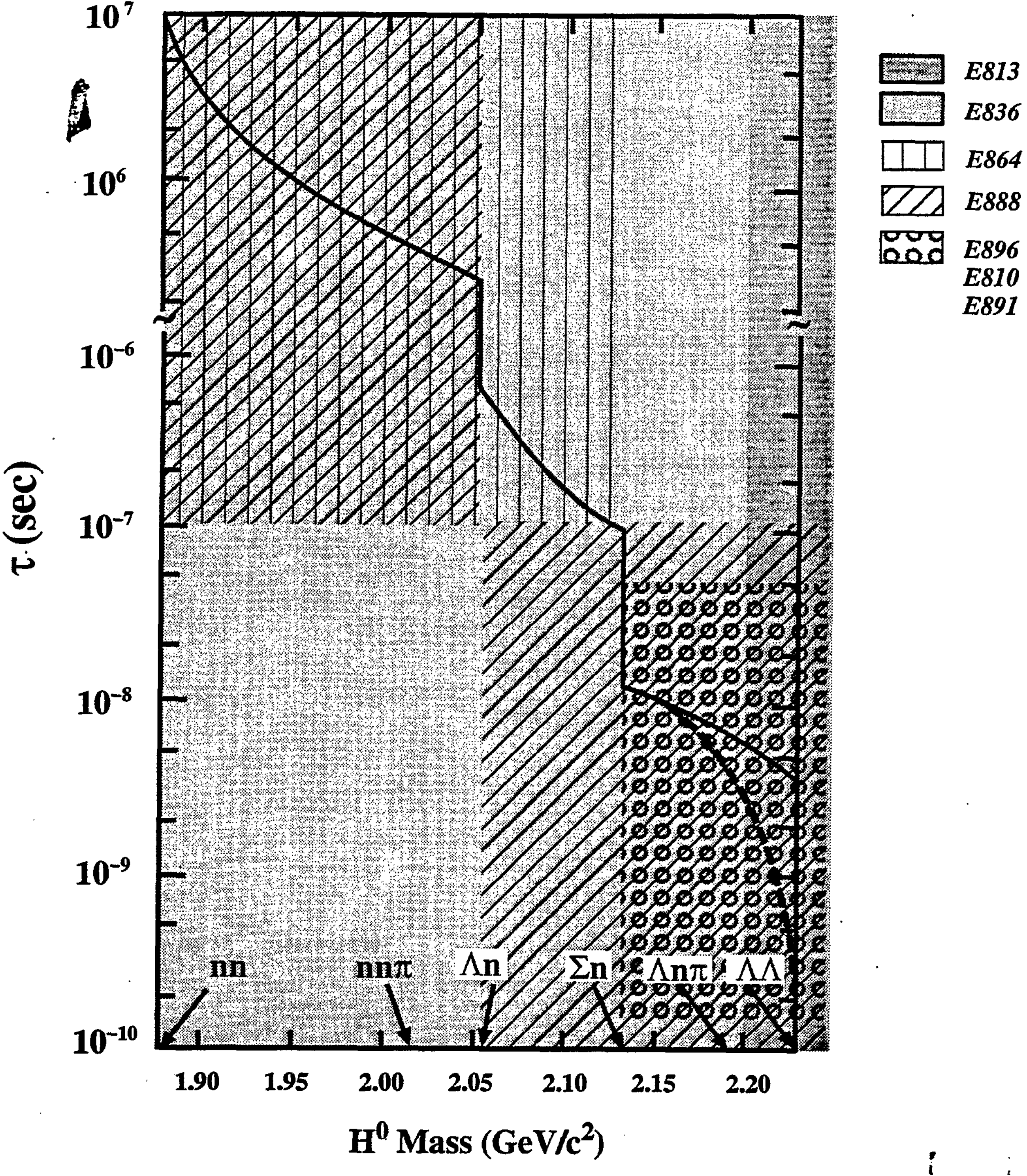


~1.2 μb
@ ~5 GeV



~ 50 nb

Weak decay lifetime of H^0 dibaryon



BNL-24296
EP&S 78-2
INFORMAL REPORT
LIMITED DISTRIBUTION

A LOW ENERGY, LOW INTENSITY AND GOOD DUTY CYCLE PROTON BEAM FROM THE AGS

A. S. Carroll and J. W. Glenn III

April 14, 1978

TYPICAL PROTON BEAM INTENSITIES FOR 7.0 SECOND SPILL, 8 sec rep.

AGS circulating intensity		2.5×10^{12}
CE 010	SEC	1.0×10^{11}
B target	SEC	2×10^{10}
Experimental Ion Chamber		3×10^{9}

B1 Line (RR)

PROTON BEAM MOMENTUM CALIBRATIONS

(For a description of the methods, see the text.)

Gauss Clock	RF Frequency	B1 Dipoles	Neutron Mass*
5.0	5.12 ± 0.026	-	5.12 ± 0.01
5.29 ± 0.05	5.40 ± 0.027	5.38 ± 0.010	5.38 ± 0.01
5.80 ± 0.03	5.95 ± 0.030	5.97 ± 0.020	5.92 ± 0.01

*Assumed $p_\perp$ kick of the 18D36 spectrometer magnets was 303 MeV/c.

Subject: Re: Talk on AGS Expt 703, For Ted Kycia Symposium
Date: Wed, 03 May 2000 11:42:25 -0500
From: Michael Witherell <witherell@fnal.gov>
Organization: Fermilab
To: Alan Carroll <acarroll@bnl.gov>

Hello Alan,

I remember the experiment well, but probably not very much that Laurie Littenberg has not already supplied. I remember most vividly the fact that we were running the accelerator in a new mode, one with low energy and long, long spill. (My memory is that the beeper in the trailer had an eerie wail during the spill, but my memory may not be that reliable.)

It was great fun working on an experiment that could be done so quickly. To get to the desired sensitivity without building a completely new apparatus required a heroic effort to suppress the backgrounds. It was a great opportunity for some younger physicists like Bob Webb, Laurie Littenberg, and myself to solve these problems.

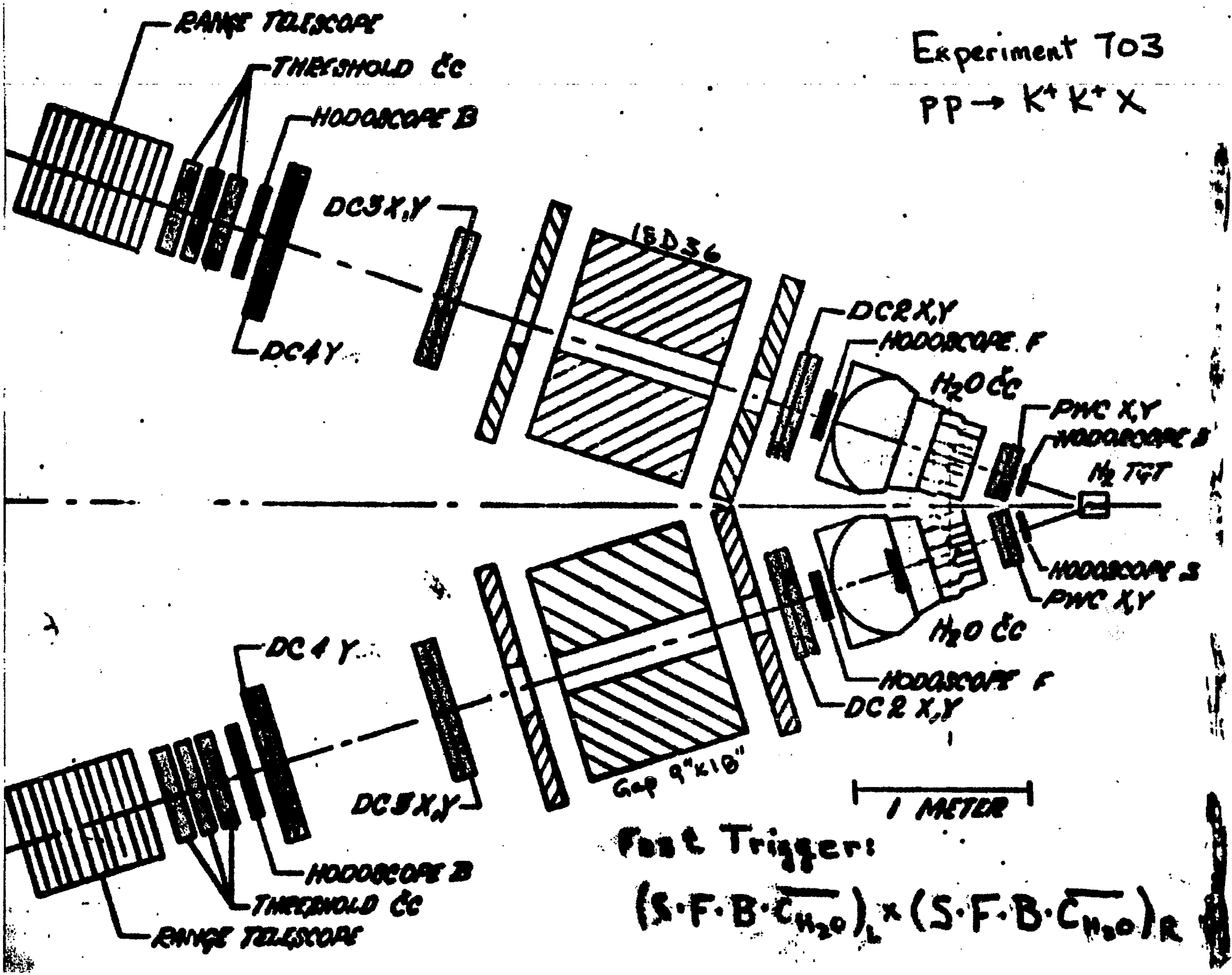
Ted was an excellent group leader and a good person to work with. I am sure that he will be missed especially by those of you who worked closely with him for many years.

Best regards,

Mike

Experiment 703

$pp \rightarrow K^+K^+X$



Fast Trigger:

$$(S\cdot F\cdot B\cdot \overline{C_{H_2O}})_L \times (S\cdot F\cdot B\cdot \overline{C_{H_2O}})_R$$

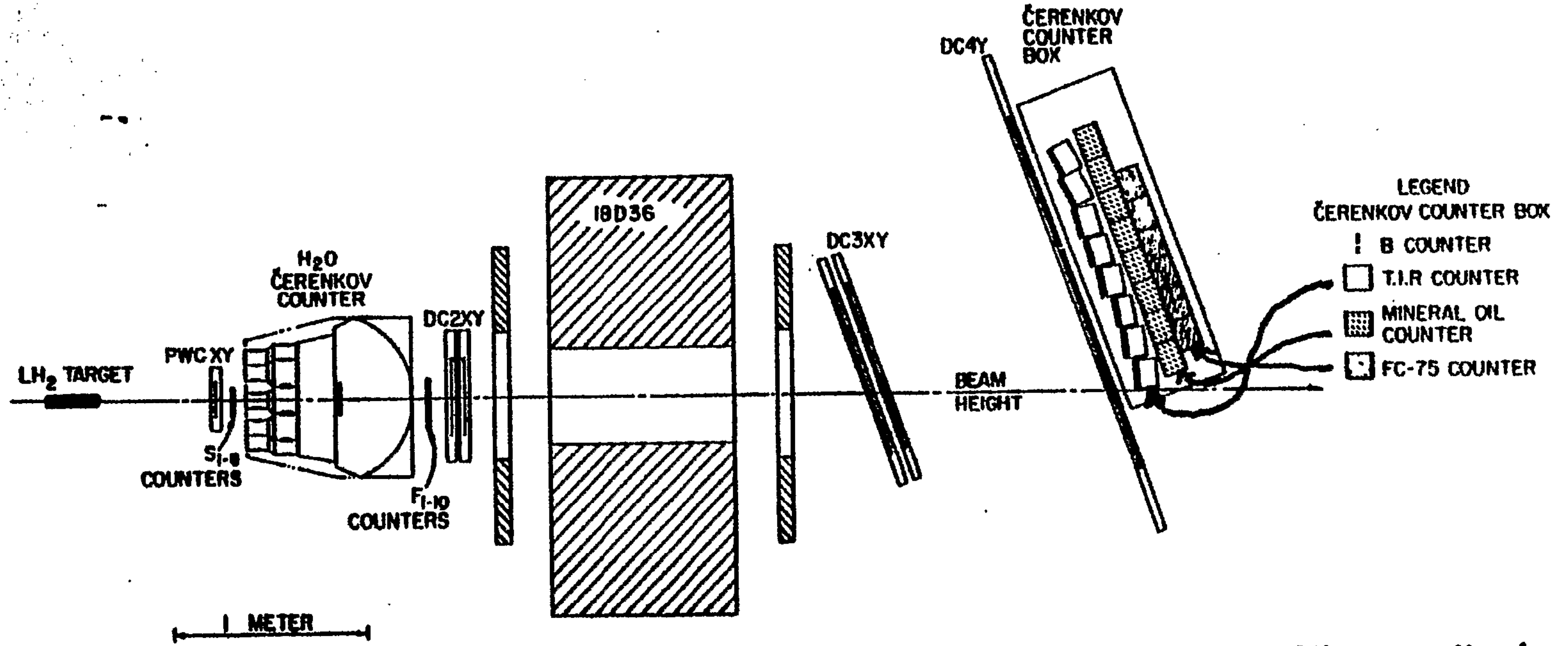
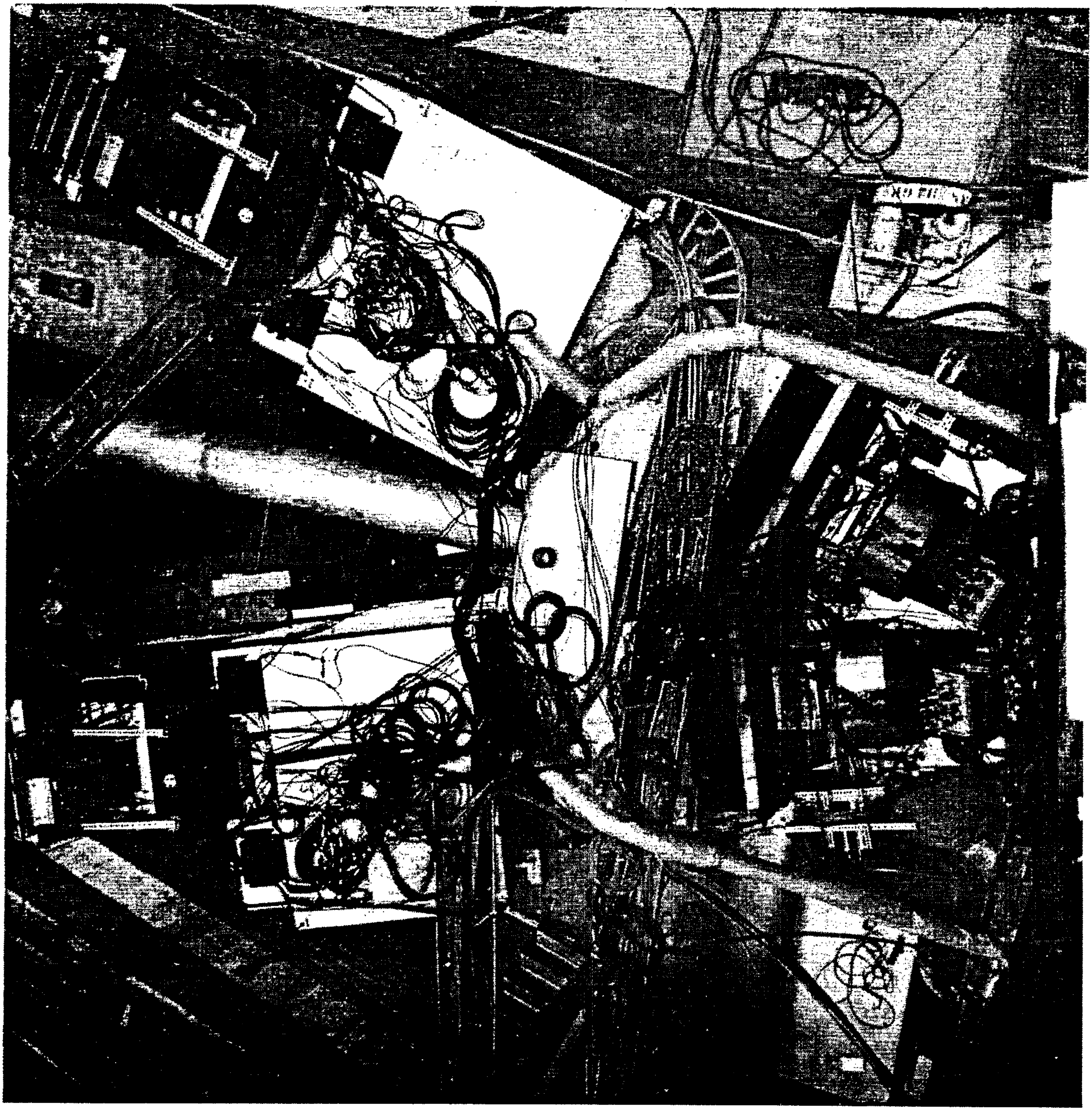


FIG. 1. Elevation view of one arm of the spectrometer. PWC and DC indicate the positions of the proportional wire and drift chambers.



ACCEPTANCE FOR $PP \to K^+K^+H$

$P_{INC} = 5.0$ GeV/c

MAGNET BEND = 300 MeV/c

K^+ DECAY INCLUDED

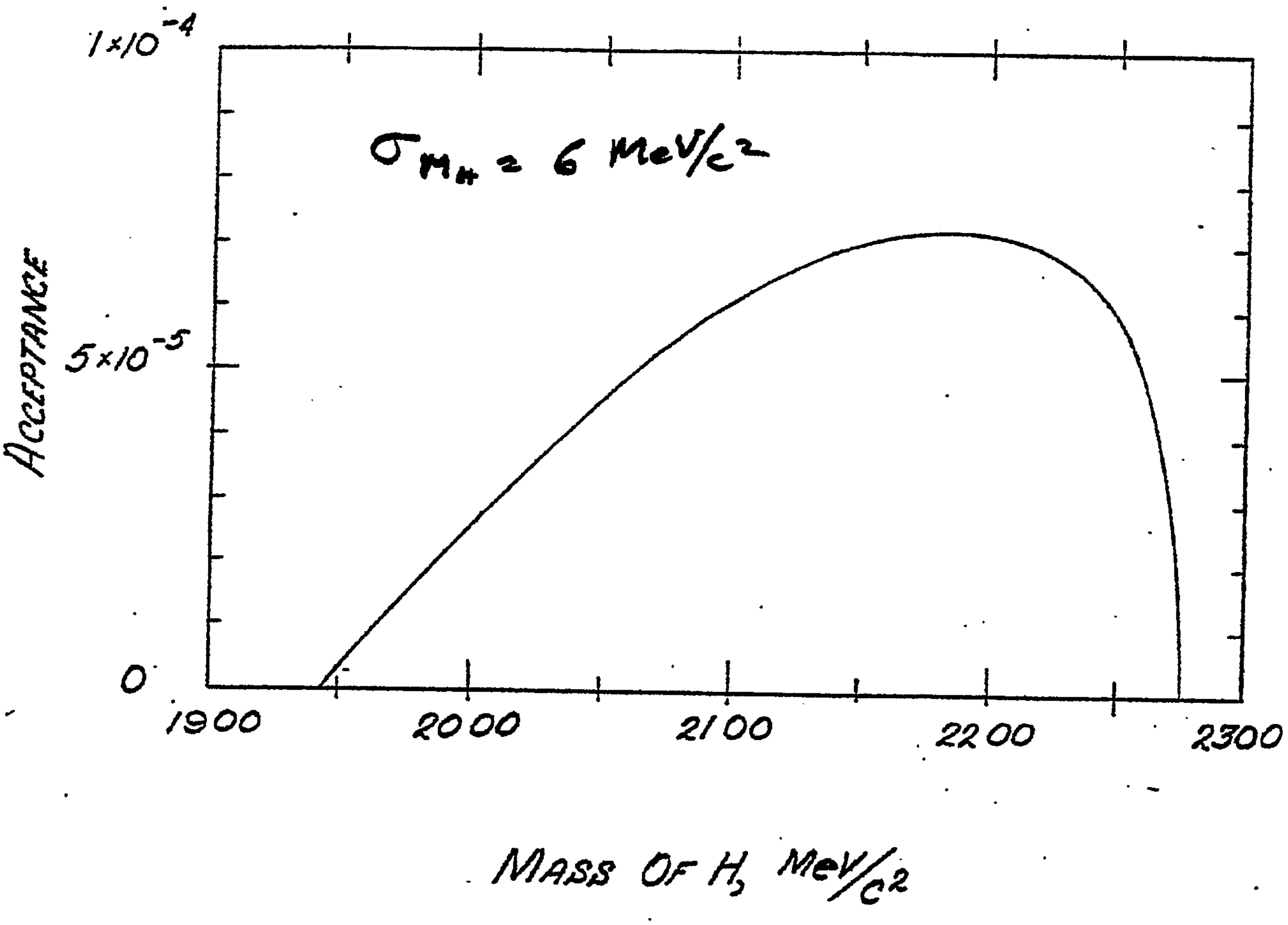
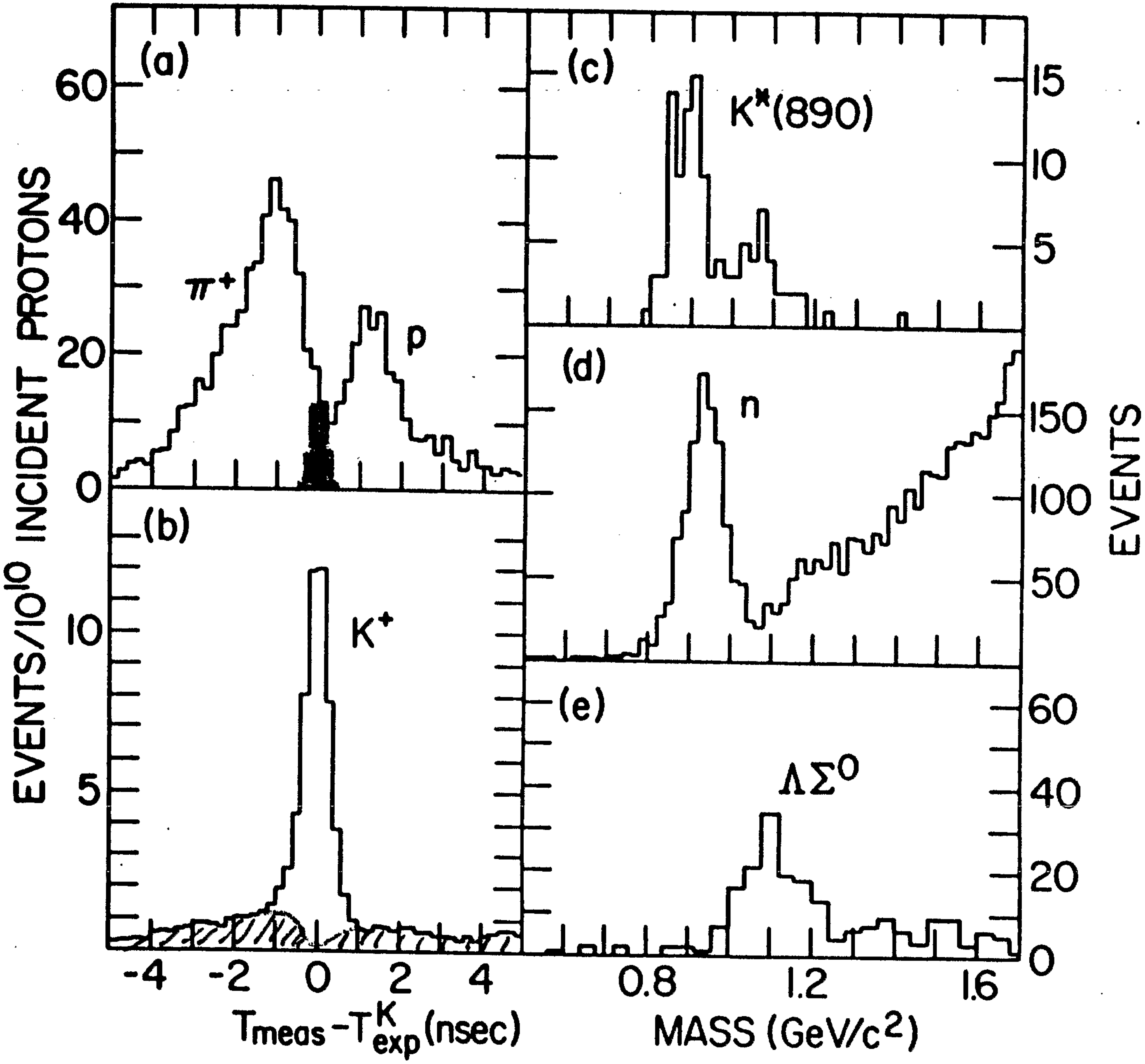


FIGURE 3

Exp. 703


(a)
(b)
(c)
(d)
(e)
π+
p
K+
K*(890)
n
ΛΣ0
EVENTS/10^10 INCIDENT PROTONS
EVENTS
60
40
20
0
10
5
15
10
5
150
100
50
60
40
20
0
-4
-2
0
2
4
Tmeas - TKexp (nsec)
0.8
1.2
1.6
MASS (GeV/c2)

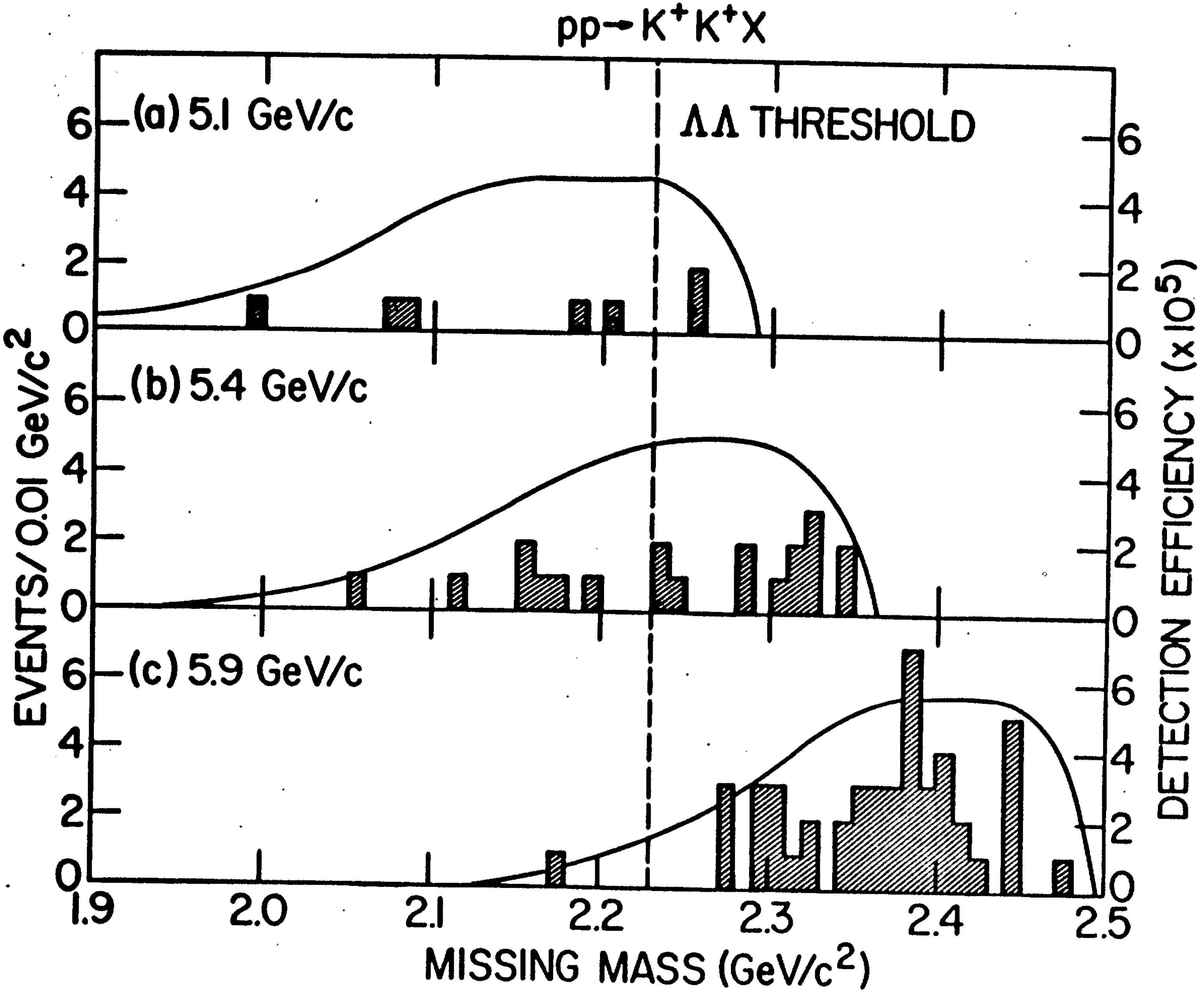

pp→K⁺K⁺X
(a) 5.1 GeV/c
(b) 5.4 GeV/c
(c) 5.9 GeV/c
ΛΛ THRESHOLD
EVENTS/0.01 GeV/c²
DETECTION EFFICIENCY (x 10⁵)
MISSING MASS (GeV/c²)
0
2
4
6
1.9
2.0
2.1
2.2
2.3
2.4
2.5

Figure 2

TABLE I. 90%-confidence-level (90% C.L.) upper limits for the production cross section (in nanobarns) of narrow dihyperon resonance.

Beam momentum (GeV/c)	Mass interval (GeV/c^2)	90% C.L. upper limits (nb)
5.1	2.0–2.1	130
5.1	2.1–2.23	50
5.4	2.1–2.23	40
5.4	2.23–2.35	30
5.9	2.23–2.35	130
5.9	2.35–2.48	90

Dedicated H Search
Dedicated Strangelet Searches

H° and Strangelet Search Experiments

Exp. No.	Spokesperson	Title	Beam	Remarks	Status
810	Lindenbaum/Platner	Search for quark matter (QGP) & other new phenomena utilizing HI collisions at the AGS	Si	H° & Strangelets	Completed 1991
813	Franklin/Barnes	Search for a strangeness -2 dibaryon	Ξ^-	H°	Completed (?) 1993
814	Braun-Munzinger	Study of extreme peripheral collisions & of the transition from peripheral to central collisions in reactions induced by relativistic HI	Si	Strangelets	Completed 1992
836	Franklin/Barnes	Search for a strangeness -2 dibaryon using a ^{3}He target	K^-	H°	Running 1994
858	Crawford	Measurement of negative particle yield at 0° for 15A GeV Si+Au collisions	Si	Strangelets	Completed 1991
864	Sandweiss	Production of rare composite objects in relativistic HI collisions	Au	H° & Strangelets	Begins 1994
878	Crawford	Investigation of antinucleus production & search for new particles in nucleus-nucleus collisions at AGS	Si & Au	Strangelets	Completed 1993
882	Price	Search for particles with $\lvert Z \rvert \geq 3$ & negative charge or large A/Z produced in central nucleus-nucleus collisions	Si & Au	Strangelets	Completed 1993
885	May/Franklin/Davis	Experiment to detect $\Lambda\Lambda$ hypernuclei	Ξ^-	H° nuclei	Engineering 1994/run 1995
886	Imai/Pile/Diebold	Search for new particles in nucleus-nucleus collisions	Si & Au	Strangelets	Completed 1993
888	Cousins/Schwartz	Search for the H dibaryon	p	H°	Completed ~~1993~~ 1992
891	Platner	A search for quark matter (QGP) & other new phenomena utilizing Au-Au collisions at AGS	Au	H° & Strangelets	Not yet scheduled
896	Crawford/Hallman	Search for a short-lived H° dibaryons, strange matter, etc.	Au	H° & Strangelets	Not yet scheduled

"Universal" Relevance

BNL
BROOKHAVEN NATIONAL LABORATORY

Committee Report on Speculative "Disaster Scenarios" at RHIC

Synopsis of committee report
(link to complete report can be found at the end of this document)

John Marburger, Director
Brookhaven National Laboratory
October 6, 1999

Three different kinds of "disaster" scenarios have been discussed in connection with high energy particle collisions:

A. Creation of a black hole that would "eat" ordinary matter.
B. Initiation of a transition to a new more stable universe.
C. Formation of a "strangelet" that would convert ordinary matter to a new form.

"1. At present, despite vigorous searches, there is no evidence whatsoever for stable strange matter anywhere in the Universe."

"2. On rather general grounds, theory suggests that strange matter becomes unstable in small lumps due to surface effects. Strangelets small enough to be produced in heavy ion collisions are not expected to be stable enough to be dangerous."

"3. Theory suggests that heavy ion collisions . . . are not a good place to produce strangelets. Furthermore, it suggests that the production probability is lower at RHIC than at lower energy heavy ion facilities like the AGS and CERN. . . ."

"4. It is overwhelmingly likely that the most stable configuration of strange matter has positive electric charge."

E732

The Search for the η_c

Twenty Years Later

Randy Johnson
University of Cincinnati

Kycia Memorial Symposium
Brookhaven National Laboratory
May 19, 2000

BROOKHAVEN
NATIONAL LABORATORY

managed by Brookhaven Science Associates
for the U.S. Department of Energy

E732

The Search for the η_c

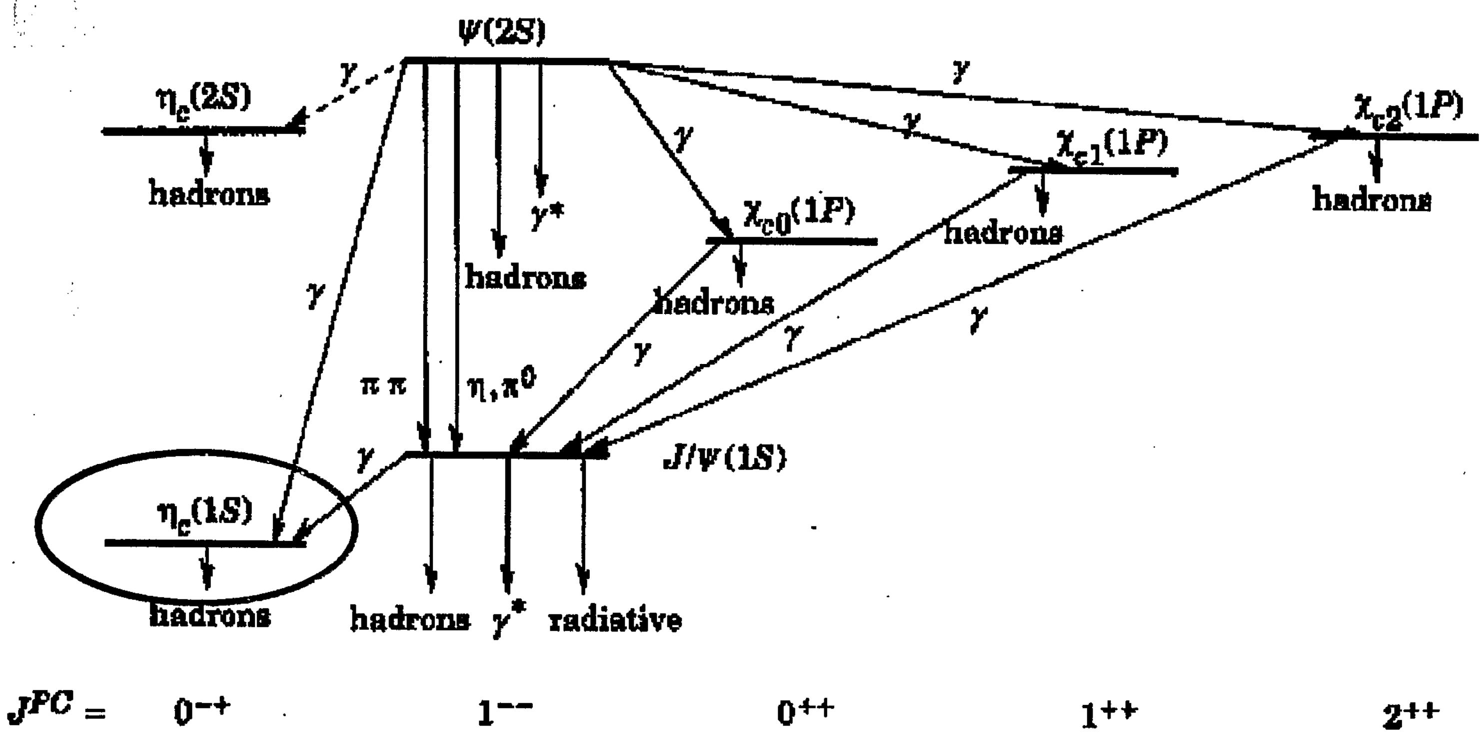
Twenty Years Later

Randy Johnson
University of Cincinnati

Kycia Memorial Symposium
Brookhaven National Laboratory
May 19, 2000

THE HOLY GRAIL OF HADRON MACHINES

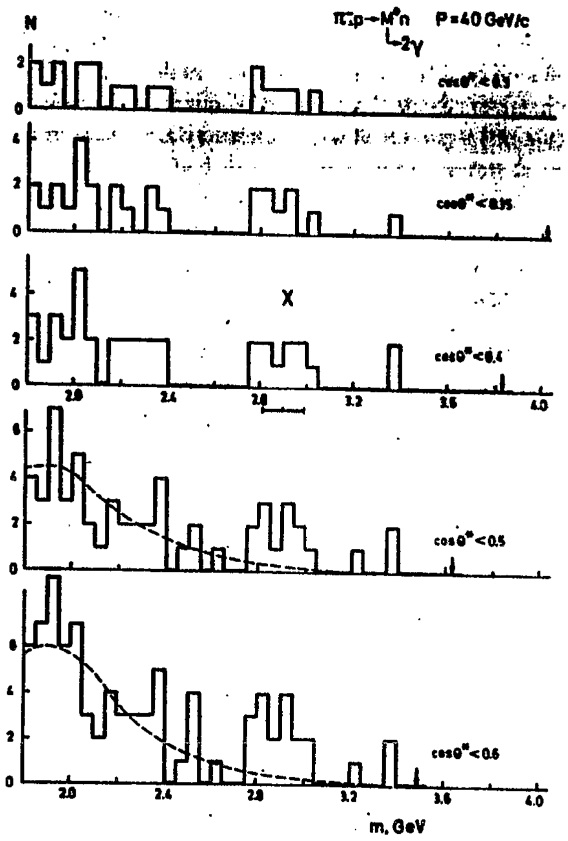
THE CHARMONIUM SYSTEM



and BNL wants another piece of the action

Expectations 20 Years Ago

X(2880)



+ Verified DESY result

+ Indicated hadronic production was possible

- Too low of mass to be η_c (possible ccqq state?)

W. D. Apel, et al., PL 72B 500(1978)

Expectations 20 Years Ago

η, η', η_c mixing

Harari, PL 60B, 172(1976)

η_c contains 10% η and 30% η'

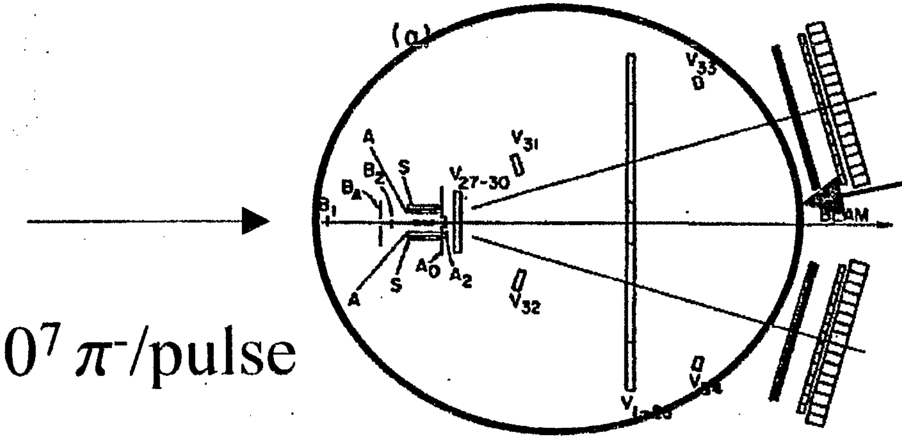
Fritzsch and Jackson, PL 66B (1977)

η_c contains 1% η and 2% η'

$\eta_c \Longrightarrow \gamma\gamma$

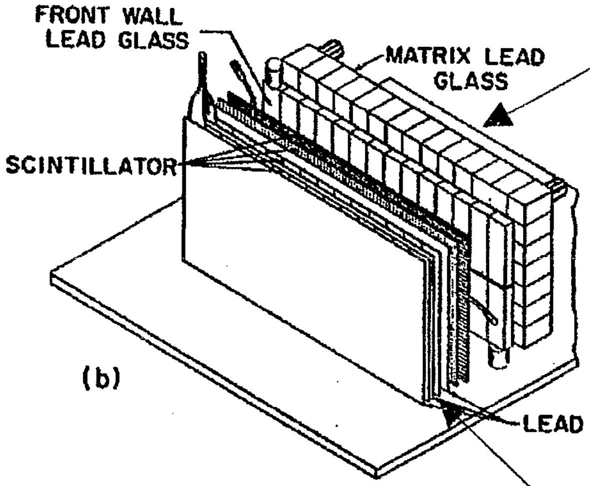
QCD ⇨ BR ~ 1×10^{-3}

The Detector



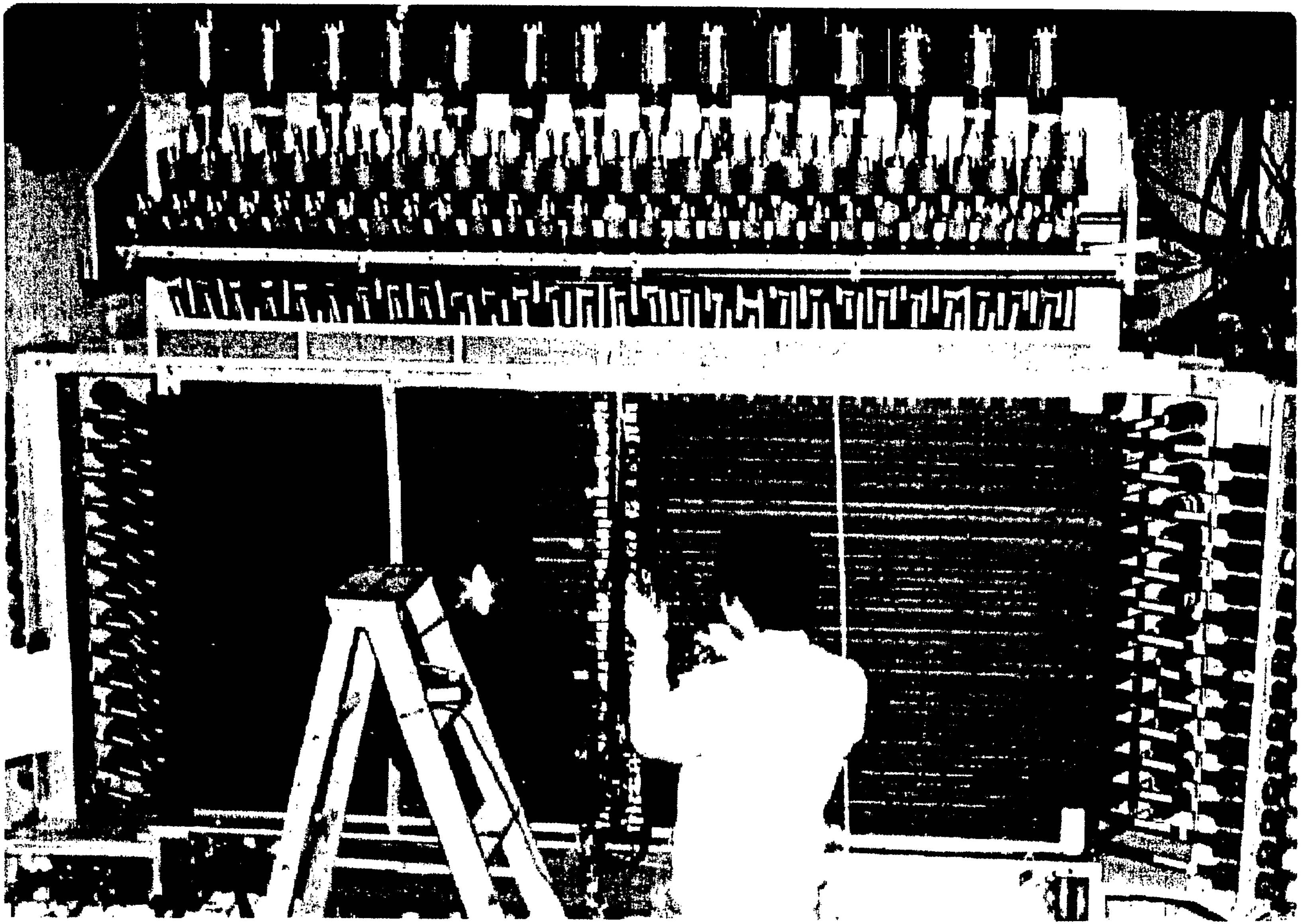
$10^7 \pi^-$/pulse

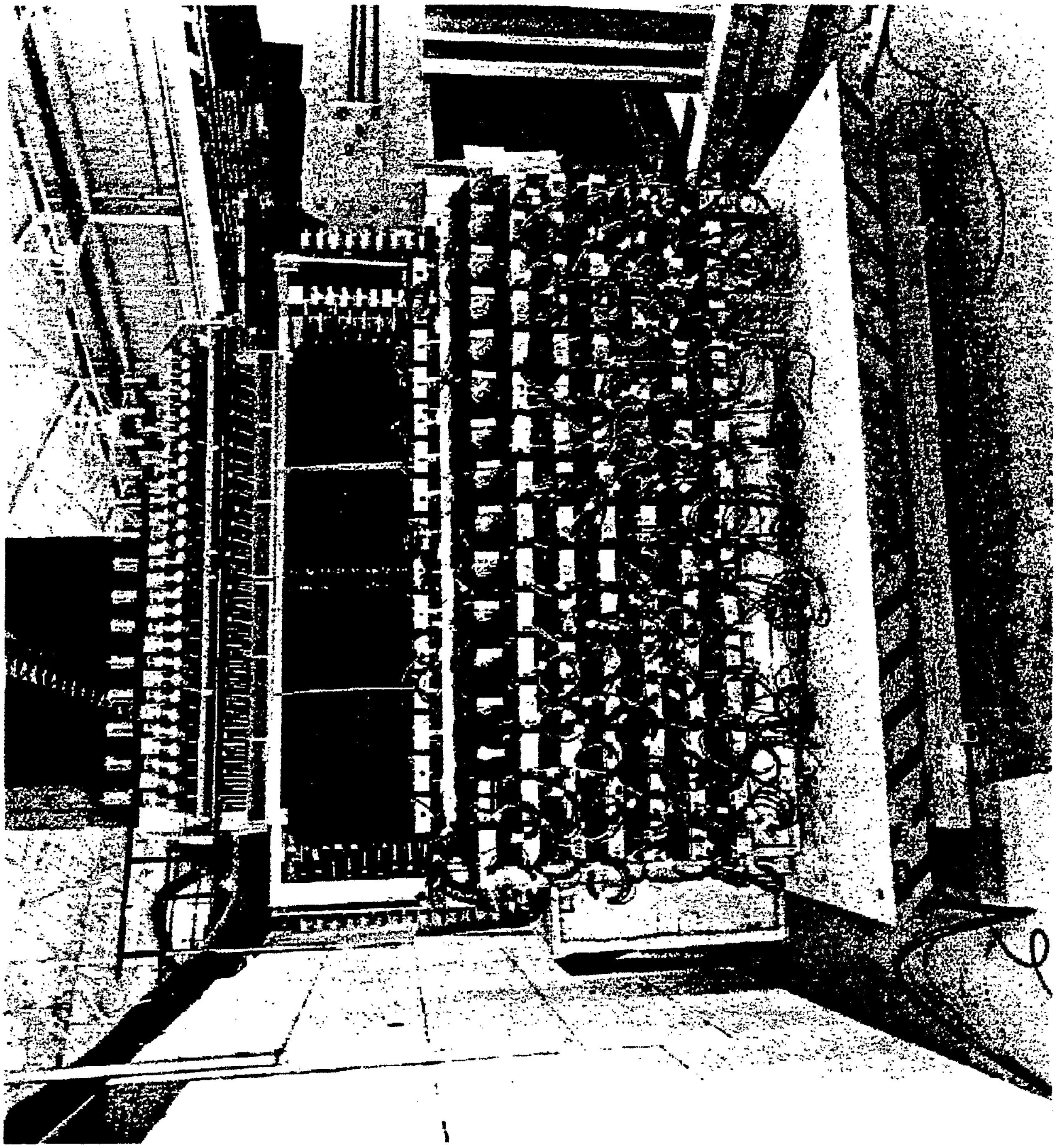
Gamma and Charged
Particle Vetos



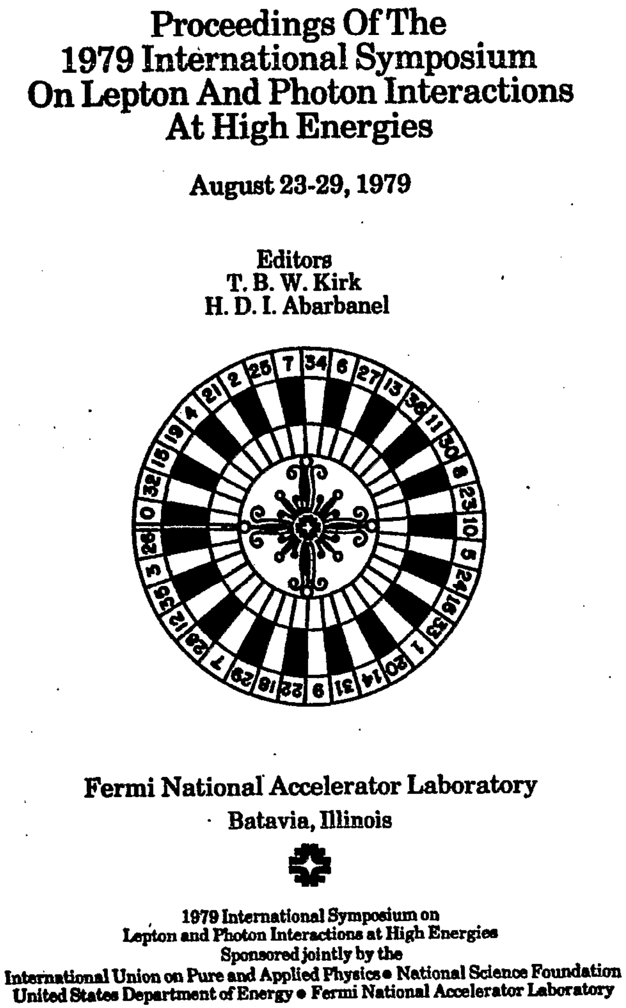
E631 Lead Glass

Lead Scintillator Converter





In the Interim....



Proceedings Of The
1979 International Symposium
On Lepton And Photon Interactions
At High Energies

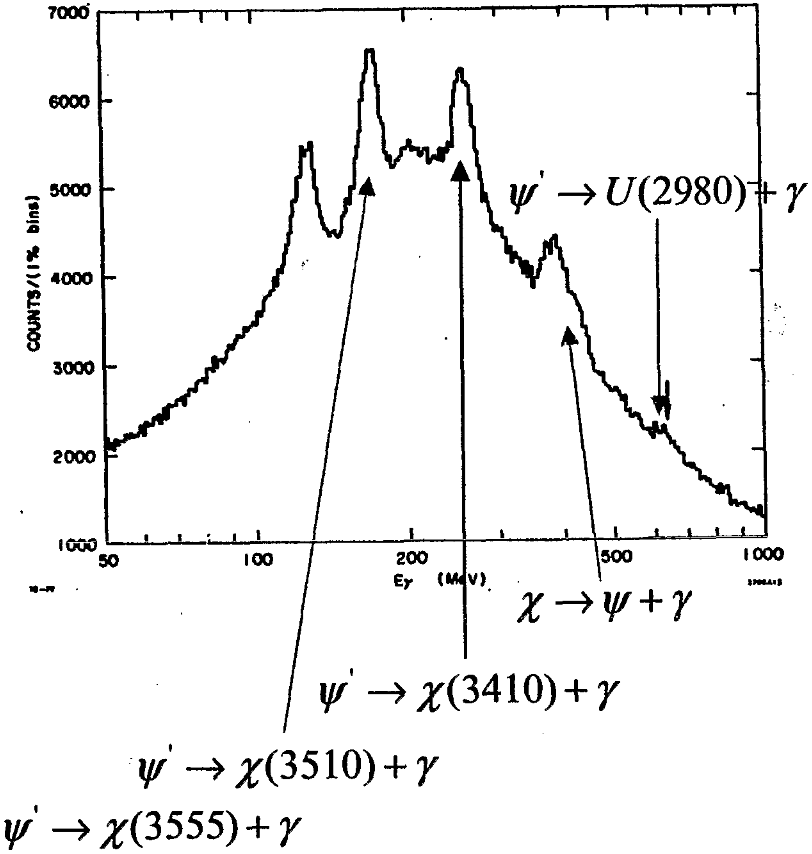
August 23-29, 1979

Editors
T. B. W. Kirk
H. D. I. Abarbanel

Fermi National Accelerator Laboratory
Batavia, Illinois

1979 International Symposium on
Lepton and Photon Interactions at High Energies
Sponsored jointly by the
International Union on Pure and Applied Physics • National Science Foundation
United States Department of Energy • Fermi National Accelerator Laboratory

Results from the Crystal Ball



Taking Our Show on the Road

Experimental Meson Spectroscopy-1980
(Sixth International Conference, Brookhaven)

Editors
S. U. Chung
Brookhaven National Laboratory
and
S. J. Lindenbaum
Brookhaven National Laboratory
and City College of New York

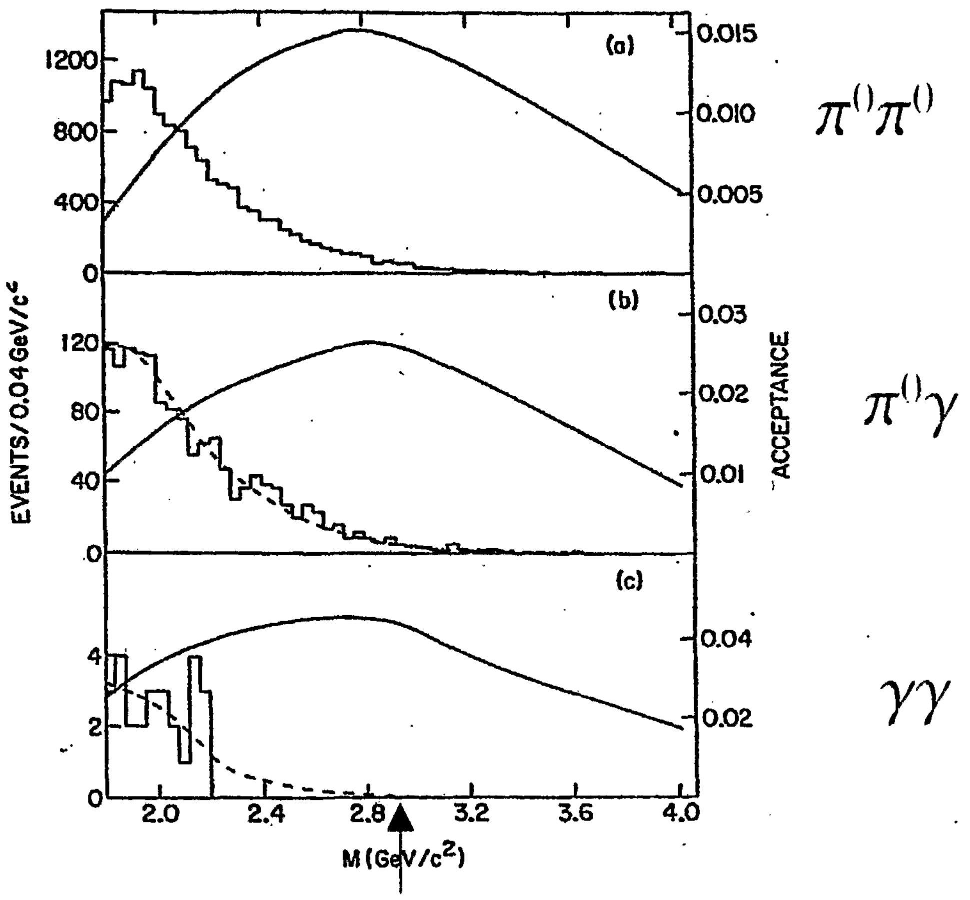
High Energy Physics-1980
(XX International Conference, Madison, Wisconsin)

Part 2

XX ICHEP

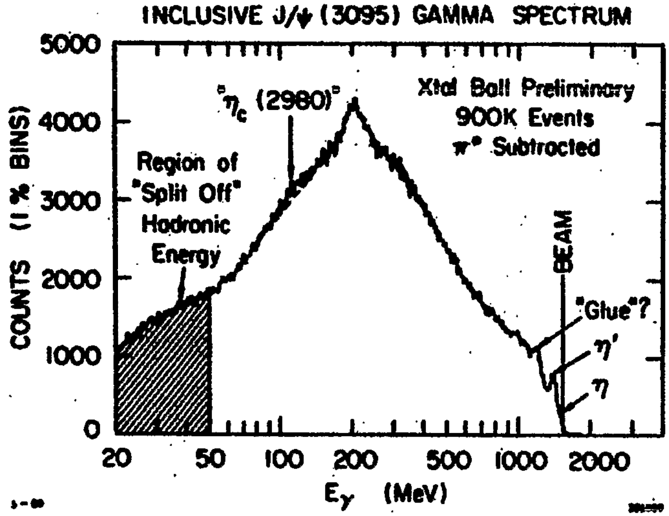
Editors
Loyal Durand and Lee G. Pondrom
University of Wisconsin

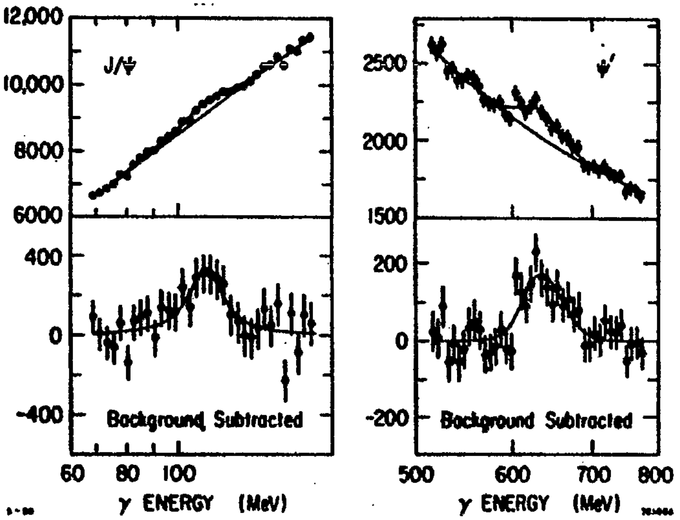
Intermediate Results



No X(2880)

But So Does the Crystal Ball





Experimental Meson Spectroscopy-1980
(Sixth International Conference, Brookhaven)

Elliot Bloom

Editors
S. U. Chung
Brookhaven National Laboratory
and
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Brookhaven National Laboratory
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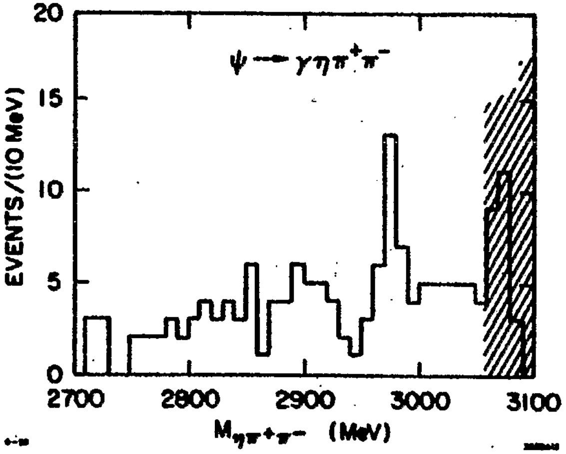

Published Results

EXPERIMENTAL SEARCH FOR NARROW RESONANCES IN THE REACTION $\pi^- p \to \gamma\gamma n$ AT 13 GeV/c [☆]

I.H. CHIANG, R.A. JOHNSON, B.P. KWAN, T.F. KYCIA, K.K. LI,
L.S. LITTENBERG, A.R. WIJANGCO [1]
Brookhaven National Laboratory, Upton, NY 11973, USA

A.M. HALLING [2], G.E. HOGAN [3], C.G. LU [4], K.T. McDONALD, A.J.S. SMITH, M.H. YE [4]
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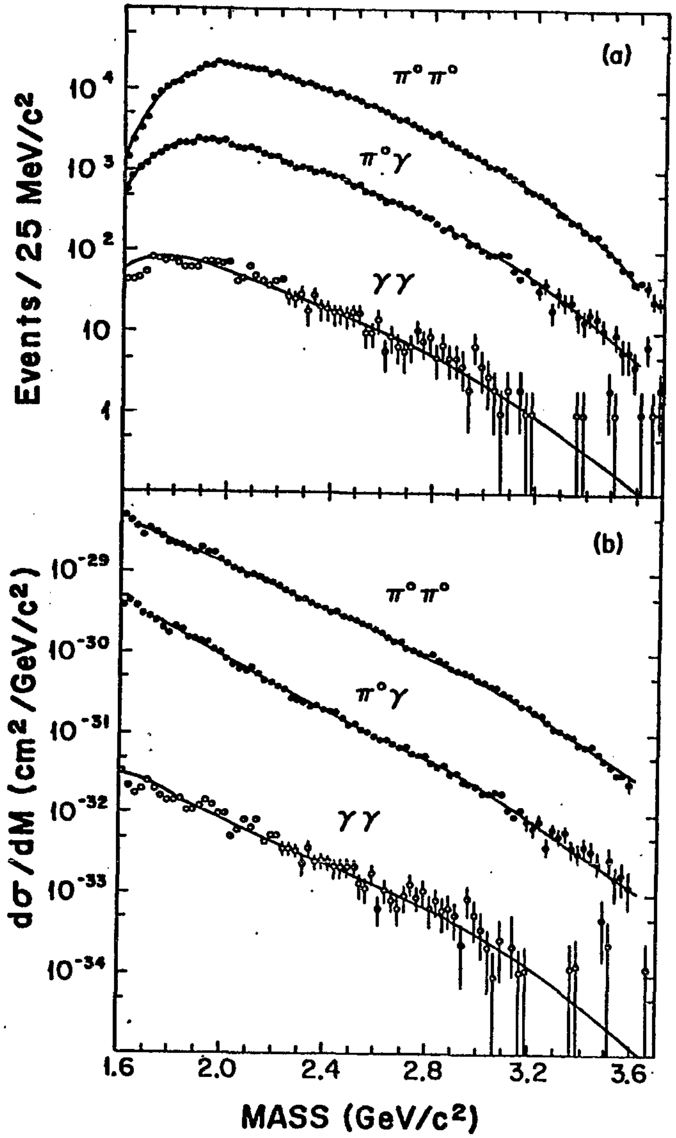
and

L.A. GARREN [5] and J.J. THALER
University of Illinois, Urbana, IL 61801, USA

Physics Letters, 140B 145(1984)

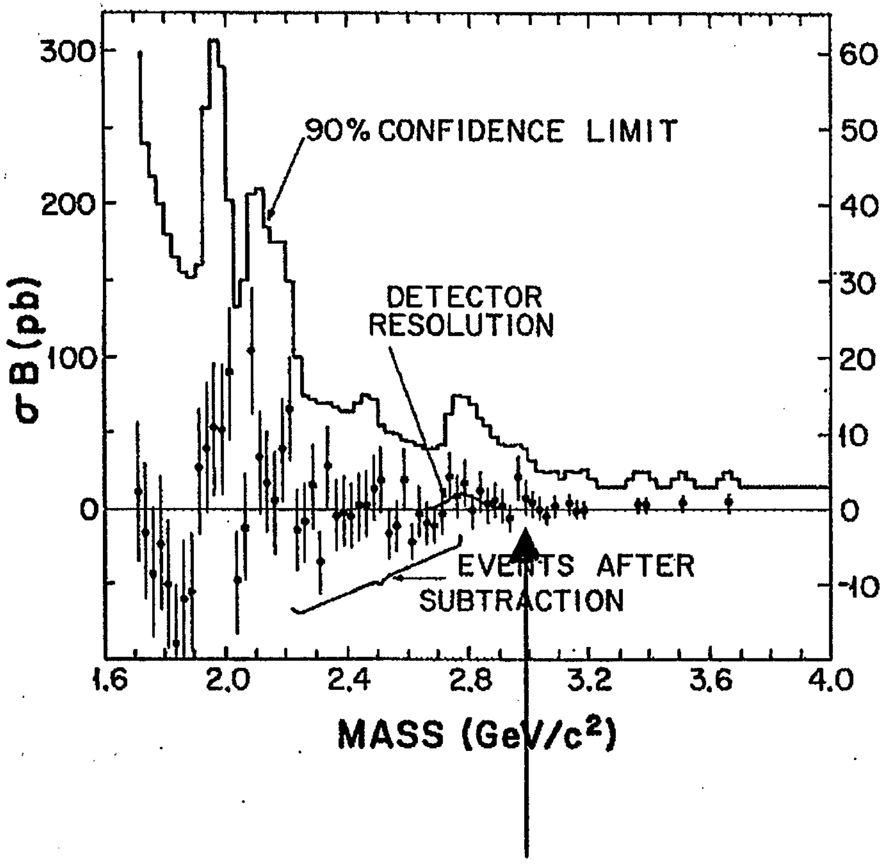


Raw Events

$\gamma\gamma$ events predicted from $\pi^0\gamma$ and $\pi^0\pi^0$ events

Acceptance Corrected Events

Final Result



η_c mass

σ x Br < 44 pb

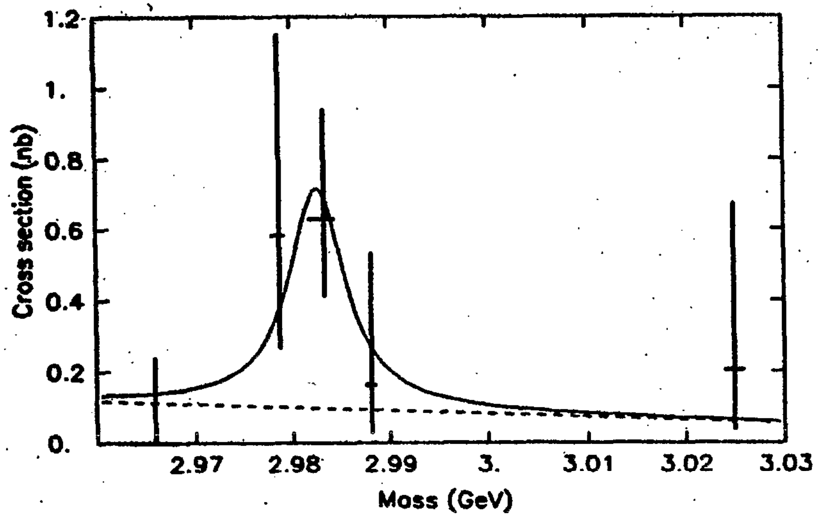
$\sigma(\pi^- p \text{ -> } \eta_c n) < .15\ \mu b$

$$\frac{\sigma(\pi^- p \text{ -> } \eta_c n)}{\sigma(\pi^- p \text{ -> } \eta n)} < .02$$

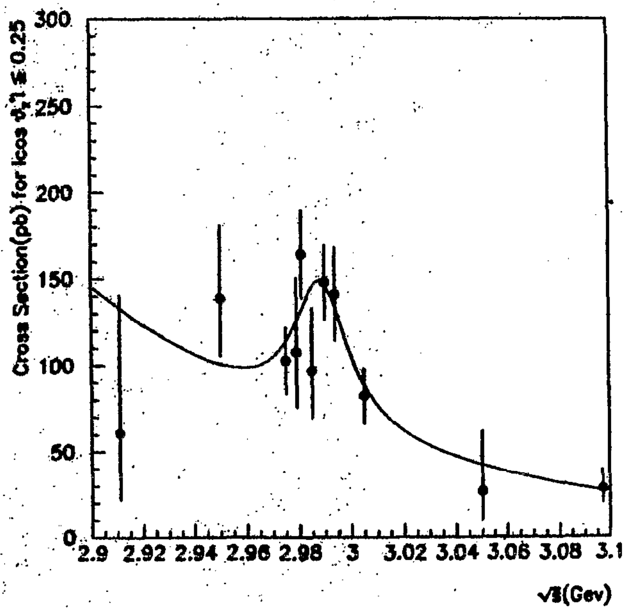
Physics Post Script

$\eta_c \Longrightarrow \gamma\gamma$ is found

CERN $\bar{p}p \rightarrow \gamma\gamma$ FNAL



Baglin, *et al.*, PL **B187**, 191(1987)

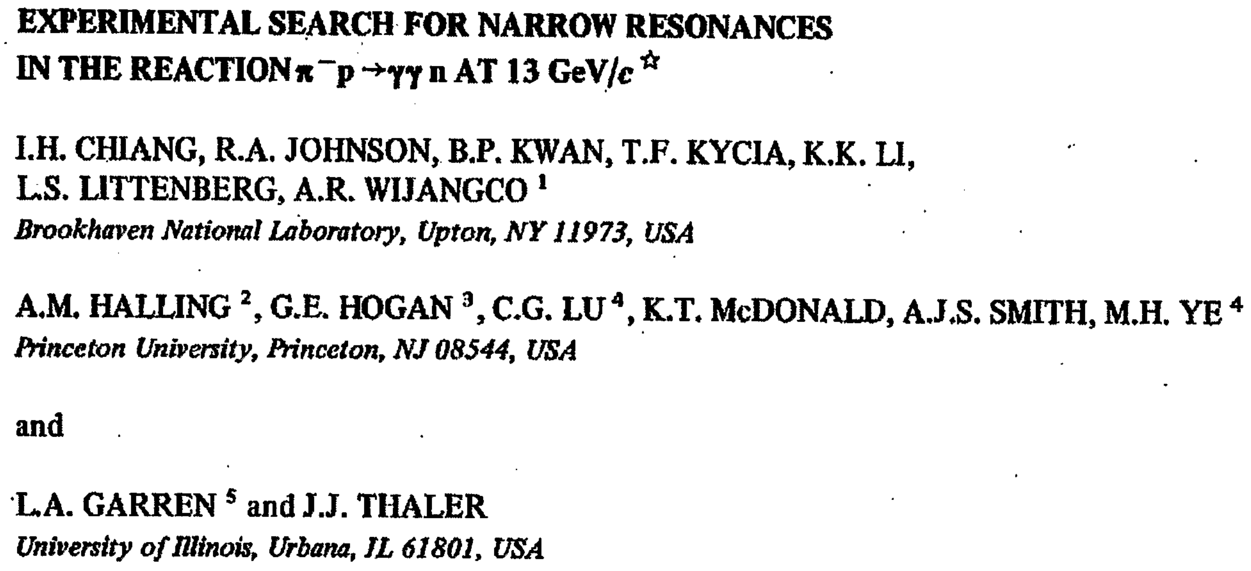


Armstrong, *et al.*,
PR **D52**, 4839(1995)

Physics of E732 – Twenty Years Later

- η_c's are still scarce
- Br($\eta\chi \Longrightarrow \gamma\gamma$) ~ .3 x 10^{-3} (theory 1 x 10^{-3})
- X(2880) has disappeared
- η_c does not mix with the η, η'

Where are they now?



EXPERIMENTAL SEARCH FOR NARROW RESONANCES IN THE REACTION $\pi^- p \rightarrow \gamma\gamma n$ AT 13 GeV/c ☆

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L.S. LITTENBERG, A.R. WIJANGCO [1]
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and

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Physics Letters, 140B 145(1984)

Mike Halling

EXPERIMENTAL SEARCH FOR NARROW RESONANCES IN THE REACTION $\pi^- p \rightarrow \gamma\gamma n$ AT 13 GeV/*c* ☆

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and

L.A. GARREN [5] and J.J. THALER
University of Illinois, Urbana, IL 61801, USA

Susan, Seth and Mike

Designs and builds ion accelerators
Eaton Corp., Beverly, MA

EATON

Physics Letters, 140B 145(1984)

Lynn Garren

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~~University of Illinois~~, Urbana, IL 61801, USA

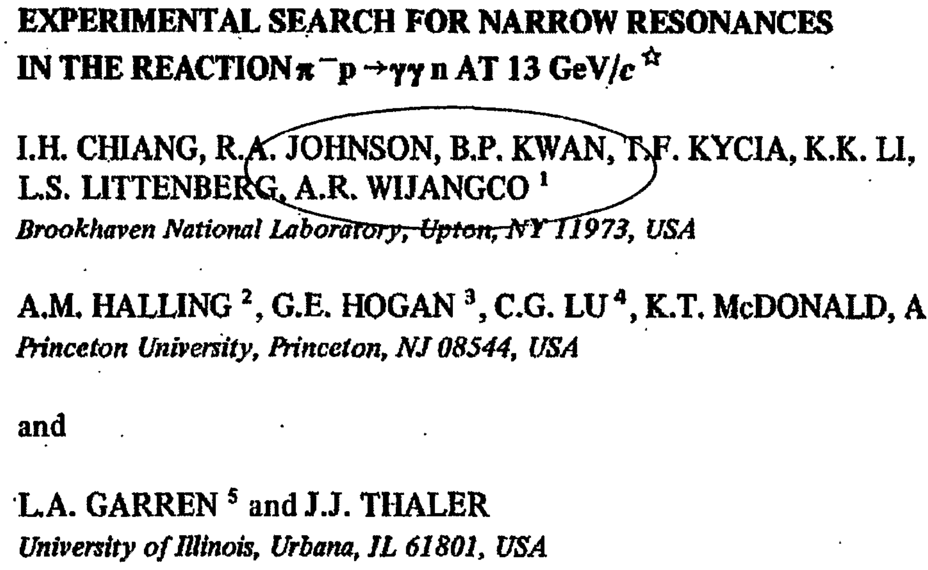
E831 FOCUS

Computing Division, Focus, BTeV
Fermilab BTEV/CO

Fermilab
Discovering the Nature of Nature

Physics Letters, 140B 145(1984)

Tony Wijangco
Betty Kwan



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University of Illinois, Urbana, IL 61801, USA

?

Physics Letters, 140B 145(1984)

Gary Hogan

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and

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$\mu \Longrightarrow e\gamma$

Proton Radiography

Physics Letters, 140B 145(1984)

Jon Thaler

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Professor, University of Illinois
CLEO

Physics Letters, 140B 145(1984)

Kirk McDonald

ARROW RESONANCES
13 GeV/c ☆

. KWAN, T.F. KYCIA, K.K. LI,
CO [1]
, *NY 11973, USA*

C.G. LU[4], K.T. McDONALD, A.J.S. SMITH, M.H. YE [4]
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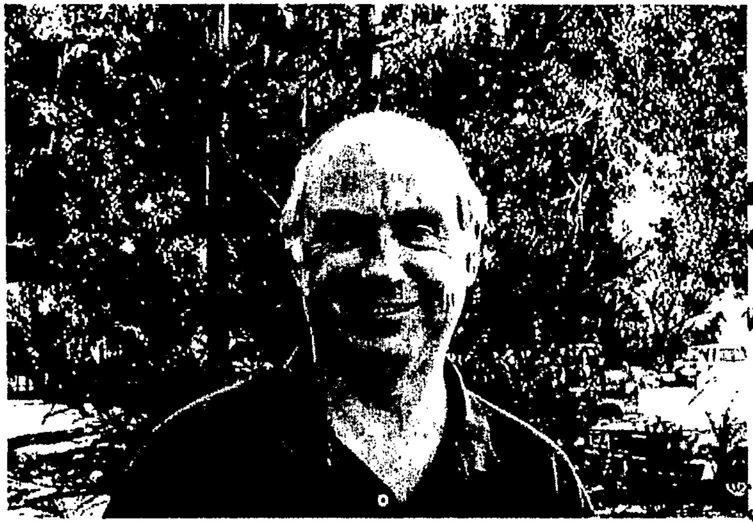
University of Illinois, Urbana, IL 61801, USA

Professor, Princeton
E144 and BaBar at SLAC

Physics Letters, 140B 145(1984)

Stu Smith



ROW RESONANCES
GeV/c ☆

VAN, T.F. KYCIA, K.K. LI,

11973, USA

LU[4], K.T. McDONALD, A.J.S. SMITH, M.H. YE[4]
SA

Smith, Stewart

and

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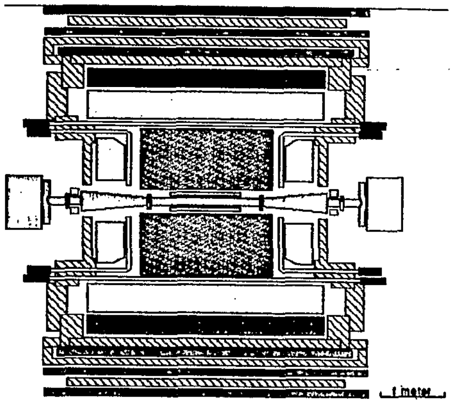
Professor, Princeton
Former Department Chair
Technical Coordinator - BaBar

Physics Letters, 140B 145(1984)

Mr. Ye (Ming Han)



BES Detector
Institute of High Energy Physics
Beijing, P.R.C.

EXPERIMENTAL SEARCH FOR NARROW RESONANCES IN THE REACTION $\pi^- p \rightarrow \gamma\gamma n$ AT 13 GeV/*c* [☆]

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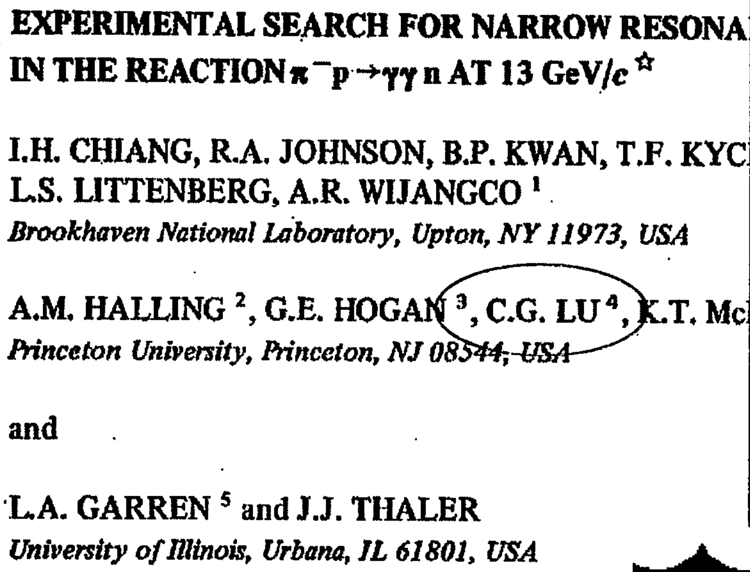
Former Director (retired)

Institute for High Energy Physics

Beijing

Physics Letters, 140B 145(1984)

Mr. Lu (Chang Guo)



EXPERIMENTAL SEARCH FOR NARROW RESONA
IN THE REACTION $\pi^- p \to \gamma\gamma n$ AT 13 GeV/c☆

I.H. CHIANG, R.A. JOHNSON, B.P. KWAN, T.F. KYC
L.S. LITTENBERG, A.R. WIJANGCO[1]
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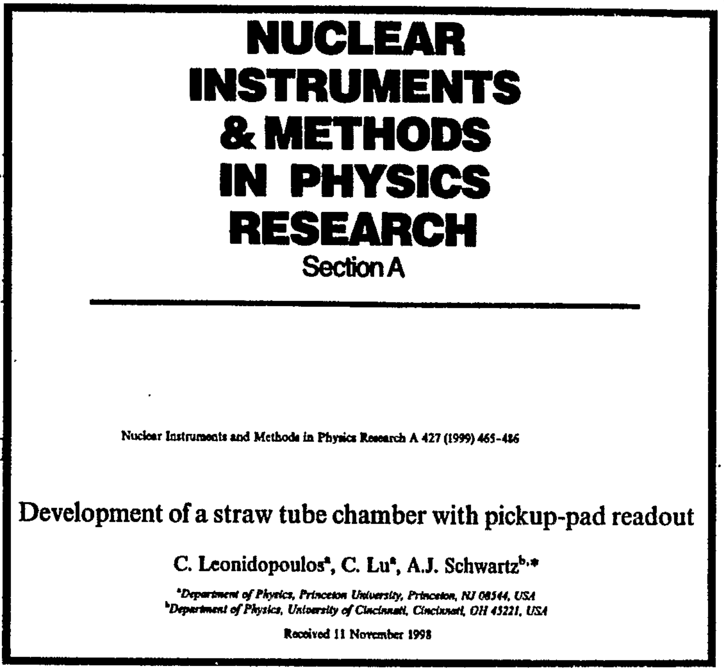


NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH
Section A

Nuclear Instruments and Methods in Physics Research A 427 (1999) 465–486

Development of a straw tube chamber with pickup-pad readout

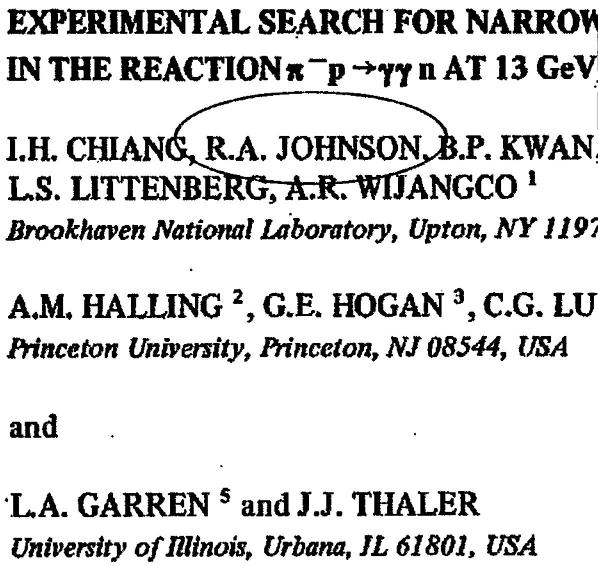
C. Leonidopoulos[a], C. Lu[a], A.J. Schwartz[b,*]

[a]*Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[b]*Department of Physics, University of Cincinnati, Cincinnati, OH 45221, USA*

Received 11 November 1998

Physics Letters, 140B 145(1984)

Yours Truly



EXPERIMENTAL SEARCH FOR NARRO
IN THE REACTION $\pi^- p \to \gamma\gamma n$ AT 13 GeV

I.H. CHIANG, R.A. JOHNSON, B.P. KWAN
L.S. LITTENBERG, A.R. WIJANGCO [1]
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Professor, Cincinnati
NuTeV and BooNE, FNAL

Physics Letters, 140B 145(1984)

The rest of the Brookhaven Group

EXPERIMENTAL SEARCH FOR NARROW RESONANCES
IN THE REACTION $\pi^- p \to \gamma\gamma n$ AT 13 GeV/*c* ☆

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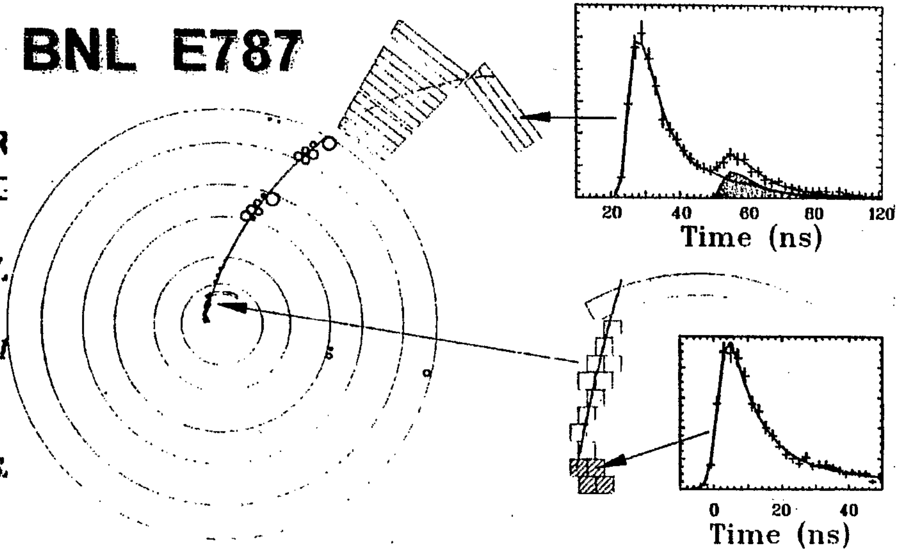
BROOKHAVEN
NATIONAL LABORATORY

managed by Brookhaven Science Associates
for the U.S. Department of Energy

Physics Letters, 140B 145(1984)

The rest of the Brookhaven Group

BNL E787



EXPERIMENTAL SEARCH FOR NARR
IN THE REACTION $\pi^- p \to \gamma\gamma n$ AT 13 C

I.H. CHIANG, R.A. JOHNSON, B.P. KW.
L.S. LITTENBERG, A.R. WIJANGCO [1]
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Physics Letters, 140B 145(1984)

Ted Kycia Memorial Symposium
May 19, 2000

E787: Searching for New Physics at the Sensitivity Frontiers

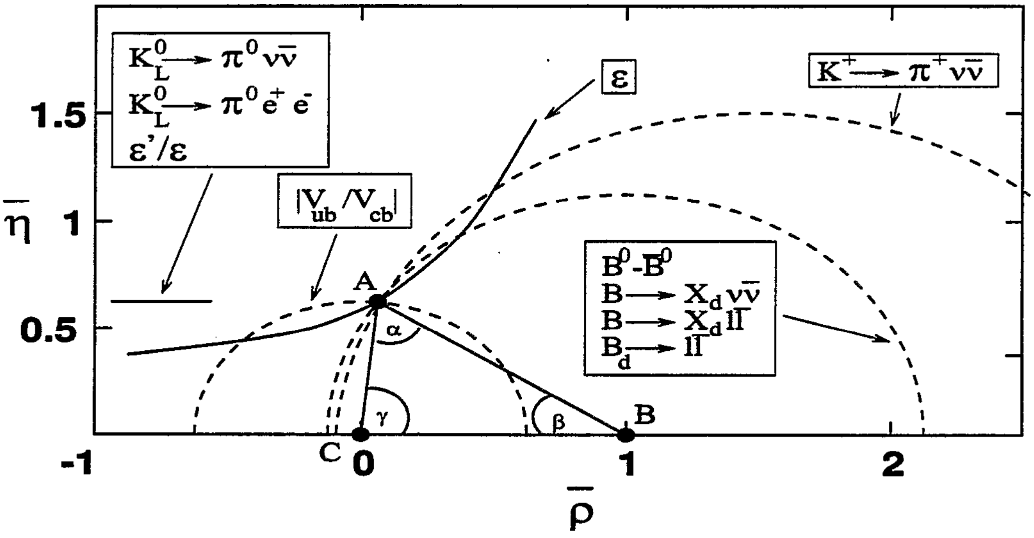
Douglas Bryman
University of British Columbia
Vancouver Canada

The "Generation Puzzle" persists fifty years after the discovery of strangeness and the first non-discovery of $\mu \to e\gamma$

$$\begin{array}{cccccc} u & c & t & e & \mu & \tau \\ d & s & b & \nu_e & \nu_\mu & \nu_\tau \end{array}$$

- KAONS at the center of action in particle physics.
- CP/T violation has been seen (only) in Kaon deacys.
- Lepton flavor-violating decays are still absent but LFV may have shown up in neutrino oscillations.

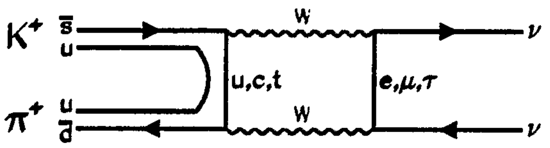
Unitarity relations e.g. $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

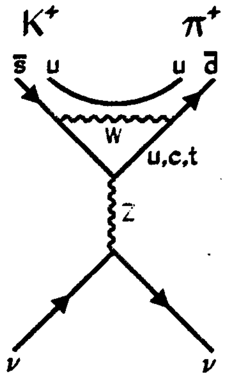


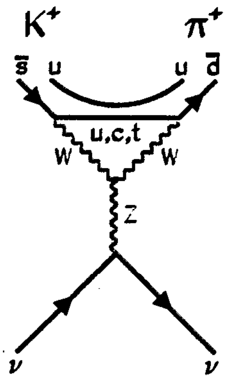
Four "Super-clean" K and B physics inputs will test the SM CP-V picture. (Buras)

$K^+ \longrightarrow \pi^+ \nu\bar{\nu}$	BNL-E787,E949, FNAL-CKM
$K_L^0 \longrightarrow \pi^0 \nu\bar{\nu}$	BNL KOPIO, FNAL KAMI
$B_d \longrightarrow \Psi K_s$	BABAR,BELLE,CDF,HERA-B
$\frac{x_s}{x_d} = \frac{B_s - \overline{B_s}}{B_d - \overline{B}_d}$	LHCB,BTEV

$K \rightarrow \pi\nu\bar{\nu}$ in the Standard Model



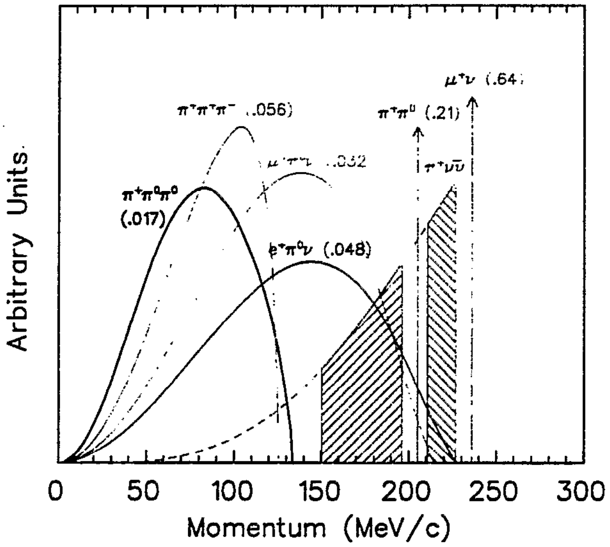




	$K^+ \rightarrow \pi^+\nu\bar{\nu}$	$K_L^0 \rightarrow \pi^0\nu\bar{\nu}$
Top Dependence	$\lvert\lambda_t\rvert = \lvert V_{ts}^* V_{td}\rvert$	$\mathrm{Im}(\lambda_t) = \mathrm{Im}(V_{ts}^* V_{td})$
Calc. BR (10^{-10})	0.82 ± 0.32	0.28 ± 0.1
Est. Theory Uncertainty	5% (charm)	1%

- Negligible long distance effects (10^{-13}).
- Hadronic matrix elements from isospin analog $K^+ \rightarrow \pi^0 e^+ \nu_e$.

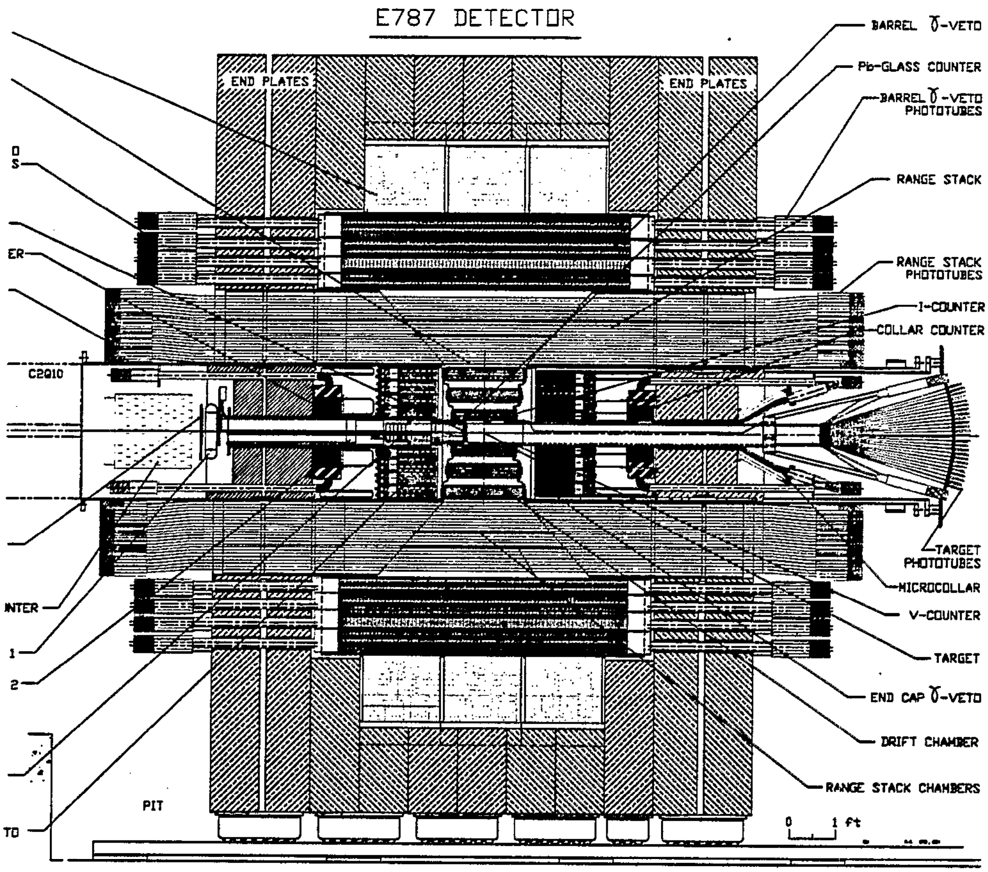
E787: Measuring $K^+ \to \pi^+\nu\bar{\nu}$



$K^+ \to$	π^+	$\nu\bar{\nu}$
Stopped $K \to \pi$	Momentum	4π Veto
C.M. system	Energy	
	Range	
	$\pi \to \mu \to e$	

PHILOSOPHY:

- Get as much information as possible!
- Suppress backgrounds ($K \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, ...) S/N = 10.
- Perform "blind" analysis to avoid bias.



$K : \pi \sim 4:1 \longrightarrow \check{C}_K \longrightarrow$ **BeO degrader** $\longrightarrow$
active, segmented target

$\pi^+ \longrightarrow$ **1.0 T drift chamber** $\longrightarrow$
21-layer, segmented range stack

photon veto: **14 X_0 barrel, 13.5 X_0 CsI endcap,**
Pb glass, collars

data acquisition: $\sim 1.0 \times 10^6$ K^+ **stops in target per 1.5-sec spill**
$\sim$ **200;** $K^+ \longrightarrow \pi^+ \nu\bar{\nu}$**triggers per spill**

AGS Proposal

Title: A Study of the Decay $K^+ \to \pi^+\nu\bar{\nu}$.

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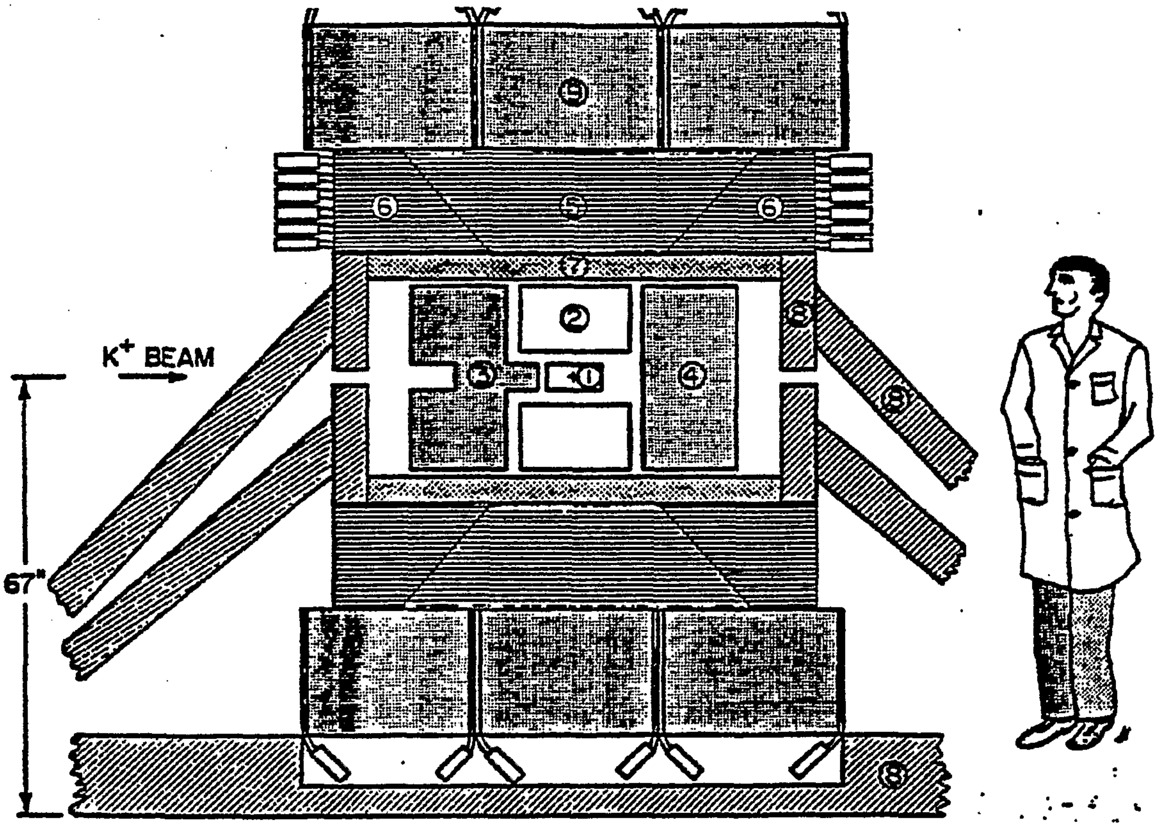
Detectors: Solenoidal drift chamber magnetic spectrometer, scintillation counters, shower counters.

Time Requested: 2100 hours of data taken with 5×10^{12} protons/pulse; 400 hours of testing with $0.5\text{-}2 \times 10^{12}$ proton/pulse.

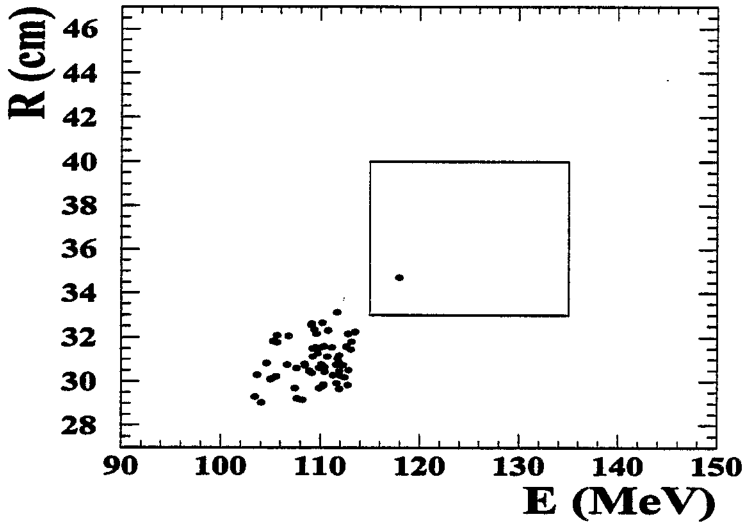


PHASE I RARE KAON DETECTOR AT BNL
SIDE VIEW
0 1 2 Feet

Evidence for the Decay $K^+ \longrightarrow \pi^+\nu\bar{\nu}$ (E787)

1995-97 Data: One event observed.

Estimated background: $n_b = 0.08 \pm 0.02$.
$N_K = 3.24 \times 10^{12}$ **Acceptance= $0.208 \pm 0.005(stat) \pm 0.021(syst)$**



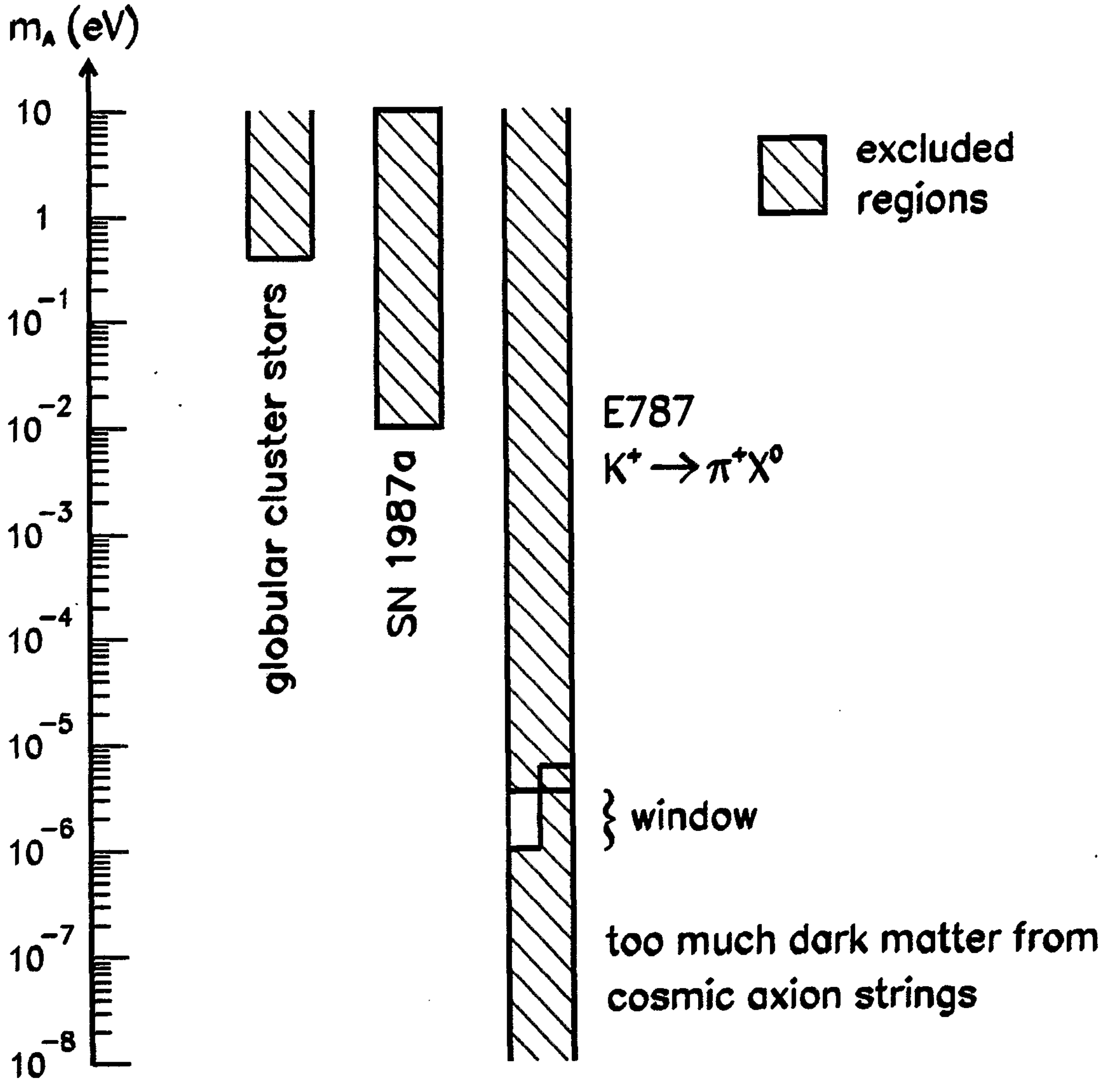
Results:

$$R(K^+ \rightarrow \pi^+\nu\bar{\nu}) = \frac{\Gamma(K^+\rightarrow\pi^+\nu\bar{\nu})}{\Gamma(K^+\rightarrow all)} = 1.5^{+3.4}_{-1.2} \times 10^{-10}$$

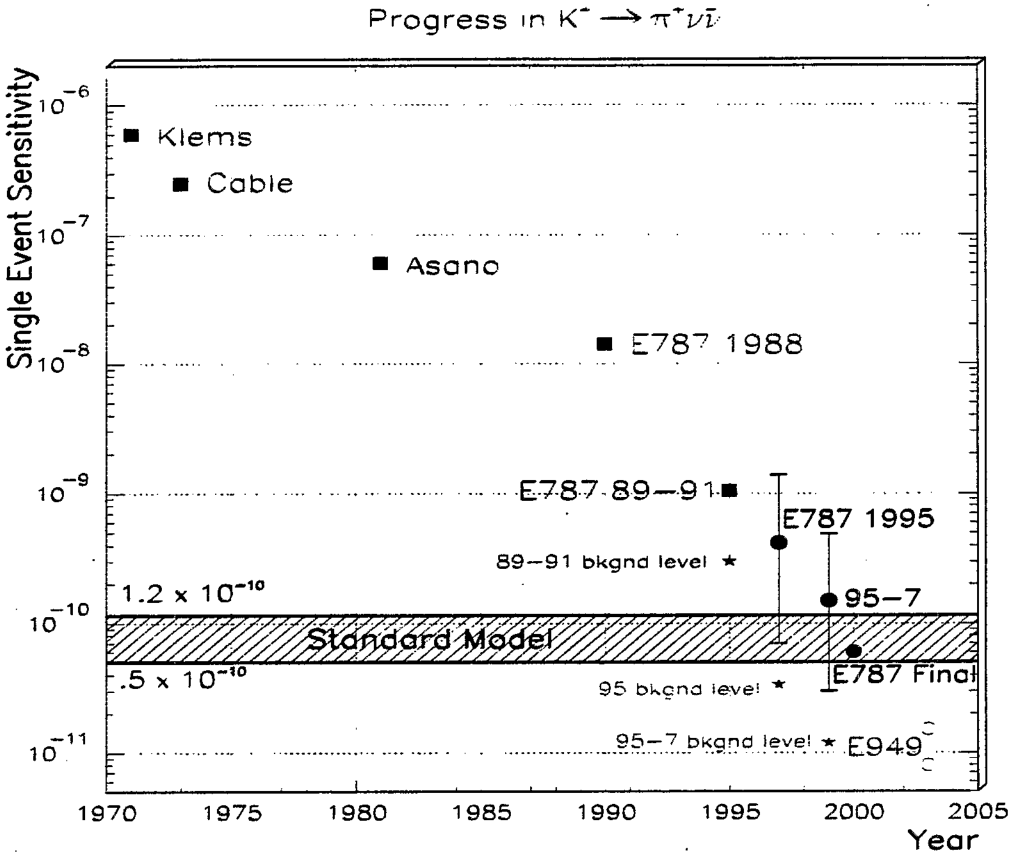
$$0.002 < |V_{td}| < 0.04$$

Search for "Familons"

R($K^+ \longrightarrow \pi^+ x$)$< 1.1 \times 10^{-10}$ (90% c.l.) for $m_x =$ 0.



$K^+ \to \pi^+ \nu\bar{\nu}$Progress

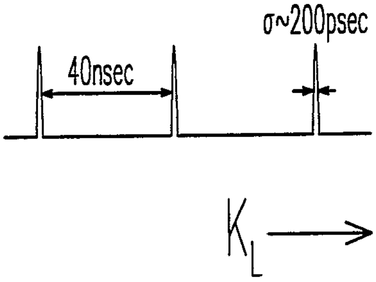


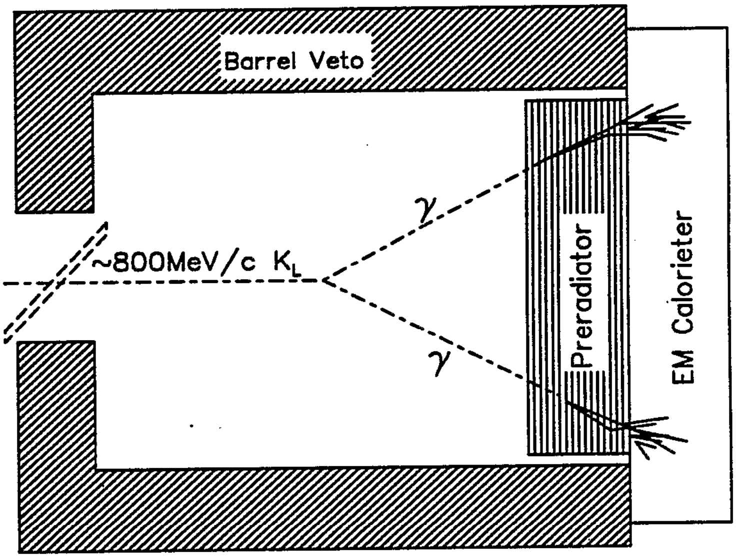
- **Background in E787 95-97 data OK for measurement.**
- **E787 1998 data comparable in sensitivity to previous total.**
- **E787 now becomes E949 aiming for 5x sensitivity of E787. Running starts at the AGS in 2001.**
- **CKM proposal at FNAL aims for 10x greater sensitivity.**

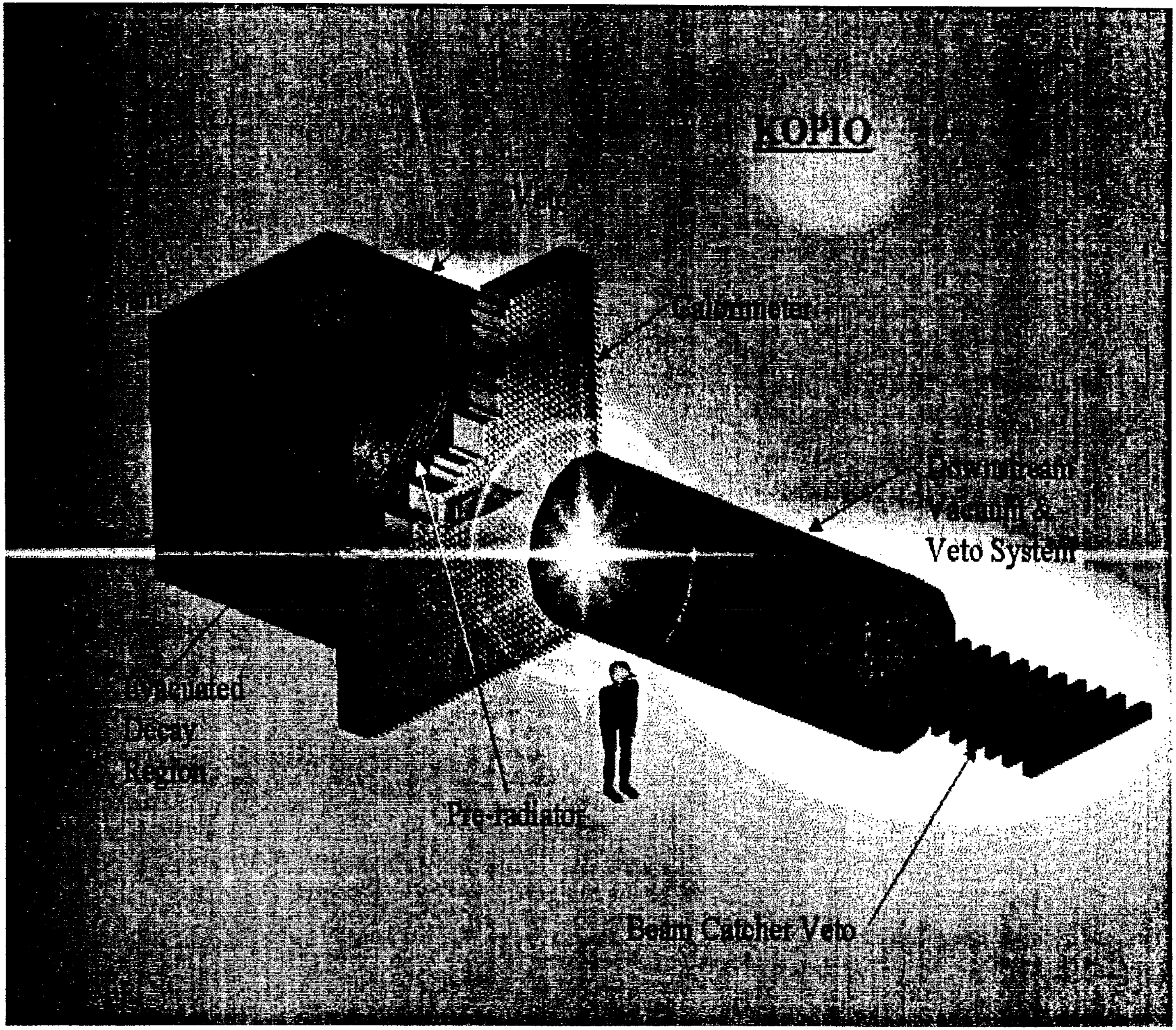
KOPIO: A Proposal to Measure $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

Lessons from E787:

- Measure as much as possible:
  Energy, position and *ANGLE* of each photon.
- Work in the C.M. system :
  Use TOF to get the K_L^0 momentum.
- Photon Veto limited by photonuclear interactions at low energies.







KOPIO

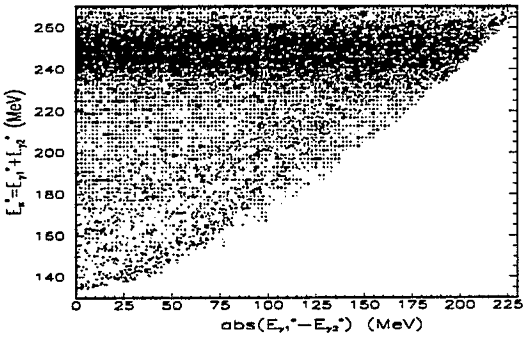
Calorimeter
Downstream Vacuum & Veto System
Evacuated Decay Region
Pre-radiator
Beam Catcher Veto

KOPIO: Challenges and Goals

- Largest background source $K_L^0 \longrightarrow \pi^0\pi^0$.
  Weapons: Kinematic reconstruction, photon veto.
  Eliminate events with missing low energy photons.
- **Photon inefficiency : 10^{-4} at 200 MeV.**
  (Comparable to E787).
- Photon angular resolution : 17 mr at 350 MeV
  (10 mr achieved by GLAST)
- **Energy resolution : $\frac{3.5\%}{\sqrt{(E(GeV)}}$.**
  (Achievable with "Shashlik")

$K_L^0 \longrightarrow \pi^0\pi^0$ Background

$E^*_{\pi^0}$ vs. $|E^*_{\gamma 1} - E^*_{\gamma 2}|$



Using the 24 GeV AGS (between RHIC pulses), 10^{14} p/spill, expect 1.5×10^{14} K decays.

KOPIO GOAL: 65 Events with S/N=2.

Estimated event levels for signal and backgrounds

Process	Modes	Main source	Events
$K_L^0 \to \pi^0 \nu \bar{\nu}$			65
K_L decays ($\bar{\gamma}$)	$\pi^0\pi^0$,$\pi^0\pi^0\pi^0$,$\pi^0\gamma\gamma$	$\pi^0\pi^0$	24
$K_L \to \pi^+\pi^-\pi^0$			9
$K_L \to \gamma\gamma$			0.04
K_L decays ($\overline{charge}$)	$\pi^\pm e^\mp \nu$,$\pi^\pm \mu^\mp \nu$,$\pi^+\pi^-$	$\pi^- e^+ \nu$	0.06
K_L decays ($\bar{\gamma}, \overline{charge}$)	$\pi^\pm l^\mp \nu\gamma$, $\pi^\pm l^\mp \nu \pi^0$,$\pi^+\pi^-\gamma$		0.1
Other particle decays	$\Lambda \to \pi^0 n, K^- \to \pi^-\pi^0$	$\Lambda \to \pi^0 n$	0.03
Interactions	n, K_L, γ	$n \to \pi^0$	0.5
Accidentals	n, K_L, γ	n, K_L, γ	0.3
Total Background			33

E787 RESULTS 1988-2000

MODE	RESULT(E787 GAIN)	COMMENT
$K^+ \to \pi^+ \nu\bar{\nu}$	$(1.5^{+3.4}_{-1.15})10^{-10}$(580)	Discovery!
$K^+ \to \pi^+ \mu^+ \mu^-$	$(5.0 \pm 1.0)10^{-8}$(4500)	Discovery!
$K^+ \to \pi^+ \gamma\gamma$	$(1.1 \pm 0.3)10^{-6}$(100)	Discovery!
$K^+ \to \mu^+ \nu\gamma$	$(1.33 \pm 0.12)10^{-5}$(1000)	Discovery!
$K^+ \to \pi^+ \pi^0 \gamma$	$(4.72 \pm 0.77)10^{-6}$ (2)	D.E. Rad.
$K^+ \to \pi^+ x$	$< 1.1 \times 10^{-10}$(346)	Familon?
$K^+ \to \mu^+ \nu\mu\mu$	$< 4.1 \times 10^{-7}$(2.4M)	Higgs?
$K^+ \to e^+ \nu\mu\mu$	$< 5 \times 10^{-7}$(2M)	Higgs?
$\pi^0 \to \nu\nu$	$< 8 \times 10^{-7}$(10)	Search?
$\pi^0 \to \gamma X$	$< 5.3 \times 10^{-4}$(1900)	Vector?
$K^+ \to \pi^+ \pi^0 \nu\bar{\nu}$	$< 4.3 \times 10^{-5}$(new)	Non-SM

AND TECHNOLOGIES

500 MHz/ 10 μs Transient Digitizers
500 MHz Gallium Arsenide CCDs
Pure CsI Crystal Detectors
Scintillating Fiber Target
Inflated foil Central Drift Chamber

A Tribute to Ted Kycia

Brad Tippens

May 19, 2000

As a physicist, Ted Kycia was a purist. He did not seek prestige, influence, money, or honor for his work. The only motivation was the pleasure that his work gave him. Along with this, and perhaps partly because of it, Ted exhibited the highest qualities of human character: humility, sincerity, honesty, integrity, and honor. He respected those he worked with and expected no less from them. He held high standards for himself and his work and he inspired no less in those with whom he worked. Thus, Ted exemplified true leadership qualities. He never coerced or dominated his colleagues; instead, he inspired them to achieve beyond what they thought they could. Ted had a permanent and positive influence on everyone who had the honor to work with him. For this, they all admired and respected him. This made Ted a great physicist and a great human being.

E927: PRECISION MEASUREMENT OF THE RATE AND SPECTRUM FOR $K^+ \to \pi^0 e^+ \nu$

PHYSICS

TECHNIQUE

DESIGN

Physics

☞Condition for Unitarity of the CKM Matrix:

$$\Delta = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2$$
$$= 0.0027 \pm 0.0017$$

$$|V_{ud}|^2 = 0.9489 \pm 0.0011$$
$$|V_{us}|^2 = 0.0484 \pm 0.0013 \quad (0.0003)$$
$$|V_{ub}|^2 = 9 \pm 6 \times 10^{-6}$$

☞**Improving the determination of V_{us} is heightened by the recent interest in improving the measurement of V_{ud} at Los Alamos and elsewhere.**

☞**Improving V_{us} will make a significant improvement in the determination of other parameters of the CKM matrix.**

$$\begin{pmatrix} 1-0.5\lambda^2 & \lambda & \lambda^3 A\ (\rho-\iota\eta) \\ -\lambda & 1-0.5\lambda^2 & \lambda^2 A \\ \lambda^3 A\ (1-\rho-\iota\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

Example : $\Gamma(K^+ \rightarrow \pi^+ \nu\bar{\nu}) \approx \lambda^{10}$

$f_{K^+} = 159.8 \pm 1.4 \pm 0.44$ MeV

TECHNIQUE

Goal: 0.7% for BR(K_{e3}) gives 0.35% in V_{us}

$K_{\mu 2}$	$K^+ \to \mu^+ \nu$	63.5%	K_{e3}	$K^+ \to \pi^0 e^+ \nu$	4.8%
$K_{\pi 2}$	$K^+ \to \pi^+ \pi^0$	21.2%	$K_{\mu 3}$	$K^+ \to \pi^0 \mu^+ \nu$	3.2%
K_τ	$K^+ \to 2\pi^+ \pi^-$	5.6%	$K_{\tau'}$	$K^+ \to 2\pi^0 \pi^+$	1.7%

Method:

We measure all 6 major decay modes so that only the relative differences in the acceptance have to be determined.

$$BR(K_{e3}) = \frac{N_{Ke3}\,\alpha_{Ke3}^{-1}}{\sum_i N_i \alpha_i^{-1}} = \frac{N_{Ke3}}{\sum_i N_i}(1-\delta)^{-1} \qquad \delta \sim .2$$

We experimentally determine all major sources of systematic error.

Determine δ using $K_{\pi 2}$	~0.2%
Finite target effects - 2 tgts	
α	0.2%
λ_+ $\quad f_+(t) = f_+(0)\left(1 + \lambda_+ \frac{t}{m_\pi^2}\right)$	0.34%
Identifying π, μ, and e	0.2%

Dominant error comes from Kπ2 and Kμ3 background.

We identify and include radiative modes

EXPERIMENT DESIGN

☞Take advantage of ~4π CB by using stopped K^+.

- clean trigger - we count all K^+ decays
  π^+ background ~0.02%
- large acceptance ⇒ high statistics
  less dependence on acceptance differences
- measure radiative corrections

☞Identify $K_{\pi 2}$ and $K_{\mu 3}$ using CB crystal TDC & Cerenkov detector.

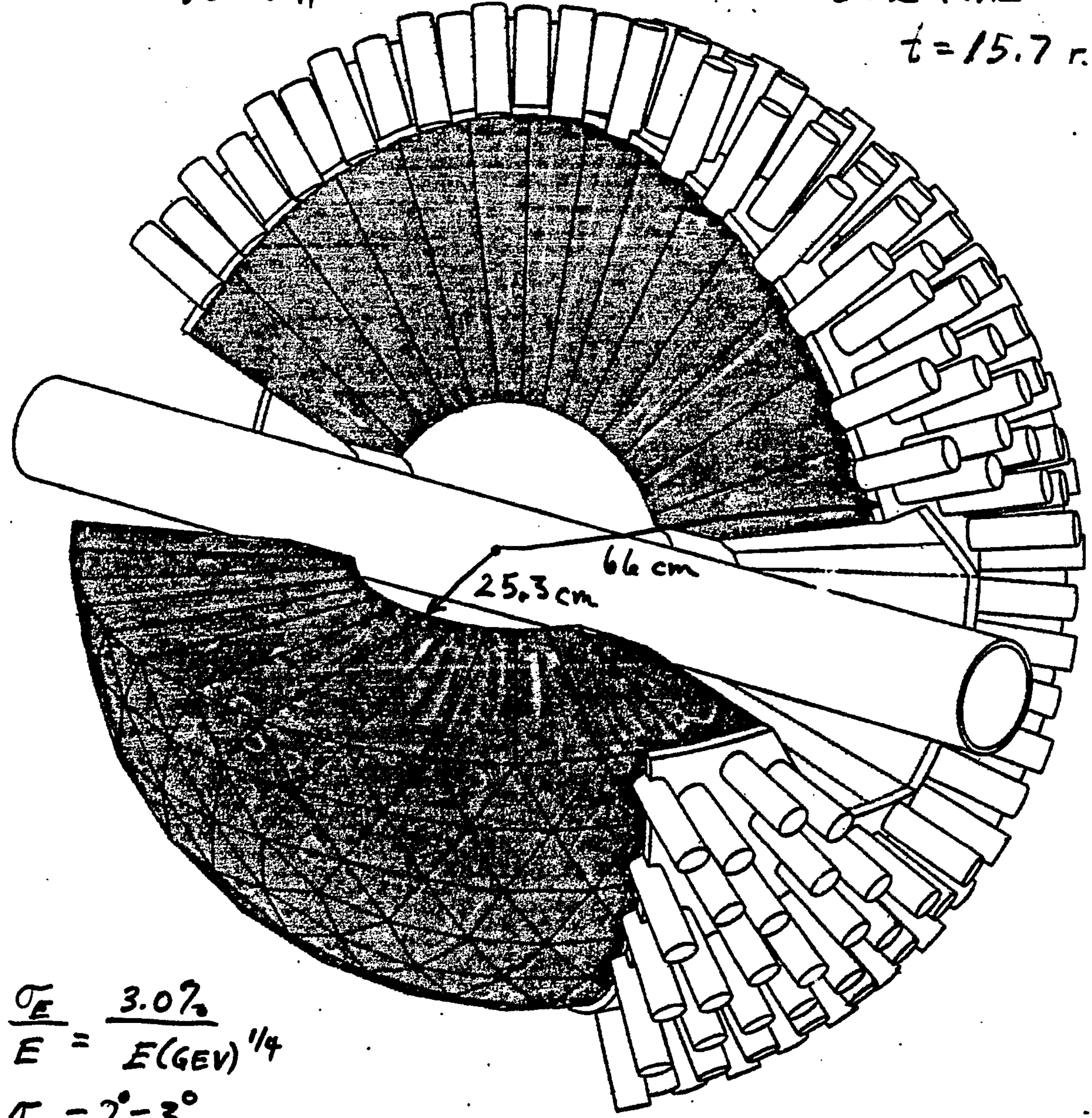
- two independent methods allow determination of efficiency
- TDC method gives ~ 1.3% bgrd
- Cerenkov counter should have > 90% eff.
- TDC's on crystals are necessary to reduce accidental backgrounds.

THE CRYSTAL BALL

$\Omega = 93\%\ 4\pi$

672 NaI Crysta

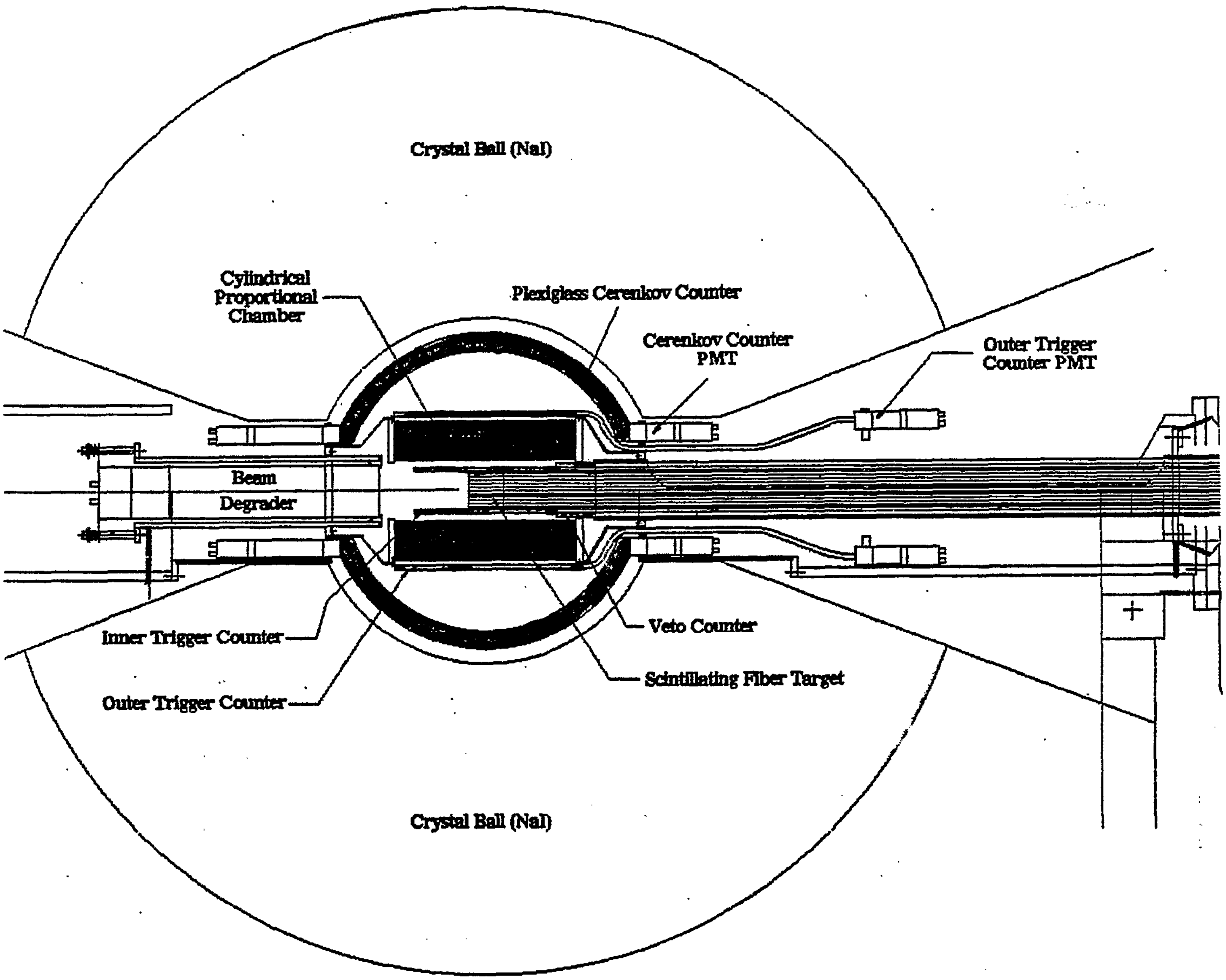
$t = 15.7$ r.l.

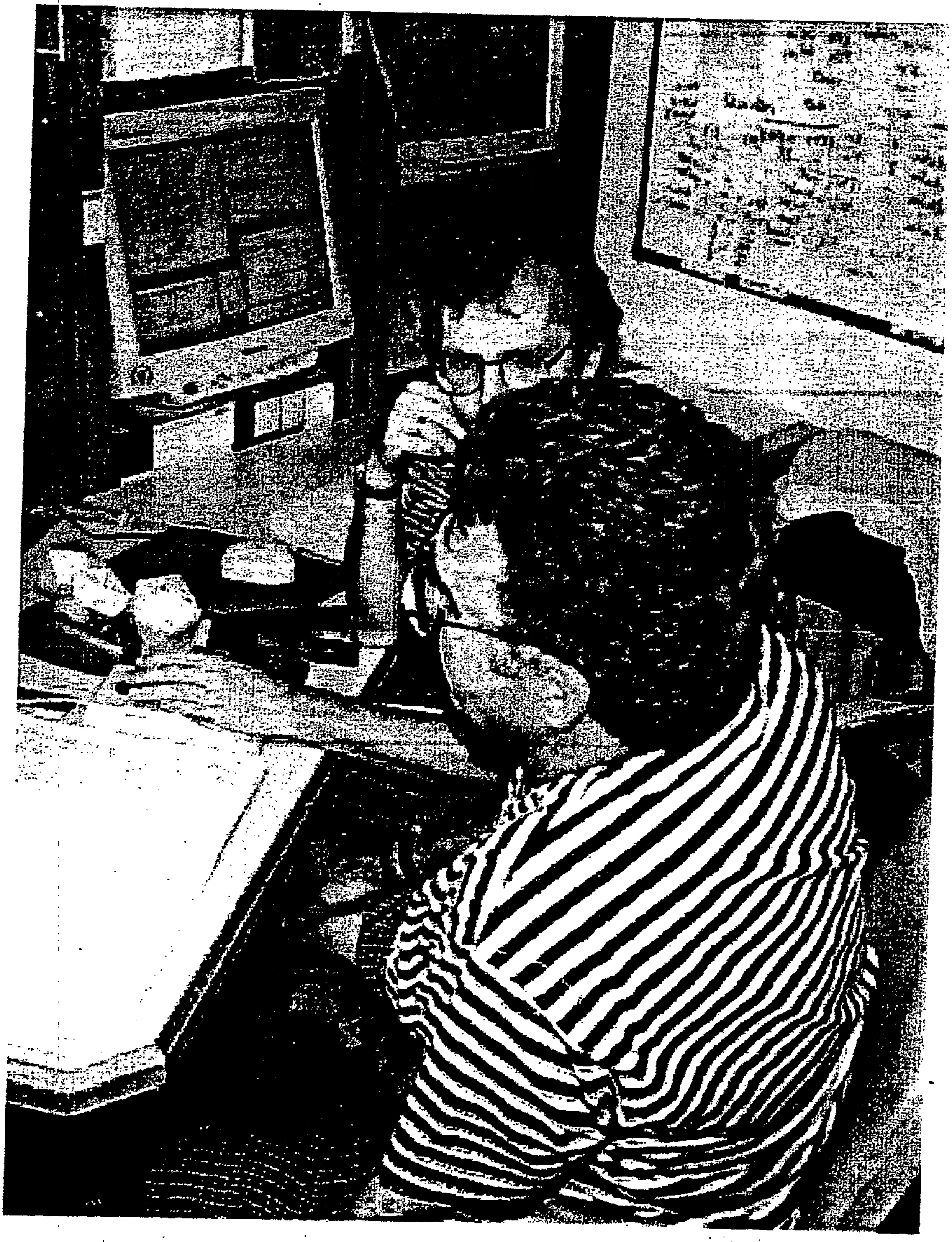


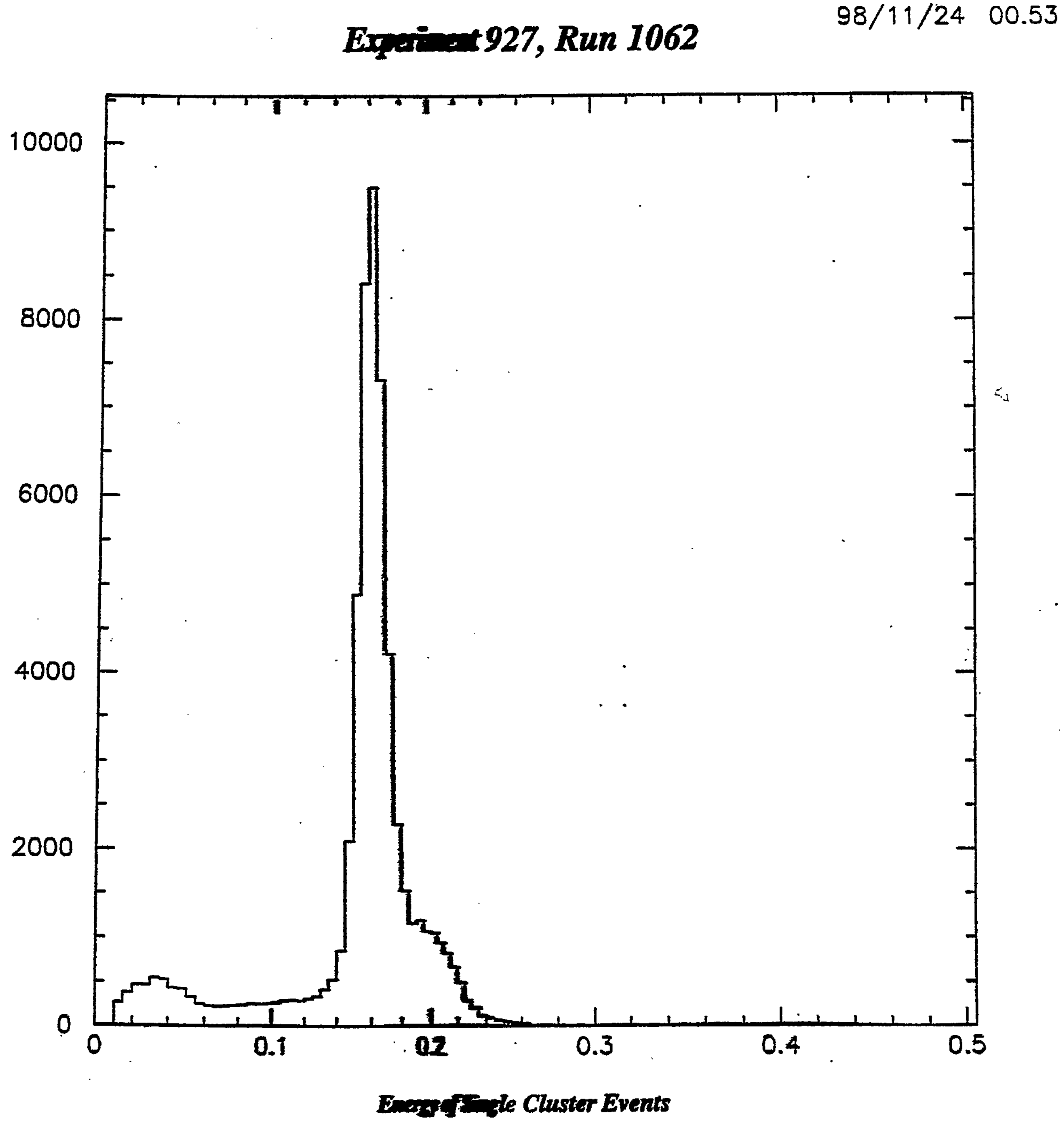
$$\frac{\sigma_E}{E} = \frac{3.0\%}{E(\mathrm{GEV})^{1/4}}$$

$$\sigma_\theta = 2^\circ - 3^\circ$$

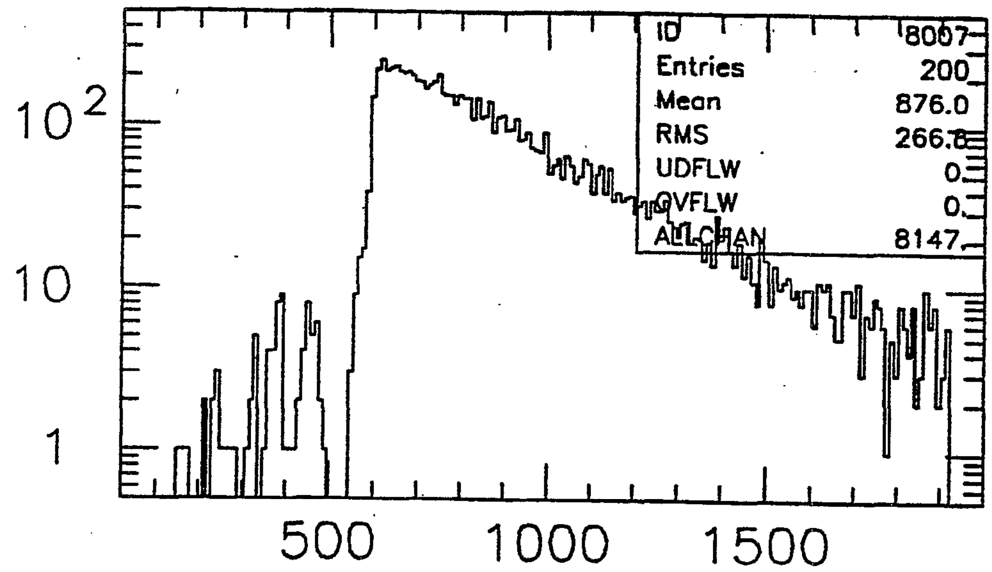
$$\sigma_\phi = \sigma_\theta / \sin\theta$$


Crystal Ball (NaI)
Cylindrical Proportional Chamber
Plexiglass Cerenkov Counter
Cerenkov Counter PMT
Outer Trigger Counter PMT
Beam Degrader
Inner Trigger Counter
Outer Trigger Counter
Veto Counter
Scintillating Fiber Target
Crystal Ball (NaI)

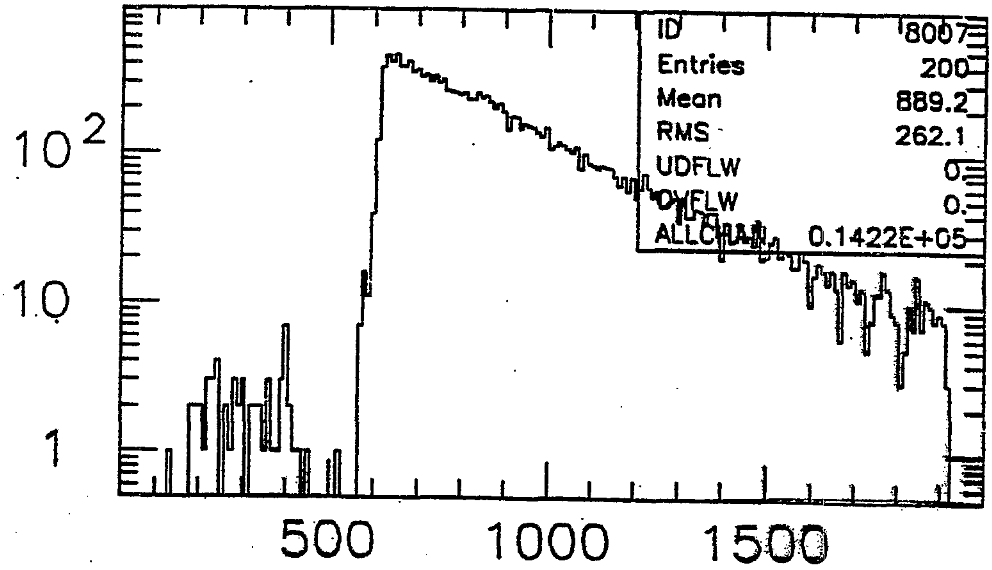



98/11/24 00.53
Experiment 927, Run 1062
10000
8000
6000
4000
2000
0
0
0.1
0.2
0.3
0.4
0.5
Energy of Single Cluster Events

π^+ contamination ~ .02%



Trigger Counter TDC 2



STATUS

☞ Stopping rate measurements were very successful.
  Sufficient rate and purity.
  Small pileup in CB from degrader.
  1 week was not enough time to test TDC's.

☞ Basic Design & Engineering completed.

☞ Second Test Run to prove Particle ID.
  TDC's
  Cerenkov Counter

☞ Further running conditioned on success of Test Run.