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FROM THE NEUTRON TO THREE LIGHT NEUTRINO SPECIES: SOME HIGHLIGHTS FROM SIXTY YEARS OF PARTICLE PHYSICS

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Introduction

I would like to dedicate this survey to Dick Dalitz with my admiration. We are about the same age, so it is true that the entire development of modern particle physics - as we know it today - occurred during the course of our lives.

I consider the beginning of modern particle physics to be in 1932-33, when James Chadwick discovered the neutron at Cambridge, England, and Carl Anderson discovered the positron in Pasadena, California. (See Figures 1 - 3.) I leave out the discoveries of the electron by J. J. Thomson, the nucleus and the proton by Ernest Rutherford, as well as the photon introduced by Albert Einstein and the neutrino as hypothesized by Wolfgang Pauli, as having occurred "before my time."

I was thus able to follow - and sometimes participate in - all the developments of modern particle physics.

The story I will tell is as the unfolding of the field looked, to me - an experimental particle physicists. As with Rashomon, this is as I see it. To get a different point of view, and no doubt there are many, you need a different observer.

One might ask, what did I know about physics in the 1930s, anyway? It so happens that I did hear about Chadwick's discovery at the time, mainly because my brother Maurice was working with him in 1934 on the photo-disintegration of the deuteron, and on the first good measurement of the neutron mass.

I will concentrate on the thirty years, 1930 to 1960 which include Dick Dalitz' important early contributions. I will then skip most of the next thirty years for lack of time, and end up with the study of the Z^0 in e^+e^- annihilation. For more details, and explicit references to published papers, I will refer the reader to a recent book by Robert Cahn and myself.(1)

Experimental Results.

The first indication for the neutron was observed by Bothe who observed penetrating radiation from the α + Be reaction. Madame Curie-Joliot and M. Joliot followed this up by observing that the ionization produced by this radiation was greatly enhanced when material containing hydrogen was introduced. They ascribed this effect to the ejection of protons by energetic γ-rays. It was Chadwick who showed by experiment and logic that fifty MeV γ-rays could not be responsible for the protons observed, but rather that a neutron giving rise to elastic np scattering was responsible. (See Figure 2.)

During the 1940s, while I was studying physics at the Hebrew University in Jerusalem, and later, as a graduate student at the University of Wisconsin in Madison, Wisconsin, I became aware of Heideki Yukawa's prediction in 1935 that the nuclear force was transmitted by a particle of mass $\approx 200\ m_e$, the mesotron. Furthermore, a particle of such a mass, now known as the μ, was observed in a Cosmic Ray cloud chamber experiment by Seth Neddermeyer and Carl Anderson in 1936 (see Figure 4, 5), and confirmed by J. C. Street and E. C. Stevenson shortly thereafter. (See Figure 6.) It took another decade to show that the μ did not fit the picture of a strongly interacting particle. (See Figure 7.)

The 1940s were, of course, overshadowed by World War II. All the same, Le Prince-Ringuet and L'Heritier managed to observe a positive particle that gave a d-ray in a cloud chamber experiment in the Haute-Alps. From their measurements, they concluded a mass of 990 me to an accuracy of 12%, presumably a K^+! Unfortunately, the particle was positive which left the lingering doubt that it could have been a mismeasured proton. (See Figure 8.)

The year 1947 brought a veritable explosion of data! M. Conversi, E. Pancini, and O. Piccioni published their remarkable experiment - carried out under very difficult conditions in Italy during the War. The experiment consisted of a measurement of Cosmic Ray μ decay rates for positive and negative muons at rest which had been separated with suitable magnets designed by B. Rossi. Tomanaga and Araki had calculated that negative "mesotrons" stopping in Carbon would interact rather than decay. The experiment showed, however, that the Cosmic Ray particles - now known as muons - did decay. They could not be Yukawa's Mesotron! (See Figure 9.)

That same year, Don Perkins - then at Imperial College in London - observed an example of a π^- which gave a σ-star in photographic emulsion, and hence behaved as Tomanaga and Araki had predicted for the mesotron. (See Figure 10.) Soon thereafter, Powell's group at Bristol discovered a number of examples of the $\pi^+ \rightarrow \mu^+$ decay in photographic emulsions, showing clearly that two different "mesons" were involved. (See Figure 11.) H. Bethe and R. Marshak in the U.S., as well as S. Sakata, T. Inoue, and Y.

Tanikawa in Japan had actually come up with the suggestion that two kinds of mesons might be the origin of the mesotron puzzle.

To top off the year, G. D. Rochester and C. C. Butler discovered two examples of "forked tracks" in a cosmic ray cloud chamber experiment at the University of Manchester. This was clearly the beginning of strange particles. (See Figure 12.) Two years later, the τ meson - which is central to our discussion today - was discovered in photographic emulsions as well. See Figure 13.

Cosmic Ray discoveries followed fast and furious, well into the 1950s.

An important technical development was the discovery by Ed McMillan and independently by V. I. Veksler: the principle of Phase Stability. This allowed the construction of the Synchrotron and Synchrocyclotron, and eventually led to the Cosmotron at Brookhaven, the Bevatron at Berkeley and the Phasotron at Dubna.

The 1950s saw the application of these devices to the study of pions. See Figure 14. Jack Steinberger, W.K.H. Panofsky, and J. Stellar, as well as Burton Moyer and coworkers at Berkeley contributed to the discovery of the π^{o}, simultaneously with the Cosmic Ray emulsion experiment of A. G. Carlson (now known as A. G. Ekspong), J. E. Hooper, and D. T. King which gave a lifetime limit. Furthermore, Panofsky and coworkers measured the spin and parity of the pion: $J^P = O^-$.

Dalitz pairs.

This brings me to Dick Dalitz. I first became aware of Dalitz' contribution to Particle Physics in connection with Dalitz pairs; that is, a form of internal conversion in π^o decay where one of the gammas converts into an e^+e^- pair. This has a probability of 1/80. The possibility also exists for both photons to convert into Dalitz pairs which has then a probability of $(1/160)^2$, or about 4 x 10^{-5}. These Dalitz pairs were observed in photographic emulsion experiments, as pairs essentially coming from the origin of a π or K interaction or decay. An important application of the double Dalitz-pair decay occurred in 1959, in an experiment by Plano and coworkers, that measured the parity of the π^o; Figure 15 shows the angular distribution which they observed. For a scalar π^o particle, an angular distribution proportional to

$\bar{e}_1 \bullet \bar{e}_2$ which results in $\cos^2\varphi$ or $1+\cos 2\varphi$ is expected. For a pseudoscalar p^o

particle, we have the triple scalar product: $\bar{e}_1 x \bar{e}_2 \bullet \bar{k}$, etc. which gives rise to a $\sin^2\varphi$ distribution, or

1-cos2φ. Here $\vec{e}_1$ and $\vec{e}_2$ are the polarization vectors of the two photons, and $\vec{k}$ is one of their momenta. As you can see in the figure, the data is a good fit to the latter distribution.

Next came the discovery - again in photographic emulsions - of a hyperfragment by M. Danysz and J. Pniewski of Poland. (See Figure 16.) This subject has occupied Dick Dalitz until this day, and will be discussed by A. Gal at this conference. A. Pais, as well as R. Nambu, K. Nishijima, and Y. Yamaguchi, proposed associated production of the new particles, and M. Gell-Mann and independently K. Nishijima proposed the more specific scheme of the strangeness quantum number. W. Fowler, R. Shutt and coworkers indeed discovered associated production $\pi^- p \rightarrow \Lambda^\circ \theta^\circ$ in a diffusion cloud chamber at the Brookhaven Cosmotron. (See Figure 17.)

The Cosmic Ray results became clearer and more quantitative at the 1953 Bagnères-de-Bigore (France) Conference. The hyperons Λ° and $\Sigma^\pm$ and Ξ^-, and the mesons $\theta^0 \rightarrow \pi^+\pi^-$, $\tau^+ \rightarrow \pi^+ \pi^+\pi^-$, $\kappa^+ \rightarrow \mu^+\nu$ etc. were clearly and distinctly identified.

At that same conference also, Dalitz introduced his plot to determine the spin and parity of the τ^+. In Figure 18, I show Dalitz' paper where he had collected the available world's data on τ decay.

The 1950 Pisa Conference.

All this came to fruition at the 1955 Pisa Conference. (See Figure 19.) Neither Dick nor I actually came to that conference - but our data was presented, and played an important part. This was the first conference at which results from the newly operational Bevatron were presented.

Edoardo Amaldi presented a very considerable compilation of τ meson events displayed on a Dalitz plot. (See Figure 20.) It became clear, as was already suspected earlier, that the τ mesons corresponded to a uniform distribution on the Dalitz plot. For a three body decay, the feature of the Dalitz plot is that $d\Gamma \simeq |M|^2 dE_1 dE_2$. Thus, if $|M|^2$ the square of the matrix element is constant, then the distribution on the plot is uniform. See Figure 21. The decay of the $\theta^+ \rightarrow \pi^+\pi^\circ$ where the pions are pseudoscalars can have the spin parity values $J^P = O^+, 1^-, 2^+ ...$ The question was, can the τ-meson which decays to three pions have any of these quantum numbers?

We can immediately rule out O^+ as being forbidden for three pseudoscalars. Dalitz thus examined whether t decay could correspond to $J^P = 1^-, 2^+ ...$ As shown in Figure 21, these decays require the vanishing of $|M|^2$

for $T_{\pi^-} \rightarrow 0$, and were thus ruled out by the uniformity of the Dalitz plot observed experimentally. Furthermore, all experimental evidence pointed to the τ and θ having nearly equal masses and lifetimes. This evidence came from Cosmic ray experiments (the G stack) (Fig. 22), but in particular from the Bevatron experiments then in progress. (Birge, et al., Fig. 23, Chupp, et al., Fig. 24, Iloff, et al., and L. Alvarez and S. Goldhaber, Fig. 25).

<u>The τ - Θ puzzle and parity violation.</u>

This established the τ - Θ puzzle: How could two particles have nearly the same masses and lifetimes, and yet, have different quantum numbers? One possibility - as discussed by M. Gell-Mann at the same conference (Figure 26) was a close mass doublet. The puzzle persisted for nearly two years. Then, T. D. Lee and C. N. Yang came up with the correct suggestion, namely parity nonconservation in weak interactions. Not only did they offer this suggestion, but they also showed various ways in which it could be tested experimentally. This set off a flurry of activity, and Mme. C. S. Wu and E. Ambler, et al. were the first to demonstrate parity violation in the weak decay of aligned Co^{60} nuclei. This was followed in short order by two experiments which demonstrated parity violation in π - μ- e decay. R. L. Garwin, L. M. Lederman, and M. Weinrich converted, practically overnight, a running experiment on m decay at the Columbia University Nevis Cyclotron into an elegant experiment using the precession of muons which were brought to rest in carbon to demonstrate parity violation. J. I. Friedman and V. L. Telegdi had started a m decay experiment in emulsions at the Chicago cyclotron considerably earlier. However, it is the nature of emulsion experiments (or, for that matter, any experiment that needs scanning and measurements) that it takes time to analyze the data and collect statistics. They observed an asymmetry in the decay process in emulsions.

Thus, by this circuitous route, the Dalitz Plot analysis led to the discovery of the decade - parity and charge conjugation violation!

<u>A new application of the Dalitz Plot.</u>

Just at the end of the decade of the fifties, a new and exciting development occurred at Berkeley - in a Hydrogen Bubble chamber experiment at the Bevatron. Shortly after Don Glaser invented the Bubble chamber in 1953, Luis Alvarez and the group he assembled started to demonstrate that Hydrogen was feasible as a Bubble Chamber liquid. They went from a two-inch to a seventy-two-inch chamber with a series of intermediate steps.

The first resonance $\pi^+p \rightarrow \Delta^{++}$ was observed in 1953 by E. Fermi and coworkers at the Chicago Cyclotron. Alvarez and coworkers at LBL discovered a series of new resonances. The first was the $Y^*(1385)$, now called $\Sigma(1385)$. See Figure 27. The reaction was

$$K^-p \rightarrow \Lambda \pi^+\pi^-.$$

Displaying the three final state particles on a Dalitz Plot played an important role in recognizing the $Y^* \rightarrow \Lambda\pi^{\pm}$ resonances.

More on Dalitz Plots.

With the discovery of the $\omega \rightarrow \pi^+\pi^-\pi^o$, by B. Maglic' et al., in a hydrogen bubble chamber at the Berkeley Bevatron, a new three pion decay could be analyzed. Here the spin parity value $J^P = 1^-$ gave rise to a more interesting shape. M. Gell-Mann had supplied the equations for various J^P values - see Table I and Lynn Stevenson developed some aesthetic-looking plots (Figure 28). C. Zemach extended the list of matrix elements (Figure 29) which inspired me to construct contour plots for a series of these matrix elements (Figure 30).

This led to a method I developed for analyzing mass plots by cutting the data at contours on the Dalitz plot corresponding to specific J^P values. This is illustrated for the ω^o in Figure 31 for contours increasing by twenty percent steps for $J^P = 1^-$. The lowest contour $\lambda(1^-) \leq 0.2$ shows essentially no ω signal, while a very large signal is noted for $\lambda(1^-) > 0.8$. An alternative analysis was carried out by Alff, et al. (Fig. 32), where the data for the various pp masses in the ω peak is shown normalized by the matrix element.

A few highlights from the intervening years.

To do justice to the fantastic developments in particle physics from the sixties to the present, I would need an entire lecture series. I will thus mention just a few points related to my interactions with Dick.

Figure 33 shows the cover page of the 1963 Athens, Ohio Conference that both Dick and I attended. Here, side by side, we see a Dalitz plot and a triangle plot I introduced for four particle decays. This enabled us to observe double resonance production

$$K^+p \rightarrow K^{*o} + \Delta^{++}$$
$$\qquad\qquad K^+\pi^- \quad p^+\pi^-$$

A "pion exchange process" which allowed us (W. Chinowsky, et al.) to measure the K^* spin.

In 1967, Dick and I both lectured at the Hawaii Summer School (Figure 34 shows San Fu Tuan, the director, Val Fitch, myself, T. D. Lee and Dick, the lecturers, and Mrs. Carolyn Chung, the conference secretary, in the front row.

In 1977, I had to again call on the Dalitz plot to perform a measurement. After we discovered charmed mesons with the SLAC-LBL Mark I detector at SPEAR, we had the task of measuring their properties. In particular, the problem was to show that these new particles which decayed to $K^-\pi^+$ and $K^-\pi^+\pi^+$, respectively, were indeed the charmed particles predicted by Shelly Glashow, J. Iliopoulos, and L. Maiani, as opposed to another K^*. Here we had the τ–θ puzzle all over again. Ben Lee, Chris Quigg, and Jon Rosner had computed the shapes on the Dalitz plot for various J^P values (Figure 35). The experimental distribution for $D^+ \rightarrow K^- \pi^+\pi^+$ (exotic) and the non-exotic (and nonresonant) distribution $X^+ \rightarrow K^+ \pi^+\pi^-$ are shown in Figure 36. Here again, as for the θ, $D^0 \rightarrow K^-\pi^+$ can only have $J^P = 0^+, 1^-, 2^+ \ldots$ By utilizing the contour method, I illustrated for the ω^0 earlier, we obtain for the three body D^+ decay the result given in Figure 37a,b which shows the test for $J^P = 1^-$. Here the contour was chosen with nearly equal areas on the Dalitz plot to give a ratio of 1:8·2 for $J^P = 1^-$. Experiment gave ≈ 1:1. Figure 37c,d shows the contour for $J^P = 2^+$ where 1:6·5 was expected, and again ≈ 1:1 was observed. Thus we demonstrated parity violation in D decay - hence we are dealing with a charmed meson, and NOT a K^* resonance!

This brings me to the present (1990). Here I reluctantly skip the decades of the sixties, seventies, and in particular the eighties with the exciting developments at CERN of W and Z discovery and come to:

The study of the Z^0 from $e^+e^- \rightarrow Z^0$ annihilation.

We have now been studying the properties of the Z^0 at e^+e^- colliders for just over one year. The first such event was observed in the Mark II detector at the SLC on April 11, 1989. The four LEP experiments started a few months later. The primary lessons we have learned are that the people who introduced the electro-weak theory, or what is now called the Standard Model, are to be congratulated. We have tried as hard as we could to find deviation from this model - so far, there are none. To mention a few names: Shelly Glashow, Abdus Salam, Gerard t'Hooft, and Steve Weinberg, as well as many others, were responsible for this magnificent theoretical development.

The first important result to emerge from these studies is the fact that there appear to be only three species of light neutrinos. Of course, our colleagues in Astrophysics and Cosmology have expected this for a long time! They are also to be congratulated.

A new trend in particle physics.

With the advent of large electronic detectors, a new phenomenon has entered particle physics. Large collaborations are needed! The attack on the

Z^0 properties required electronic detectors attached to their own computers. To design, build, test, write the on-line programs, and analyze the river of data produced by these new detectors requires an entirely new approach to experimental particle physics. Figures 38 to 42 give the authors in our Mark II experiment at the SLC, where we have ~ $1/\alpha$ physicists, as well as those for the four LEP experiments where each experiment has nearly 100 x π and more physicists! This is a far cry from the one-to-five-people teams of the 1930s and 40s!

Comments on precision Z mass measurements.

Figure 43 shows a recent compilation by the particle data group of our data, together with the results from the four LEP experiments - their points are the ones with the smaller error bars! As we noted, the number of neutrino species which is related to the total width Γ of the Z^0 resonance (where each ν species contributes 177 MeV to Γ) is most accurately determined from the value of the peak cross-section.

Since the Z mass is one of the three fundamental constants of the electroweak theory, viz, G_F, α, and M_Z, one wants to measure it as precisely as possible. With high statistics, the final limitation of such a measurement is the systematic error. At the SLC, the absolute energy in the center of mass is obtained by a precise momentum measurement for both the electron and positron beams for each pulse.

Figure 44 is a sketch of one of the spectrometers which act on the beam after the collision and before the beam reaches the beam dump.

The momentum measurement is carried out with a vertical bend. The direction of the beam before and after this bend is determined in a novel fashion by two small horizontal bends. These give rise to synchrotron radiation which is then observed on a fluorescent screen. The measurement consists of measuring the displacement of the vertically deflected beam on the screen with a television camera. The systematic error for each beam measurement is 20 MeV. Combining these quadratically, and including an allowance for beam offsets with finite dispersion, we get an overall systematic error on M_Z of $\pm$ 35 MeV.

Figure 45 shows the predicted error in M_Z as a function of the integrated luminosity or, equivalently, the observed number of Z^0 events. With our current data, based on five hundred events, the predicted error is in agreement with our measured error of 120 MeV.

The four LEP experiments have smaller statistical errors, but finally came up against the common systematic error of $\pm$ 30 MeV, based on sending a proton beam through the LEP accelerator.

When the statistical errors become negligible, the residual systematic errors for the SLC and LEP experiments, which at present are comparable, will determine the accuracy to which M_Z is known. At that time, it will be important to have two totally independent sources of systematic errors.

Measurements of the number of light ν species.

I will illustrate the measurement of the Z^o decay parameters for the Mark II at the SLC. The procedures for the four LEP experiment were similar and with higher statistics achieved higher accuracy. Figures 46-52 present the steps taken in a self-explanatory form. I will also show examples of the results from LEP experiments. Figures 53-55 gives ALEPH results and Figure 56, 57 those of the L3 experiment. Figure 58 summarizes all the data on the number of ν species.

The search for new particles.

In Z^o decay, any new particle that couples to the neutral weak current, and for pair production, with a mass $<M_Z/2$ can be produced. At the SLC, and with greater statistical accuracy in the four LEP experiments, one has looked hard for many such possible decay modes, and ninety- to ninety-five percent CL limits have been placed on the masses, and other properties of such particles. To date, no evidence for such possible particles have been found. I will, however, not give a detailed discussion of these searches here.

References

See "The Experimental Foundations of Particle Physics," Robert N. Cahn and Gerson Goldhaber. Cambridge University Press, 1989, for references to results quoted in this paper.

Acknowledgement

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1930s
Developments in Accelerators, Nuclear Physics, and Cosmic Rays

1930 *P. A. M. Dirac suggests antiparticles.

*Wolfgang Pauli
Suggests Neutrino.

1932 James Chadwick's discovery of the neutron.

*Werner Heisenberg introduction of
Isospin.

1934 *Enrico Fermi
Theory of β decay

1935 *Heideki Yukawa Suggests mesotron
$M \sim 200 m_e$ to account for
nuclear force.

1936 Seth Neddermeyer and Carl Anderson
Discovery of the μ $M \sim 200 m_e$.

Accelerators:

J. D. Cockroft, E. T. S. Walton - Voltage doublers
R. J. Van de Graaf - Electrostatic Generators
E. O. Lawrence - Cyclotrons

Figure 1

Letters to the Editor

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.]*

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3{\cdot}2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

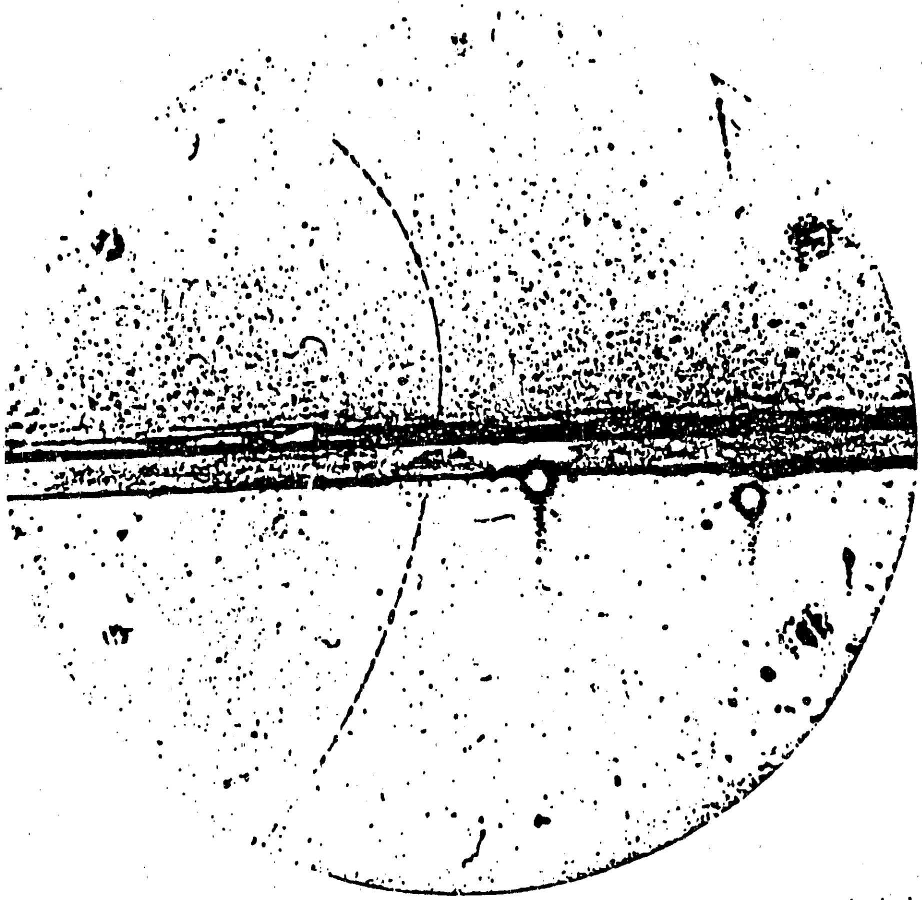
If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

Figure 2



. A 63 million volt positron ($H\rho = 2.1 \times 10^4$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Tracks of electron-positron pairs produced by 300-MeV synchrotron x rays. ***(Courtesy of Lawrence Radiation Laboratory, University of California, Berkeley.)***

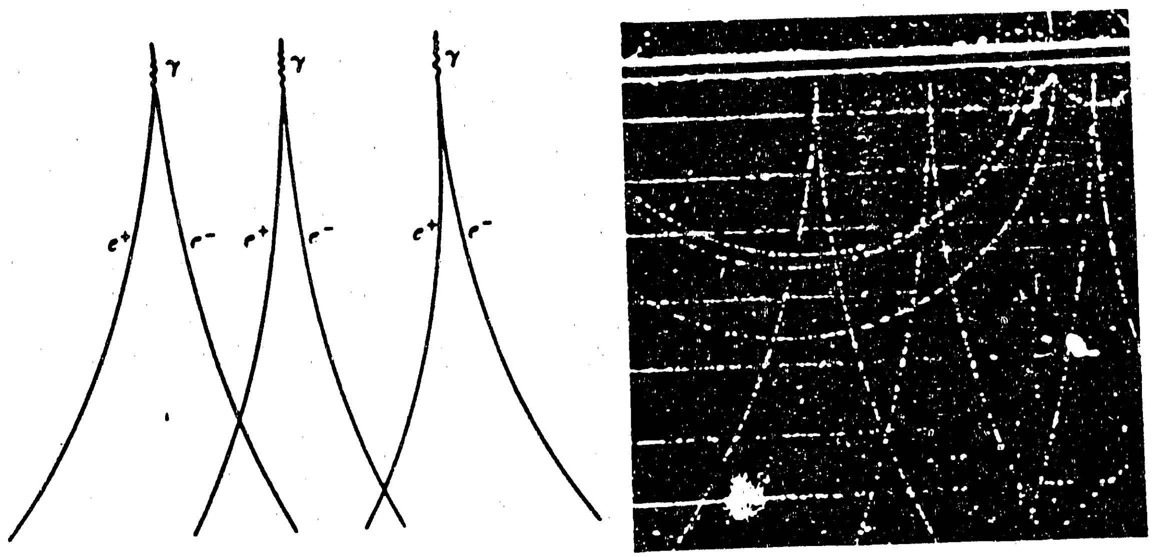


Figure 3

Note on the Nature of Cosmic-Ray Particles

SETH H. NEDDERMEYER AND CARL D. ANDERSON
California Institute of Technology, Pasadena, California
(Received March 30, 1937)

MEASUREMENTS[1] of the energy loss of particles occurring in the cosmic-ray showers have shown that this loss is proportional to the incident energy and within the range of the measurements, up to about 400 Mev, is in approximate agreement with values calculated theoretically for electrons by Bethe and Heitler. These measurements were taken using a thin plate of lead (0.35 cm), and the observed individual losses were found to vary from an amount below experimental detection up to the whole initial energy of the particle, with a mean fractional loss of about 0.5. If these measurements are correct it is evident that in a much thicker layer of heavy material multiple losses should become much more important, and the probability of observing a particle loss less than a large fraction of its initial energy should be very small. For the purpose of testing this inference and also for checking our previous measurements[2] which had shown the presence of some particles less massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory, we have taken about 6000 counter-tripped photographs with a 1 cm plate of platinum placed across the center of the cloud chamber. This plate is equivalent in electron thickness to 1.96 cm of lead, and to 1.86 cm of lead for a Z^2 absorption. The results of 55 measurements on particles in the range below 500 Mev are given in Fig. 1, and in Fig. 2 the distribution of particles is shown as a function of the fraction of energy lost. The shaded part of the diagram represents particles which either enter the chamber accompanied by other particles or else themselves produce showers in the bar of platinum. It is clear that the particles separate themselves into two rather well-defined groups, the one consisting largely of shower particles and exhibiting a high absorbability, the other consisting of particles entering singly which in general lose a relatively small fraction of their initial energy, although there are four cases in which the loss is more than 60 percent. A considerable part of the spread on the negative abscissa can be accounted for by errors; it seems likely, however, that the case plotted at the extreme left represents a particle moving upward. Particles of both signs are distributed over the whole diagram, and moreover, the initial energies of the particles of each group are distributed over the whole measured range.

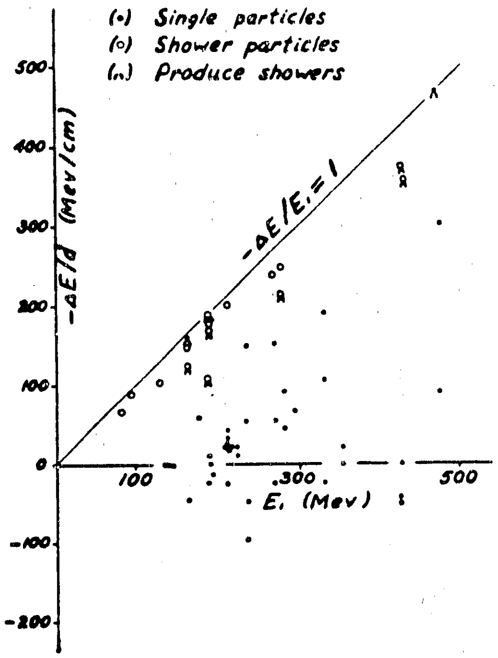


FIG. 1. Energy loss in 1 cm of platinum.

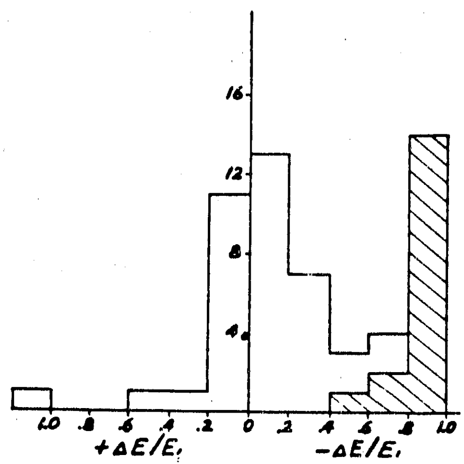
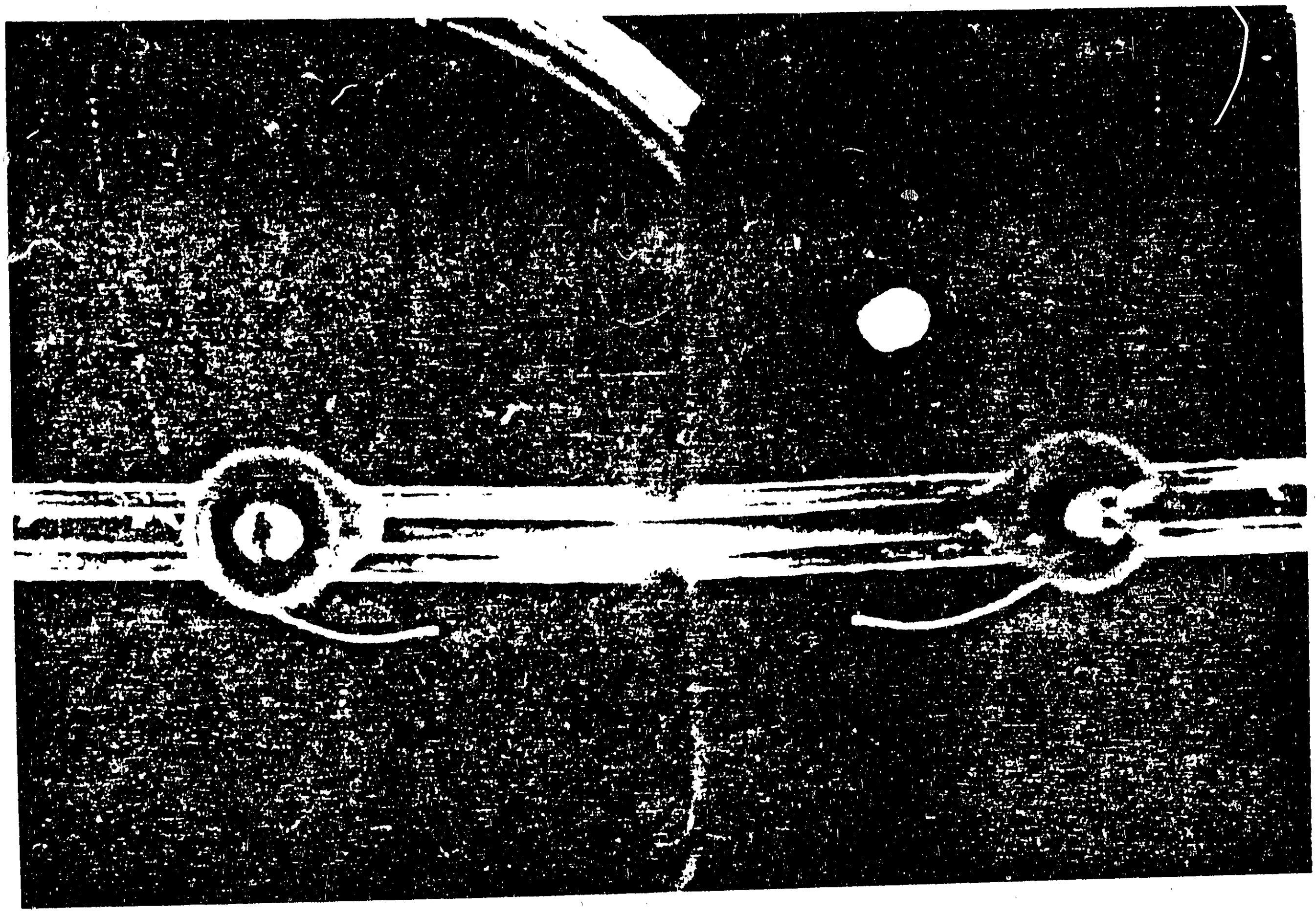


FIG. 2. Distribution of fractional losses in 1 cm of platinum.

[1] Anderson and Neddermeyer, Phys. Rev. 50, 263 (1936).
[2] Anderson and Neddermeyer, Report of London Conference, Vol. 1 (1934), p. 179.

Figure 4



A muon enters the cloud chamber from above with a momentum of 52 MeV/c. It passes through a Geiger counter and comes to rest. From the measured range the mass was determined to be 220 ± 35 electron masses. S. H. Neddermeyer and C. D. Anderson, Phys. Rev. **54**, 88 (1938).

Figure 5

J. C. Street
E. C. Stevenson

Research Laboratory of Physics,
Harvard University,
Cambridge, Massachusetts,
October 6, 1937.

New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron

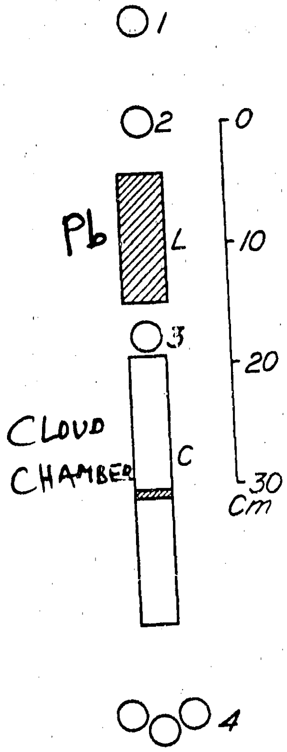


Fig. 1. Geometrical arrangement of apparatus.

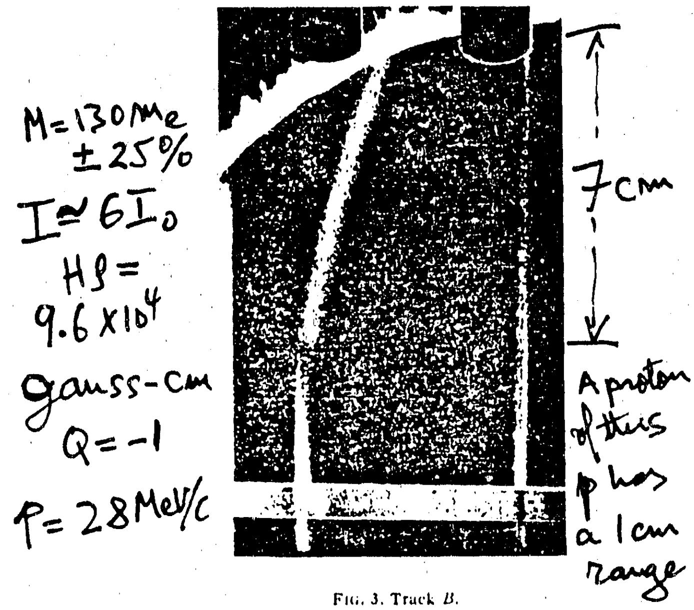


Fig. 3. Track B.

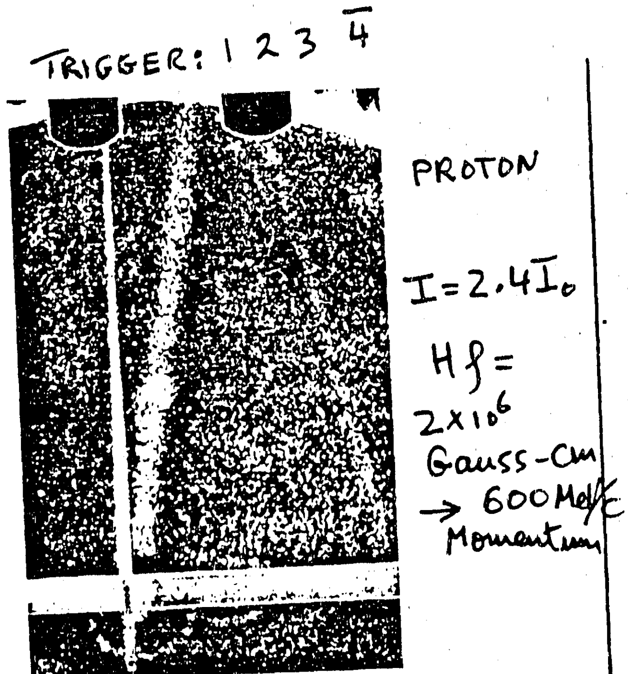


Fig. 2. Track A.

LATE EXPANSION
1 SEC DELAY
TO ENHANCE DROPLET COUNT

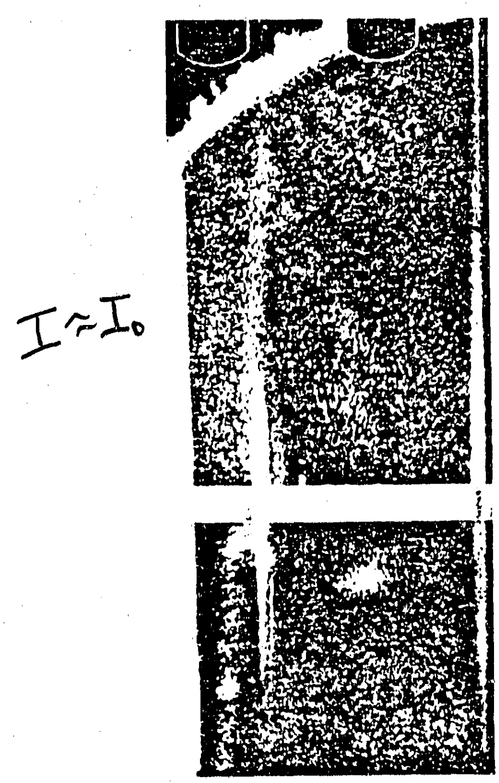


Fig. 4. Photograph of the track of a penetrating particle of high energy for comparison with A and B.

Figure 6

1940s
The Decade of Cosmic Ray Studies

1944 Le Prince Ringuet — K^+ Observation in cloud chamber Cosmic Rays.

1947 Conversi, Pancini, and Piccioni:
The μ is not Yukawa's mesotron.

Don Perkins:
π^- observation in emulsions.

Lattes, Muirhead, Occhialini, and Powell
Observation of $\pi^+ \rightarrow \mu^+$ decay in emulsions.

Rochester and Butler:
Observation of a charged and a neutral strange particle in cloud chamber.

1948 E. McMillan and V. I. Veksler - Synchrotron and Synchrocyclotron.

1949 R. Brown, et al. discovery of the τ meson

Figure 7

SÉANCE DU 13 DÉCEMBRE 1944.

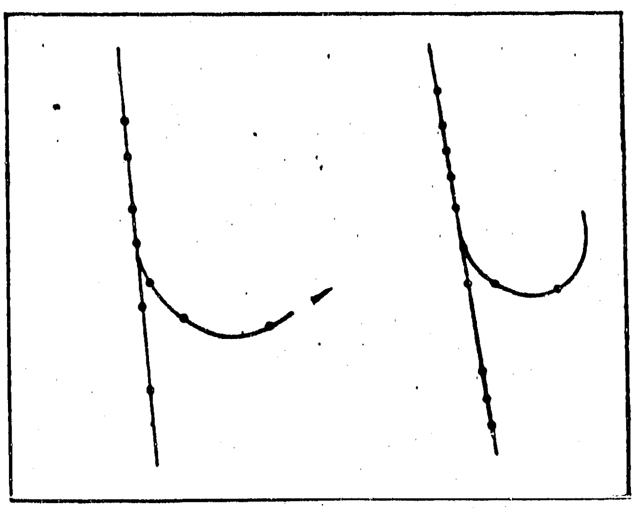
PHYSIQUE NUCLÉAIRE. — *Existence probable d'une particule de masse 990 m_0 dans le rayonnement cosmique.* Note (¹) de MM. **Louis Leprince-Ringuet** et **Michel Lhéritier**.

Nous avons pris, au cours de l'année 1943, dans le laboratoire de Largentière (Hautes-Alpes) situé à 1000^m d'altitude, une série de 10000 clichés de trajectoires cosmiques commandées par compteurs. Les rayons, filtrés par 10^{cm} de plomb, traversaient une chambre de Wilson de 75^{cm} de hauteur, placée dans un champ magnétique H de 2500 gauss environ. Nous nous sommes placés dans les conditions expérimentales les plus favorables [discutées précédemment (²), (³), (⁴)] pour profiter au mieux des clichés de collision entre particules pénétrantes et électrons du gaz de la chambre, dans le but de déterminer la masse au repos de la particule incidente.

Nous avons obtenu une dizaine de clichés intéressants. Le plus remarquable représente une collision dans le gaz pour laquelle d'excellentes conditions sont réalisées : le secondaire fait avec le plan médian de la chambre un angle ζ tel que tang$\zeta = 0,32$ et son rayon de courbure projeté (1^{cm},6), ainsi que la flèche dont il s'écarte du primaire sont mesurables avec précision. Le (Hρ) du primaire $= 1,7 \times 10^6$ gauss $\times$ cm. La formule de collision élastique donne pour le primaire, qui est positif, la masse au repos

$$\mu_0 = 990 \pm 12\ \% \text{ (limites extrêmes de l'erreur) } (^5).$$

La masse ainsi obtenue peut surprendre. Les indications suivantes, qui donnent des garanties de la validité de la mesure, nous ont poussés à publier ce résultat.



Dessin stéréoscopique de la collision.

Figure 8

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is, for the issue of the 1st of the month, the 8th of the preceding month and for the issue of the 15th, the 23rd of the preceding month. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

On the Disintegration of Negative Mesons

M. CONVERSI, E. PANCINI, AND O. PICCIONI*
Centro di Fisica Nucleare del C. N. R. Istituto di Fisica dell'Università di Roma, Italia

December 21, 1946

IN a previous Letter to the Editor,[1] we gave a first account of an investigation of the difference in behavior between positive and negative mesons stopped in dense materials. Tomonaga and Araki[2] showed that, becuase of the Coulomb field of the nucleus, the capture probability for negative mesons at rest would be much greater than their decay probability, while for positive mesons the opposite should be the case. If this is true, then practically all the decay processes which one observes should be owing to positive mesons.

Several workers[3] have measured the ratio η between the number of the disintegration electrons and the number of mesons stopped in dense materials. Using aluminum, brass, and iron, these workers found values of η close to 0.5 which, if one assumes that the primary radiation consists of approximately equal numbers of positive and negative mesons, support the above theoretical prediction. Auger, Maze, and Chaminade,[4] on the contrary, found η to be close to 1.0, using aluminum as absorber.

Last year we succeeded in obtaining evidence of different behavior of positive and negative mesons stopped in 3 cm of iron as an absorber by using magnetized iron plates to concentrate mesons of the same sign while keeping away mesons of the opposite sign (at least for mesons of such energy that would be stopped in 3 cm of iron). We obtained results in agreement with the prediction of Tomonaga and Araki. After some improvements intended to increase the counting rate and improve our discrimination against the "mesons of the opposite sign," we continued the measurements using, successively, iron and carbon as absorbers. The recording equipment was one which two of us had previously used in a measurement of the meson's mean life.[5] It gave threefold (III) and fourfold (IV) delayed coincidences. The difference (III) − (IV) (after applying a slight correction for the lack of efficiency of the fourfold coincidences) was owing to mesons stopped in the absorber and ejecting a disintegration electron which produced a delayed coincidence. The minimum detected delay was about 1 μsec. and the maximum about 4.5 μsec. Our calculations of the focusing properties of the magnetized plates (20 cm high; $\beta = 15{,}000$ gauss) and including roughly the effects of scattering, showed that we should expect almost complete cut-off for the "mesons of the opposite sign." This is confirmed by our results, since otherwise it would be very hard to explain the almost complete dependence on the sign of the meson observed in the case of iron.

TABLE I. Results of measurements on β-decay rates for positive and negative mesons.

Sign	Absorber	III	IV	Hours	M/100 hours
(a) +	5 cm Fe	213	106	155.00′	67 ± 6.5
(b) −	5 cm Fe	172	158	206.00′	3
(c) −	none	71	69	107.45′	−1
(d) +	4 cm C	170	101	179.20′	36 ± 4.5
(e) −	4 cm C + 5 cm Fe	218	146	243.00′	27 ± 3.5
(f) −	6.2 cm Fe	128	120	240.00′	0

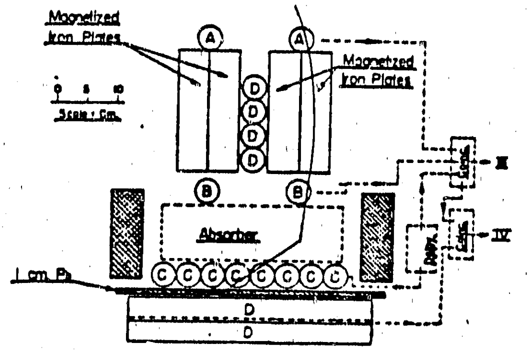


FIG. 1. Disposition of counters, absorber, and magnetized iron plates. All counters "D" are connected in parallel.

The results of our last measurements with two different absorbers are given in Table I. In this table "Sign" refers to the sign of the meson concentrated by the magnetic field. $M = (\text{III}) - (\text{IV}) - P(\text{IV})$, the number of decay electrons, is corrected for the lack of efficiency (p) in our fourfold coincidences (∼0.046).

The value M_- (5 cm Fe) is but slightly greater than the correction for the lack of efficiency in our counting, so that we can say that perhaps no negative mesons and, at most, only a few (∼5) percent undergo β-decay with the accepted half-life.

The results with carbon as absorber turn out to be quite inconsistent with Tomonaga and Araki's prediction. We used cylindrical graphite rods having a mean effective thickness of 4 cm because we were unable to procure a graphite plate. In addition, when concentrating negative mesons, we placed above the graphite a 5-cm thick plate of iron to guard against the scattering of very low energy mesons which might destroy the concentrating effect of our magnets. We alternated the following three measurements:

A. Negative mesons with 4 cm C and 5 cm Fe
B. Negative mesons with 6.2 cm Fe (6.2 cm Fe is approximately equivalent to 4 cm C + 5 cm Fe as far as energy loss is concerned.
C. Positive mesons with 4 cm C.

Figure 9

Nuclear Disintegration by Meson Capture

RECENTLY, multiple nuclear disintegration 'stars', produced by cosmic radiation, have been investigated by the photographic emulsion technique. Plates coated with 50 µ Ilford B.1 emulsions[1] were exposed in aircraft for several hours at 30,000 ft. One of these disintegrations was of particular interest, for whereas all stars previously observed had been initiated by radiation not producing ionizing tracks in the emulsion, the one in question appears to be due to nuclear capture of a charged particle, presumably a slow meson.

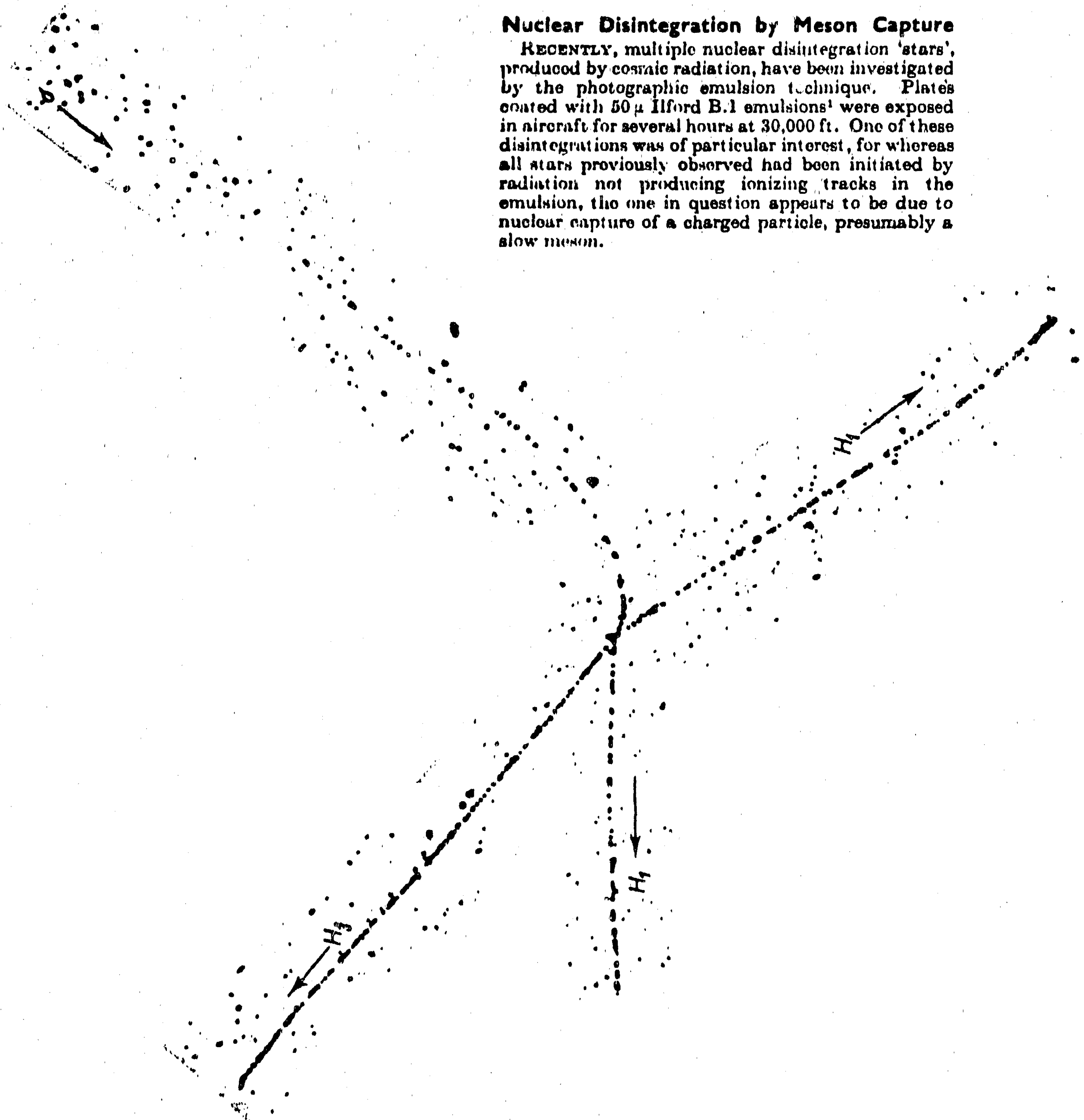


Figure 10

I am indebted to the A.O.C., Royal Air Force, Benson, Oxon., for kindly exposing the plates.

D. H. PERKINS
Imperial College of Science and Technology,
London, S.W.7.
Jan. 8.

OBSERVATIONS ON THE TRACKS OF SLOW MESONS IN PHOTOGRAPHIC EMULSIONS*

By C. M. G. LATTES, Dr. G. P. S. OCCHIALINI and Dr. C. F. POWELL

H. H. Wills Physical Laboratory, University of Bristol

INTRODUCTION. In recent experiments, it has been shown that charged mesons, brought to rest in photographic emulsions, sometimes lead to the production of secondary mesons. We have now extended these observations by examining plates exposed in the Bolivian Andes at a height of 5,500 m., and have found, in all, forty examples of the process leading to the production of secondary mesons. In eleven of these, the secondary particle is brought to rest in the emulsion so that its range can be determined. In Part 1 of this article, the measurements made on these tracks are described, and it is shown that they provide evidence for the existence of mesons of different mass. In Part 2, we present further evidence on the production of mesons, which allows us to show that many of the observed mesons are locally generated in the 'explosive' disintegration of nuclei, and to discuss the relationship of the different types of mesons observed in photographic plates to the penetrating component of the cosmic radiation investigated in experiments with Wilson chambers and counters.

TABLE 1

Event No.	Range in emulsion in microns of Primary meson	Secondary meson
I	133	613
II	84	565
III	1040	621
IV	133	591
V	117	638
VI	49	586
VII	460	616
VIII	900	610
IX	239	666
X	256	637
XI	81	590

Mean range 614 ± 8 μ. Straggling coefficient $\sqrt{\Sigma\Delta_i^2/n}$ = 4·3 per cent, where $\Delta_i = R_i - \bar{R}$, R_i being the range of a secondary meson, and $\bar{R}$ the mean value for n particles of this type.

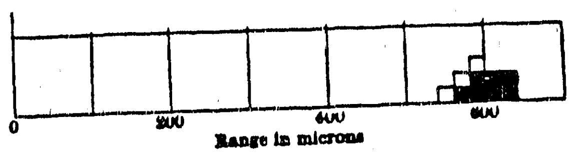


FIG. 3. DISTRIBUTION IN RANGE OF TEN SECONDARY MESONS. THOSE MARKED ■ STOP IN THE EMULSION; THE THREE MARKED □ LEAVE THE EMULSION WHEN NEAR THE END OF THEIR RANGE. MEAN RANGE OF SECONDARY MESONS, 606 MICRONS. THE RESULTS FOR EVENTS NOS. VIII TO XI ARE NOT INCLUDED IN THE FIGURE

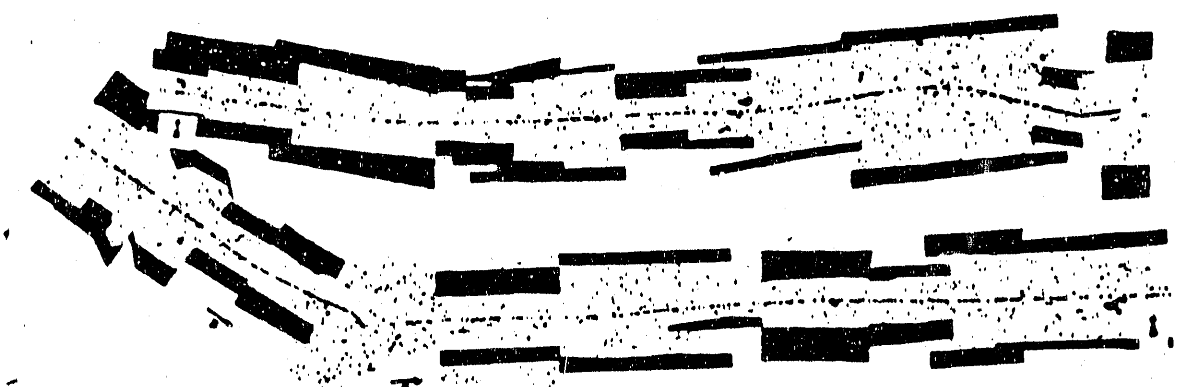


FIG. 1. OBSERVATION BY MRS. I. POWELL. COOKE × 95 ACHROMATIC OBJECTIVE; C2 ILFORD NUCLEAR RESEARCH EMULSION LOADED WITH BORON. THE TRACK OF THE μ-MESON IS GIVEN IN TWO PARTS, THE POINT OF JUNCTION BEING INDICATED BY a AND AN ARROW

Figure 11

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER
AND
Dr. C. C. BUTLER
Physical Laboratories, University, Manchester

AMONG some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character.

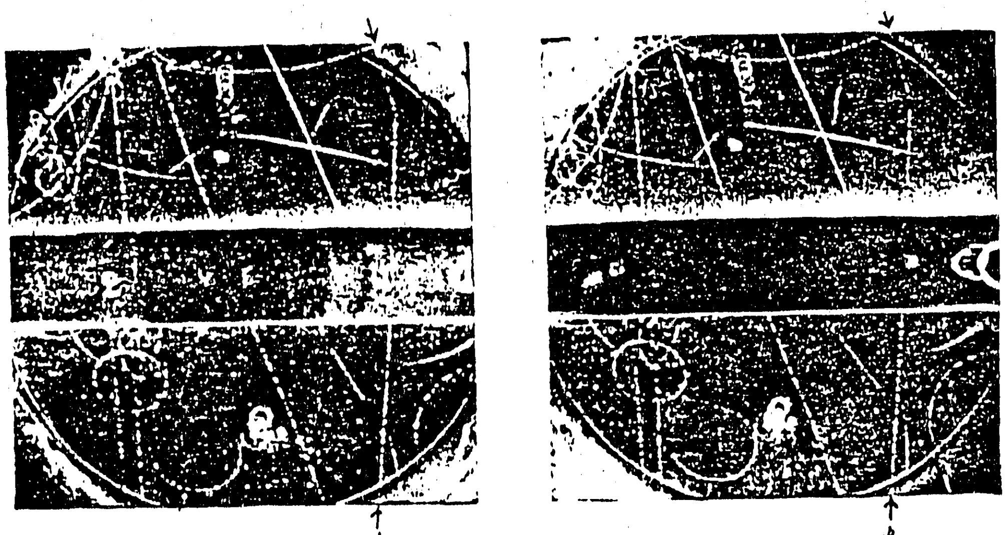


Fig. 2. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (a b). THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN A CLOCKWISE DIRECTION

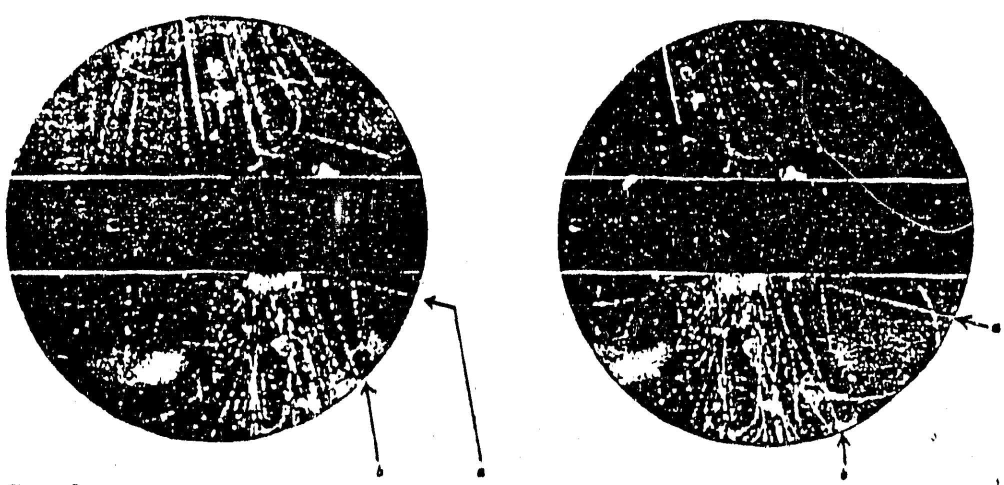


Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (a b) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

Figure 12

OBSERVATIONS WITH ELECTRON-SENSITIVE PLATES EXPOSED TO COSMIC RADIATION*

By Miss R. BROWN, U. CAMERINI, P. H. FOWLER, H. MUIRHEAD and Prof. C. F. POWELL
H. H. Wills Physical Laboratory, University of Bristol

and D. M. RITSON
Clarendon Laboratory, Oxford

PART 2. FURTHER EVIDENCE FOR THE EXISTENCE OF UNSTABLE CHARGED PARTICLES, OF MASS ~ 1,000 m_e, AND OBSERVATIONS ON THEIR MODE OF DECAY

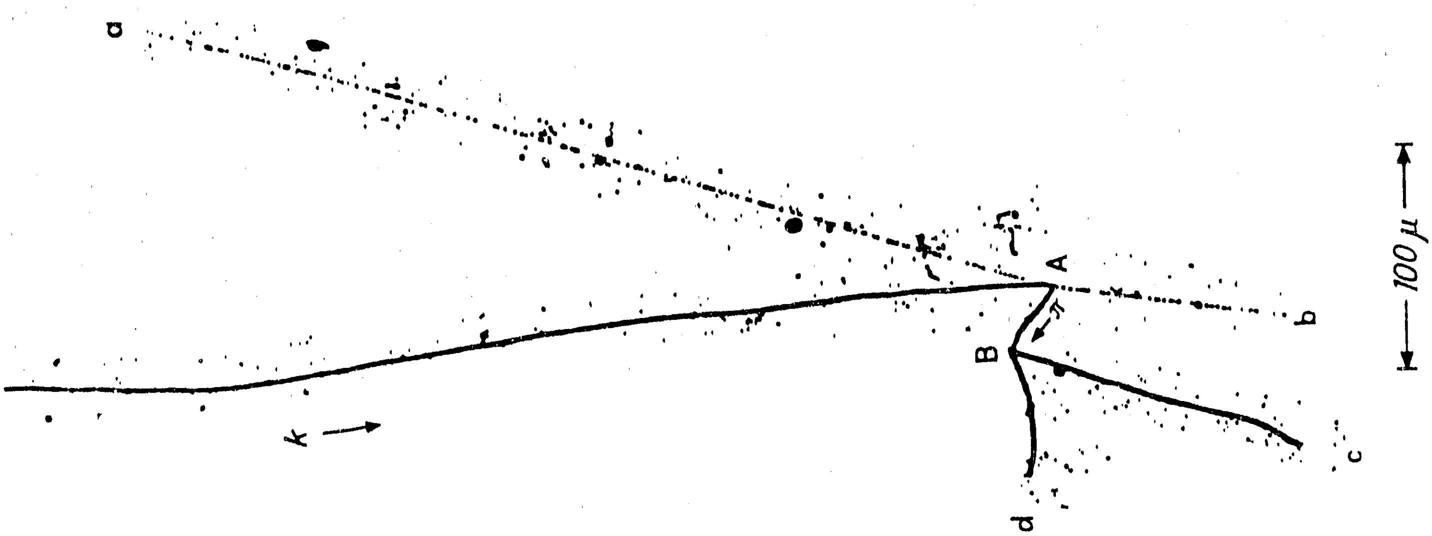


Figure 13

1950s

FROM COSMIC RAYS TO HIGH ENERGY ACCELERATORS

• Pion spin parity	W. Panofsky, et al.	
• π^o observations	Bjorklund, et al.	Synchrocyclotron
	Steinberger, et al.	Synchrotron
	Carlson, et al.	Cosmic Rays.

- A. Pais and Y. Nambu, et al. suggestion of associate production
- M. Gell-Mann - K. Nishijima - Strangeness

- E. Fermi, et al. Δ^{++} resonance
- Hyperfragments
- Hyperons
- R. Dalitz — τ - θ puzzle
- W. B. Fowler, et al. — Observation of associate production
- Don Glaser — Bubble chamber
- Antiprotons, Antineutrons at Bevatron
- T. D. Lee and C. N. Yang - Parity violation

Experiments: P and C violation observed:
C. S. Wu, E. Ambler, et al.
via Polarization in β decay.

R. L. Garwin, L. M. Lederman,
M. Weinrich
in μ decay.

J. I. Friedman and V. L. Telegdi
in μ decay.

- Observation of ν^- interactions by F. Reines - C. L. Cowan

1960 Resonances in Hydrogen Bubble Chamber
Luis Alvarez group, a new application of the Dalitz plot

Figure 14

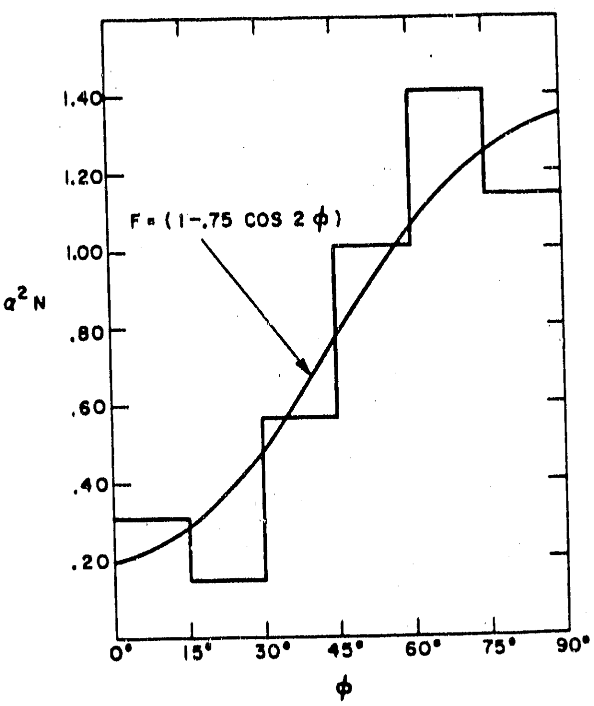
DALITZ PAIRS

$\pi^0 \rightarrow \gamma\gamma$

$\pi^0 \rightarrow \gamma\, e^+e^-$ $\sim$ $1/80$

$\pi^0 \rightarrow e^+e^- \; e^+e^-$ $\sim$ $(1/160)^2$

Utilized in 1959 by Plano and Steinberger, et al., to measure the parity of the π^0.



. Plot of weighted frequency distribution of angle between planes of polarization.

R. Plano, et al. PRL 3, 525 (1959) based on theory by C. N. Yang and N. Kroll, and W. Wada.

Figure 15

1953

M DANYSZ & J. PNIEWSKI Phil. Mag. Ser. 7, Vol. 44, Pl. 13.

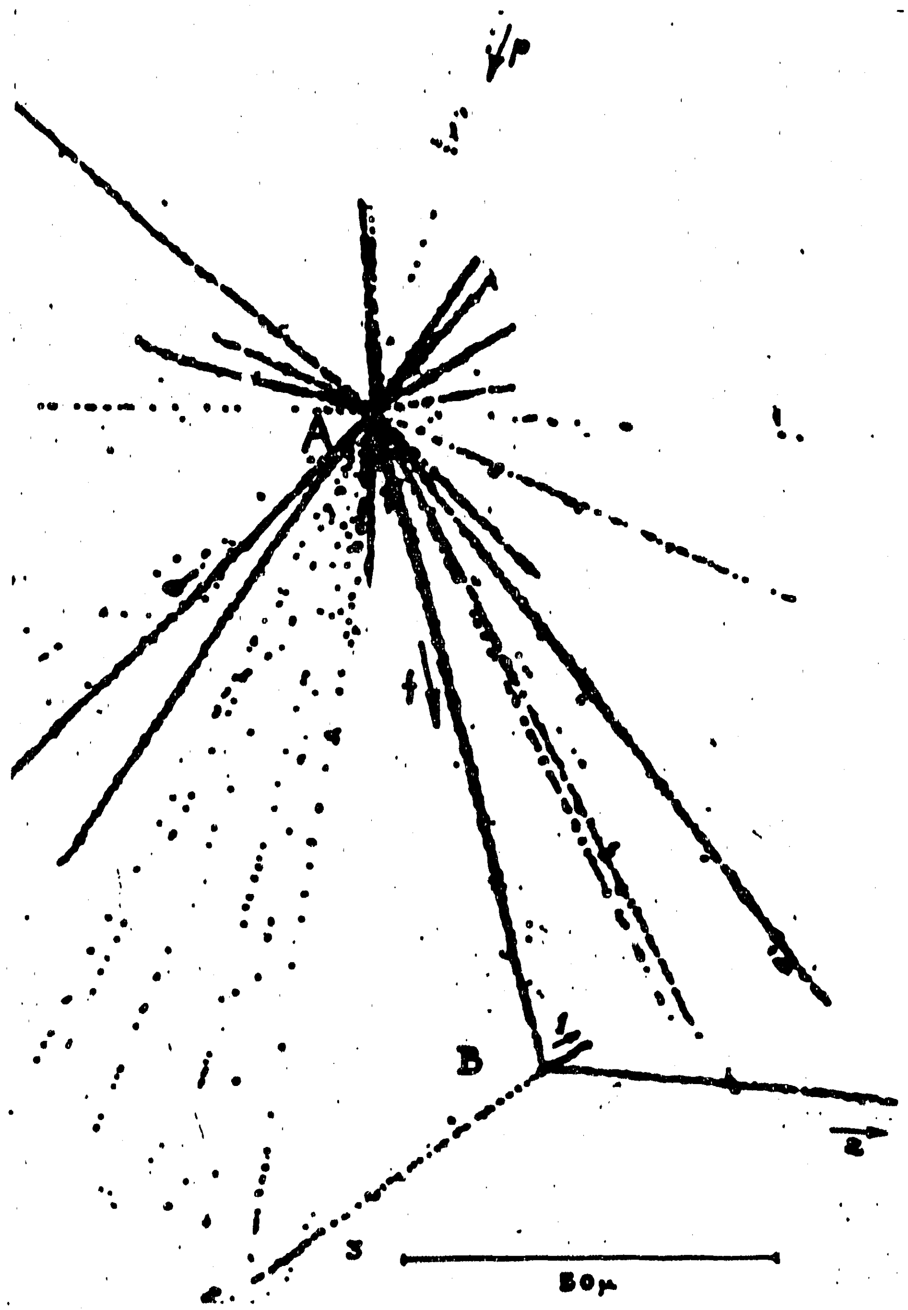


Figure 16

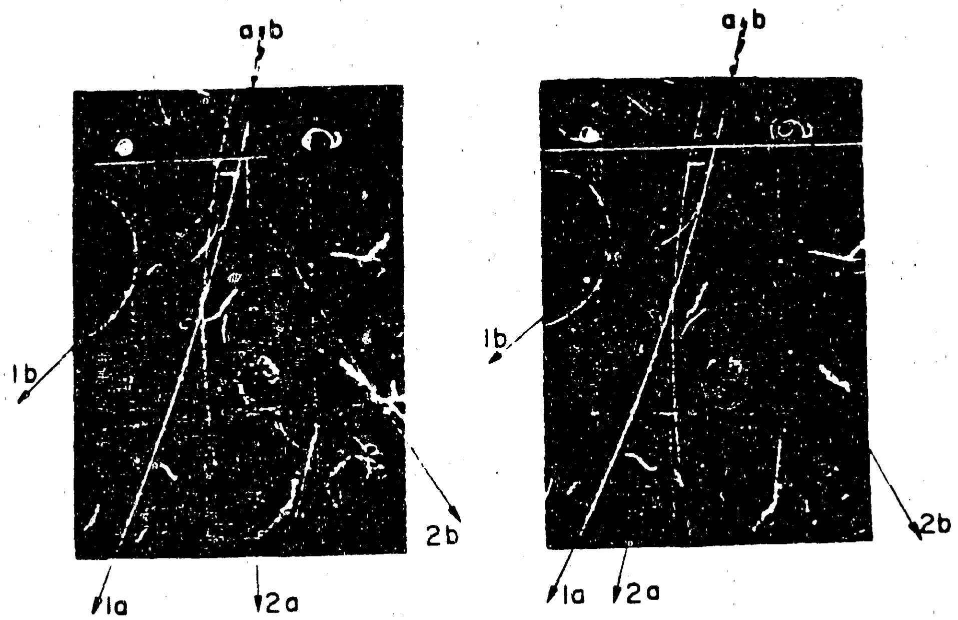


FIG. 1. Case C. Diffusion cloud-chamber photograph of two neutral V particles (a) and (b), whose lines of flight are almost colinear. (a) is believed to be a Λ^0 decaying into a proton (1a) and a negative π meson (2a). Tracks 1a and 2a practically coincide in the right view. (b) is probably a ϑ^0 decaying into π^+ (1b) and π^- (2b).

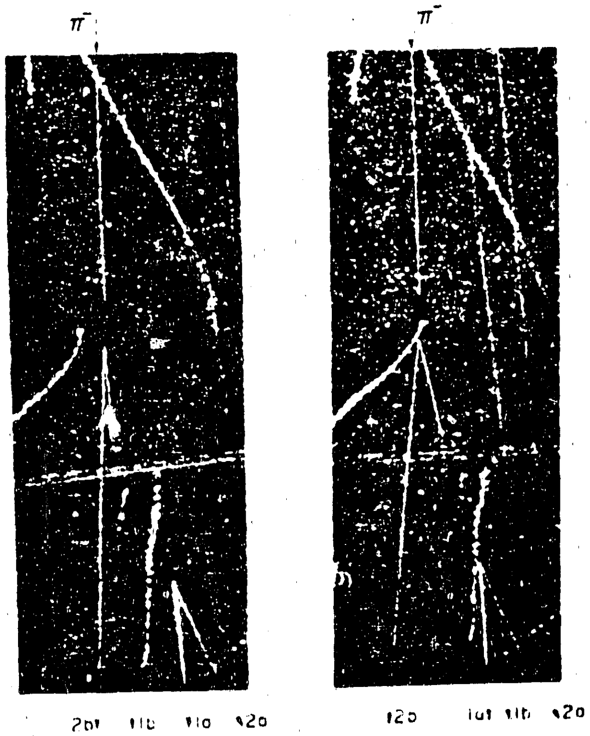


FIG. 2. Case D. Photograph of a 1.5-Bev π^- producing two neutral V particles in a collision with a proton. Tracks 1a and 2a, believed to be proton and π^-, respectively, are the decay products of a Λ^0. A ϑ^0 is probably seen to decay into π^+ (1b) and π^- (2b). Because of the rather "foggy" quality of this picture tracks 1b, 2a, and 2b have been retouched for better reproduction.

Examples of Associate Production

$$\pi^- + p \rightarrow \Lambda + \theta^o$$

Figure 17

PHYSICAL REVIEW
VOLUME 94, NUMBER 4 MAY 15, 195

Decay of τ Mesons of Known Charge*†

R. H. DALITZ‡
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
(Received February 9, 1954)

The experimental data on the 3π decay of τ mesons is summarized on a convenient two-dimensional plot, both (a) when the π-meson charges are known and (b) when they are not. Some events may be included in plot (a) only if the parent τ meson is assumed positive and arguments supporting this identification for τ mesons decaying in an emulsion are discussed. The dependence of this plot on the τ-meson spin (*j*) and parity (*w*) is discussed in general terms and those features depending particularly on *w* and on its relation with *j* are emphasized—for example, if the density of events does not vanish at the bottom of the plot, the τ meson must have odd parity and even spin. Simple estimates of the distribution, using only the lowest allowable angular momenta and a "short range" approximation, may be modified by final-state meson-meson attractions, whose effects are discussed qualitatively. The available data are insufficient for any strong conclusion to be drawn but rather suggest even spin and odd parity for the τ meson; the need for careful assessment of geometrical bias in the selection of experimental material is stressed.

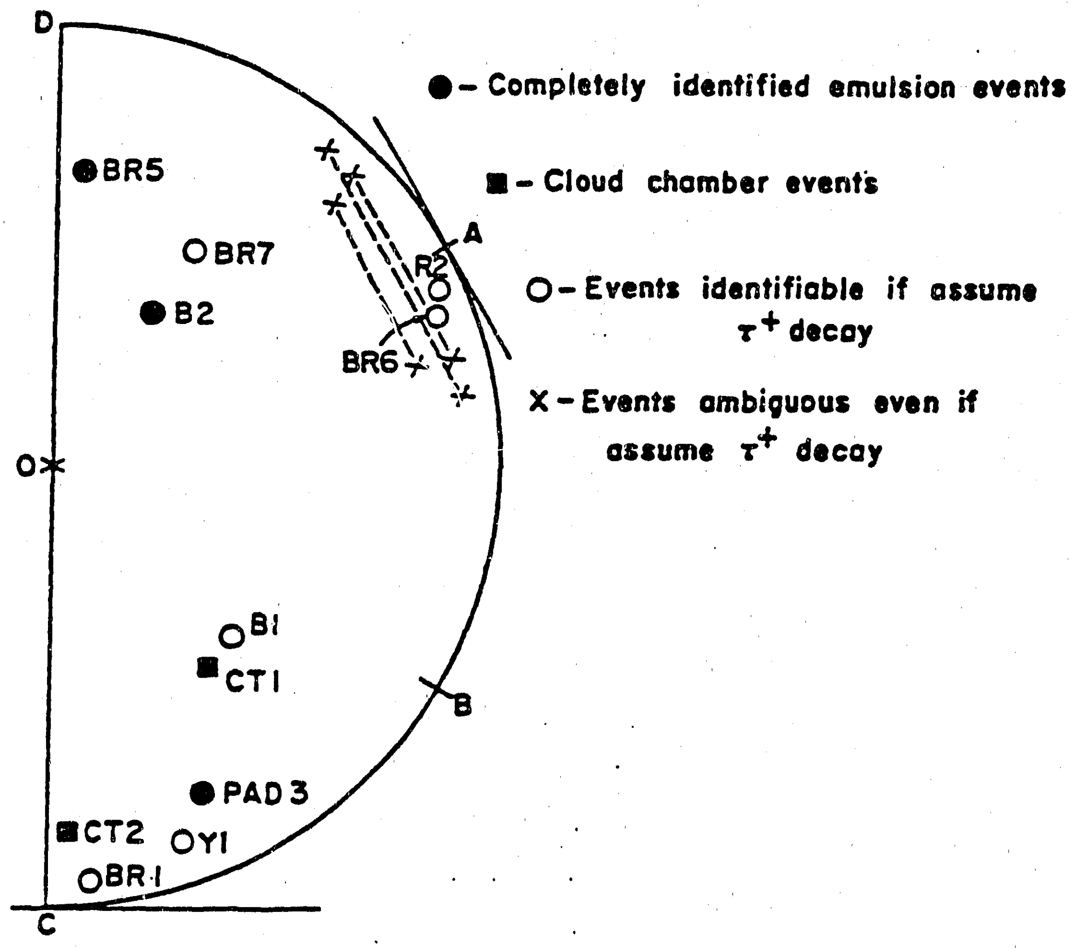


FIG. 3. The data on τ-meson decay events in which the signs of π-meson charges are established.

Figure 18

1955 PISA CONFERENCE

SUPPLEMENTO
AL VOLUME IV, SERIE X, DEL
NUOVO CIMENTO
A CURA DELLA SOCIETÀ ITALIANA DI FISICA

1956 — 2° Semestre — N. 2

CELEBRAZIONE DEL CENTENARIO DEL GIORNALE
IL NUOVO CIMENTO

CONFERENZA INTERNAZIONALE SULLE PARTICELLE ELEMENTARI
E
XLI CONGRESSO NAZIONALE DI FISICA

ORGANIZZATI DALLA SOCIETÀ ITALIANA DI FISICA

SOTTO GLI AUSPICI E COL CONCORSO
DELL' UNIONE INTERNAZIONALE DI FISICA
DEL CONSIGLIO NAZIONALE DELLE RICERCHE
DELL' UNIVERSITÀ DI PISA
E DEL COMITATO PISANO DI OSPITALITÀ

PISA, 12-18 GIUGNO 1955

RENDICONTI

Figure 19

The experimental data collected in Table I are still rather scarce; one can however try to compare them with the theoretical results in the 5 simple cases mentioned above.

A general view of the available experimental data can be obtained by plotting them in the triangular diagram of Fig. 3. Fig. 4, similar to Fig. 3, refers to 16 τ-mesons observed in cloud chambers; it was prepared and kindly sent to me by Dr. DALITZ shortly before the Conference. In such a representation the height of the triangle is taken equal to the Q-value (75 MeV) of the τ-meson, so that the three distances of a point P internal to the triangle (whose sum is always equal to its height) correspond to the kinetic energies of the 3 emitted pions [29]. Momentum conservation imposes a further restriction to the points representing τ-meson-decays: in the non-relativistic approximation they can fall only inside the inscribed circle whose diameter is $(2/3)\,Q$ (50 MeV). The relativistic corrections restrict somewhat more the permitted region whose boundary remains tangential to the sides, while the distance from the center is reduced by 8% in correspondence to its intersections with the heights of the triangle [30]. In such a representation the statistical factor, relative to a given elementary energy interval of the emitted pions (i.e. to a given element of surface inside the permitted region), is constant [31] and the relativistic corrections never exceed 2% [30]. In Fig. 3 the kinetic energy E_- of the negative pion is represented by the distance from the side AB, while the distance from the side CB corresponds to the kinetic energy E''_+

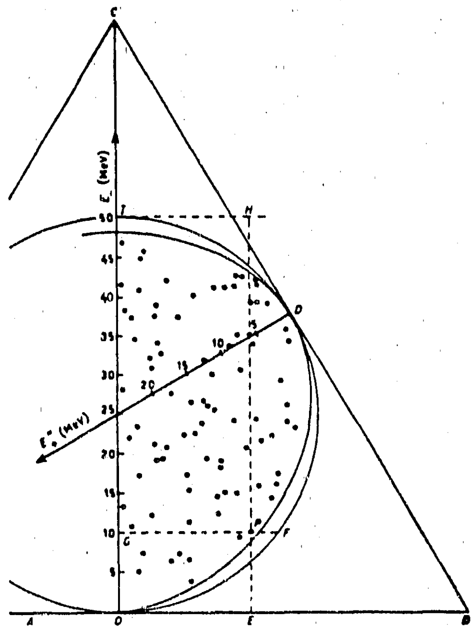


Fig. 3. – Representation of τ-meson decays observed in emulsions.

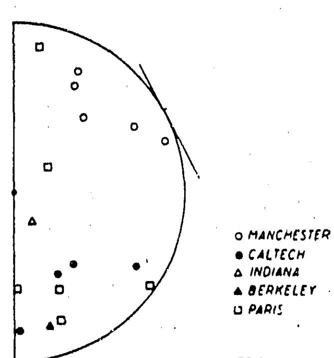


Fig. 4. – Representation of τ-meson decays observed in cloud chamber (DALITZ, private communication).

Figure 20

DALITZ PLOT

$$d\Gamma \simeq |M|^2 dE_1 dE_2 \; .$$

uniform if $|M|^2$ = constant

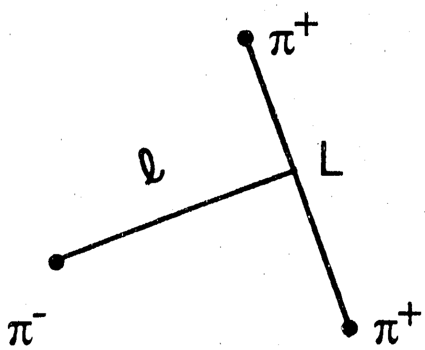
Spin and parity of the pion was known: $J^P = O^-$ for π

Thus θ^+ decay (or K^+ decay)

$$\theta^+ \rightarrow \pi^+ \pi^o$$

$$J^P = O^+, 1^-, 2^+, \ldots$$

From the Dalitz plot we can ask the question:
Can the τ^+ have these quantum numbers?



$$\tau^+ \rightarrow \pi^+ \pi^+ \pi^-$$

Here L = even (Bose statistics)

$\bar{J} = \bar{L} + \bar{\ell}$ at $T_{\pi-} \rightarrow O$

$\ell = o$

or $J^P = O^-, 2^-, \ldots$

Thus we expect a zero in the Matrix elements when

$$J^P(\tau) = 1^-, 2^+, \ldots$$

Here O^+ is ruled out for 3 Pseudoscalars.

Result: No vanishing of $|M|^2$ was experimentally observed.

Conclusion: $\tau - \theta$ puzzle

Figure 21

SUPPLEMENTO AL VOLUME IV, SERIE X
DEL NUOVO CIMENTO

N. 2, 1956
2° Semestre

COSMIC RAY RESULTS

Observations on Heavy Mesons Secondaries.

(G-Stack Collaboration)

J. H. DAVIES, D. EVANS, P. H. FOWLER, P. E. FRANÇOIS, M. W. FRIEDLANDER, R. HILLIER, P. IREDALE, D. KEEFE, M. G. K. MENON, D. H. PERKINS and C. F. POWELL
H. H. Wills Physical Laboratory - Bristol (Br)

L. CRANE, R. H. W. JOHNSON and C. O'CEALLAIGH
Institute for Advanced Studies - Dublin (DuAS)

F. ANDERSON, G. LAWLOR and T. E. NEVIN
University College - Dublin (DuUC)

G. ALVIAL, A. BONETTI, M. DI CORATO, C. DILWORTH, R. LEVI-SETTI, A. MILONE, G. OCCHIALINI, L. SCARSI and G. TOMMASINI
Istituto di Fisica dell'Università di Genova
Istituto di Fisica dell'Università di Milano (Ge-Mi)
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Sezione di Padova dell'Istituto Nazionale di Fisica Nucleare

[Una più particolareggiata e completa relazione di questo lavoro è stata pubblicata nel *Nuovo Cimento*, 2, 1063 (1955). *N. d. R.*].

CONTENTS. — 1. Introduction (C. F. POWELL). - 2. The K_μ-decay (reported by M. MERLIN). - 3. The χ-decay (reported by C. O'CEALLAIGH). - 3*a*. Unusual decay of a χ-meson (reported by D. KEEFE, on behalf of the University College, Dublin group). - 3*b*. A determination of the mass of a χ-meson by the analysis of a collision of its secondary with a proton (M. DI CORATO and L. SCARSI, reported by M. DI CORATO). - 4. The κ- and K_β-particles (reported by M. W. FRIEDLANDER). - 5. On the composition of the K-particle decay spectrum (reported by A. BONETTI).

Figure 22

SUPPLEMENTO AL VOLUME IV, SERIE X
DEL NUOVO CIMENTO

N. 2, 1956
2° Semestre

BEVATRON RESULTS

Positive Heavy Mesons Produced at the Bevatron.

R. W. BIRGE, R. P. HADDOCK, L. T. KERTH, J. R. PETERSON,
J. SANDWEISS, D. H. STORK, and M. N. WHITEHEAD
Radiation Laboratory - Berkeley, California

(Presented by D. H. STORK.)

$M_K = (963.2 \pm 2.0)\, m_e$

Nuclear emulsions have been exposed to 114, 135, and 170 MeV positive heavy mesons produced at 90° by 5·7 GeV protons striking a copper target. The exposures were made using the strong-focusing spectrometer [1].

$M_\tau = (966.1 \pm 4.7)\, m_e$

1. – The strong-focusing spectrometer.

The principal features of this apparatus consist of a strong-focusing quadrupole-magnet lens system followed by a conventional momentum-analyzing magnet. The arrangement is shown in Fig. 1. It can be shown that the flux of heavy mesons at the stack position is

$$\frac{dN_h}{dA} N_p N_t \frac{d^2\sigma}{\sigma d\Omega dE}\left(\beta c \frac{dP}{dx} M_B L_B\right)\left(\frac{\theta_B \theta_\Gamma}{M_B L_B M_\Gamma L_\Gamma}\right) e^{-t/\tau}, \qquad (1)$$

where dN_h/dA is the number of heavy mesons per unit area, N_p is the total number of protons traversing the target, N_t is the number of target nuclei per cm² in the proton beam direction, $d^2\sigma/d\Omega dE$ is the cross-section in cm²·ster⁻¹ MeV⁻¹, βc is the velocity of the heavy mesons, dP/dx is the momentum dispersion of the analyzing

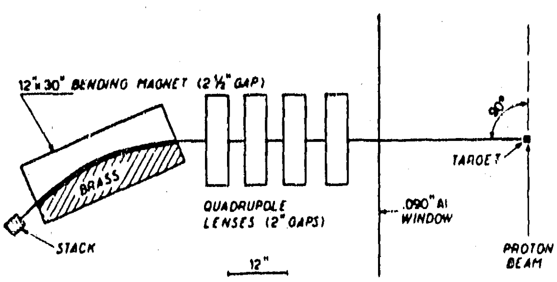


Fig. 1.

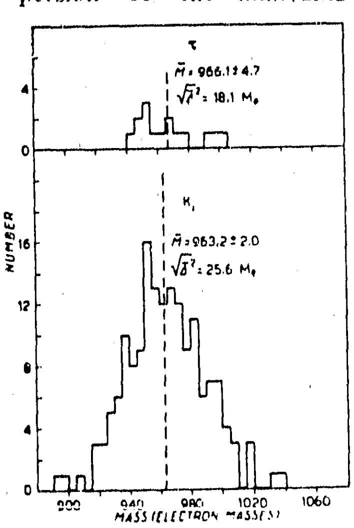


Fig. 3.

Figure 23

SUPPLEMENTO AL VOLUME IV, SERIE X
DEL NUOVO CIMENTO

N. 2, 1956
2° Semestre

BEVATRON RESULTS

K-Meson Mass from a K-Hydrogen Scattering Event [1].

W. W. CHUPP, G. GOLDHABER, S. GOLDHABER,
W. R. JOHNSON and J. E. LANNUTTI

Radiation Laboratory, Department of Physics
University of California - Berkeley, California

$$M_K = (973 \pm 12) m_e$$

A K-Hydrogen scattering event observed in a stack of nuclear emulsions exposed to the focused K^+ beam [2] enabled us to get a mass measurement

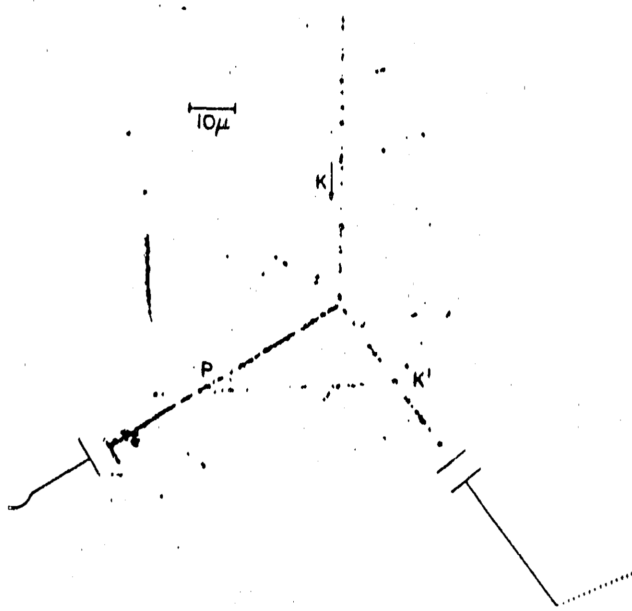


Fig. 1. – A photomicrograph of a K-hydrogen scattering event $E_K = 102$ MeV. Both outcoming particles come to rest (endings are sketched in) in the emulsion. $R_{K'} =$ $= 32.21$ mm, $R_p = 2.427$ mm. (Observer: S. LIVINGSTON, Photomicrograph: R. P. MICHAELIS).

Figure 24

SUPPLEMENTO AL VOLUME IV, SERIE X
DEL NUOVO CIMENTO

N. 2, 1956
2° Semestre

BEVATRON RESULTS

Interactions and Decay of Positive K-Particles in Flight.

W. W. CHUPP, G. GOLDHABER, S. GOLDHABER, E. L. ILOFF and J. E. LANNUTTI
Radiation Laboratory, Department of Physics
University of California - Berkeley, California

A. PEVSNER and D. RITSON
Department of Physics, Massachusetts Institute of Technology - Cambridge, Massachusetts

$$\tau_K = (1.1 \pm 0.3) \times 10^{-8} \text{ Sec}$$

To gain further information on the nature of K-particles, we have embarked on a program of study of K-particle interactions. The ideas on the nature and behavior of K-particles and hyperons as expressed by GELL-MANN and PAIS [1] and those of M. GOLDHABER [2] and R. G. SACHS [3] make rather de-[illegible]e predictions about the [illegible]tions of K particles.
[illegible] are two [illegible] [illegible]raction [illegible] [illegible]les that [illegible]

The Lifetime of the τ-Meson.

W. ALVAREZ and S. GOLDHABER
Radiation Laboratory, Department of Physics,
University of California, Berkeley

(Reported by D. H. STORK.)

[Il testo completo di questo lavoro è stato già pubblicato come lettera alla Redazione nel *Nuovo Cimento*, **2**, 344 (1955). Qui ne pubblichiamo un breve riassunto. *N. d. R.*].

$$\tau_\tau = \left(1.0 {}^{+0.07}_{-0.03}\right) \times 10^{-8} \text{ sec}$$

Summary. — Stacks of nuclear emulsions were exposed to the positive K-mesons beam at two different distances from the target of the Berkeley Bevatron (proper time of flight + slowing-down time: $1.8 \cdot 10^{-8}$ s and $1.3 \cdot 10^{-8}$ s respectively). The mean life-time of τ-meson determined from these exposures is $(1.0^{+.07}_{-.03}) \cdot 10^{-8}$ s.

Figure 25

SUPPLEMENTO AL VOLUME IV, SERIE X
DEL NUOVO CIMENTO

N. 2, 1956
2° Semestre

The Interpretation of the New Particles as Displaced Charge Multiplets.

M. GELL-MANN (*)
Institute for Advanced Study, Princeton, N. J.

1. – Introduction.

The purpose of this communication is to present a coherent summary of the author's theoretical proposals [1] concerning the new unstable particles.

Section 2 is devoted to some background material on elementary particles; the object there is to introduce the point of view adopted in the work that follows. In Section 3 the fundamental ideas about displaced multiplets are given, and in the succeeding section these are applied to the interpretation of known particles. A schéme is thus set up, which is used in Section 5 to predict certain results of experiments involving the new particles.

The work of DALITZ on the τ-meson decay spectrum indicates that the θ and τ have different parity and/or spin and thus cannot be merely two decay modes of the same particle.

Thus we expect a second pair of doublets, τ^+, $\tau^{(0)}$, $\overline{\tau^{(0)}}$, and τ^-, with strangeness ± 1 like the θ. The neutral partners, if they are as long-lived as the charged ones, could easily have escaped definite identification.

The reason for the similarity in mass of the τ and θ is of course completely unknown, but there is a further puzzle. The masses are presumably not exactly equal, and there is the possibility of electromagnetic decay of the heavier into the lighter, fully allowed by conservation of strangeness. Since both the τ and θ are metastable, something must inhibit such electromagnetic decay so that it takes at least 10^{-9} s to occur. It may be that the mass difference is very small, considerably smaller than 1 MeV, say; or it may be that the τ and θ are both spinless (the τ pseudoscalar and the θ scalar), in which case we are dealing with a $0 \rightarrow 0$ transition.

VOLUME 5, NUMBER 11 PHYSICAL REVIEW LETTERS DECEMBER 1, 1960

A NEW APPLICATION FOR THE DALITZ PLOT

RESONANCE IN THE $\Lambda\pi$ SYSTEM*

Margaret Alston, Luis W. Alvarez, Philippe Eberhard,† Myron L. Good,‡
William Graziano, Harold K. Ticho,‖ and Stanley G. Wojcicki
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California
(Received October 31, 1960)

We report a study of the reaction

$$K^- + p \to \Lambda^0 + \pi^+ + \pi^- \qquad (1)$$

produced by 1.15-Bev/c K^- mesons and observed in the Lawrence Radiation Laboratory's 15-in. hydrogen bubble chamber. A preliminary report of these results was presented at the 1960 Rochester Conference.[1]

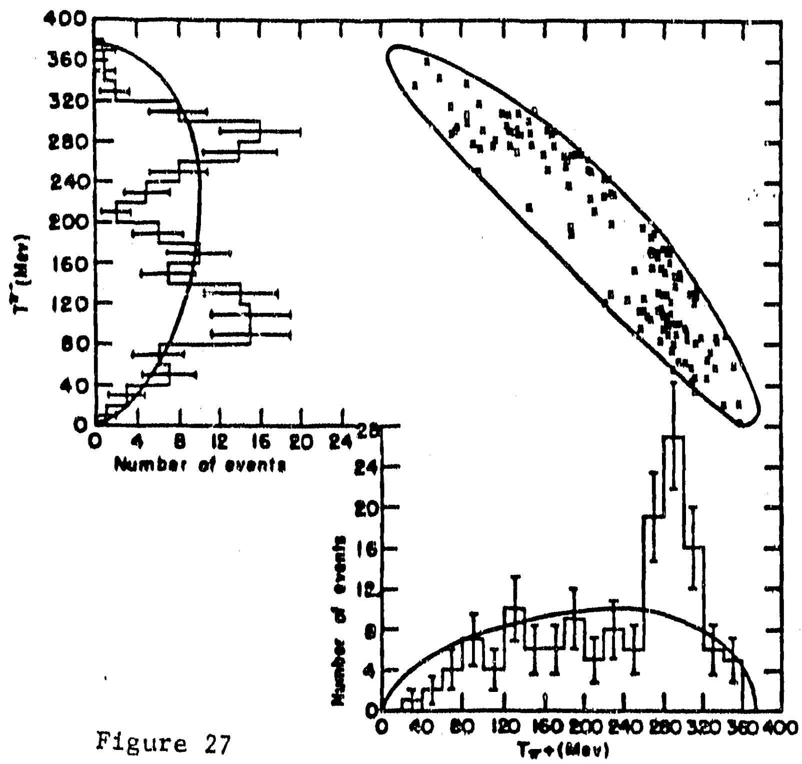


FIG. 1. Energy distribution of the two pions from the reaction $K^- + p \to \Lambda + \pi^+ + \pi^-$. Each event is plotted only once on the Dalitz plot, which should be uniformly populated if phase space dominated the reaction. The two energy histograms are merely one-dimensional projections of the two-dimensional plot, and each event is represented once on each histogram. The solid lines superimposed over the histograms are the phase-space curves.

Figure 27

TABLE I

The Square of the Matrix Elements for the Angular Momentum-Parity States $I = 0, J^P = 0^-, 1^-, 1^+, 2^-, 2^+$

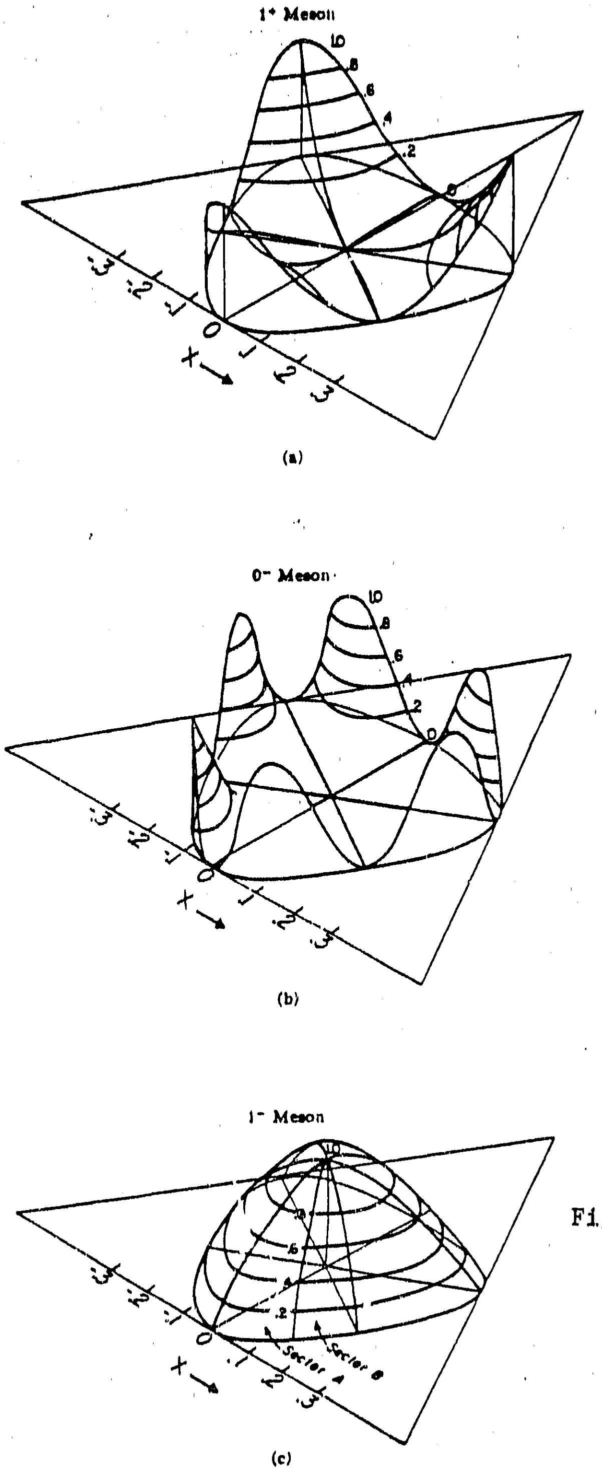
$$\lambda(0^-) = [(E_2 - E_3)(E_3 - E_1)(E_1 - E_2)]^2$$

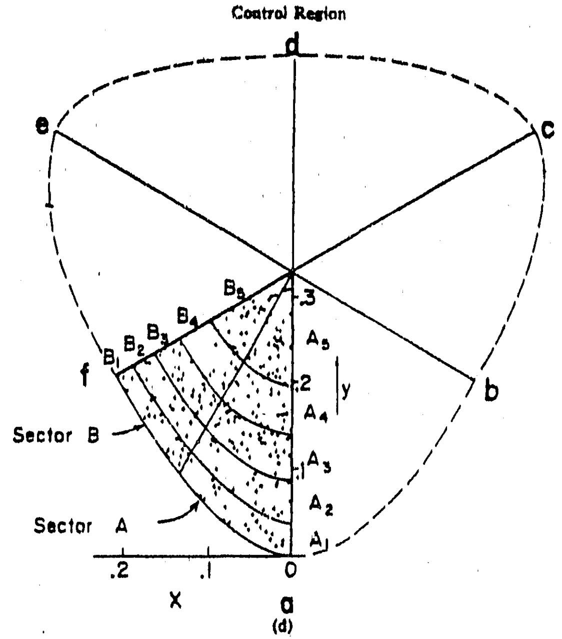
$$\lambda(1^-) = (\mathbf{P}_1 \times \mathbf{P}_2 + \mathbf{P}_2 \times \mathbf{P}_3 + \mathbf{P}_3 \times \mathbf{P}_1)^2 = q^2$$

$$\lambda(1^+) = [\mathbf{P}_1(E_2 - E_3) + \mathbf{P}_2(E_3 - E_1) + \mathbf{P}_3(E_1 - E_2)]^2$$

$$\lambda(2^-) = \sum_{(ijk)} [\tfrac{2}{3}(E_j - E_k)^2 P_i^4 + 2(E_j - E_k)(E_k - E_i)(\mathbf{P}_i \cdot \mathbf{P}_j)^2 - \tfrac{1}{3} P_i^2 P_j^2]$$

$$\lambda(2^+) = q^2(E_1\mathbf{P}_1 + E_2\mathbf{P}_2 + E_3 P_3)^2$$





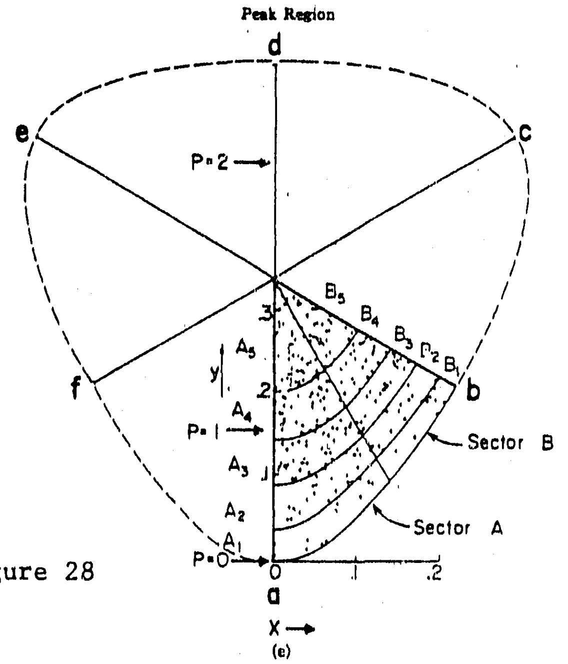


Figure 28

FIG. 1. (a), (b), and (c): Isometric drawings of the square of matrix elements for the 1^+, 0^-, and 1^- mesons expressed in terms of the normalized Dalitz variables $x=(T_- - T_+)/\sqrt{3}Q$, and $y=T_0/Q$ ($Q=T_+ + T_- + T_0 = M_1 - 3$). (d) and (e): Dalitz plots, folded six times. (d) displays 241 triplets in the control region and (e) displays 270 triplets in the peak region. The contour lines represent the projection of the contours of (c) (1^- meson).

C. ZEMACH. ZEROS ON DALITZ PLOTS

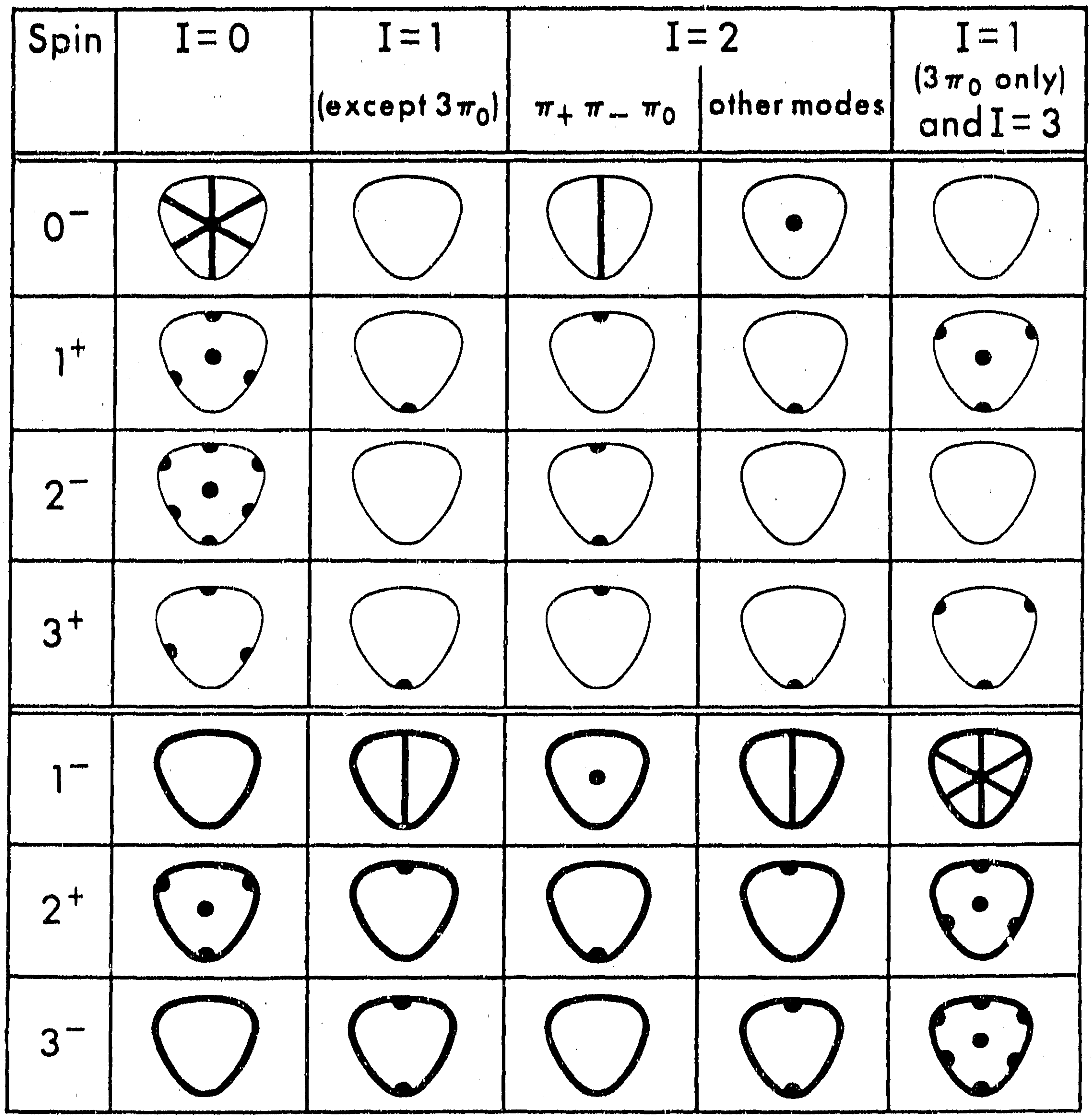
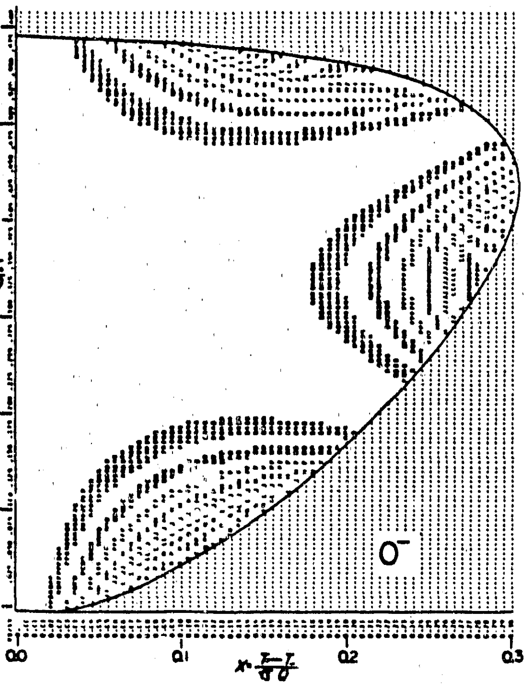
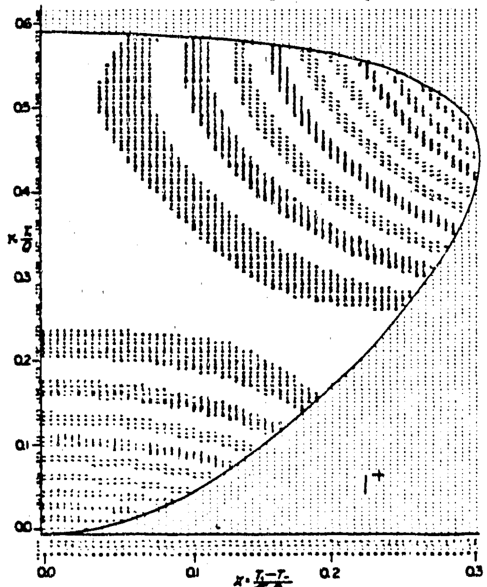
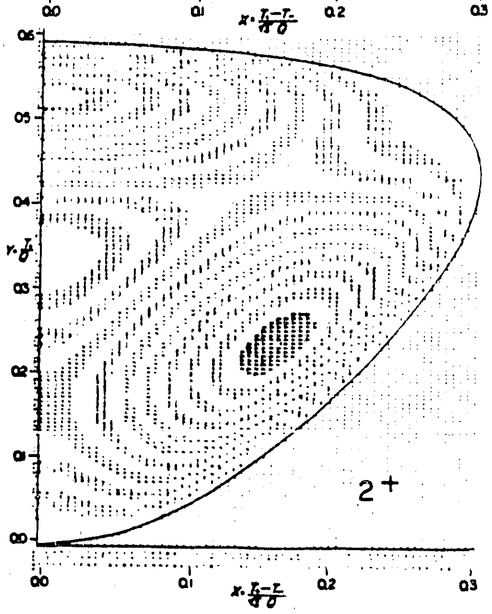


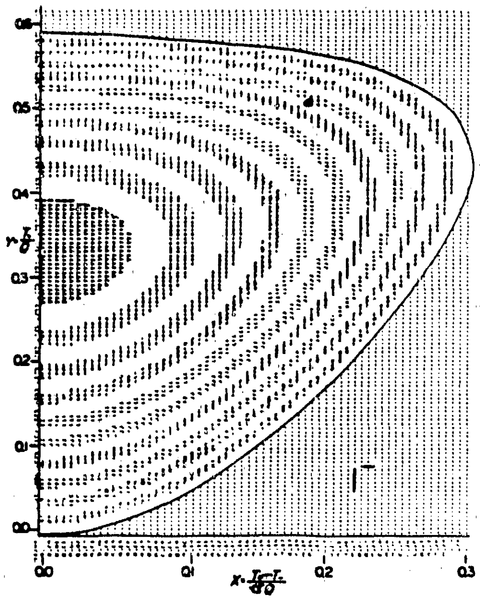
Figure 29



Contour maps for the square of the matrix elements of $I = 0$ $\pi^+\pi^-\pi^0$ decay. The contours are given in 5% steps by the letters A—T with every other letter omitted for clarity. The figures give the right-hand half of the Dalitz plot.







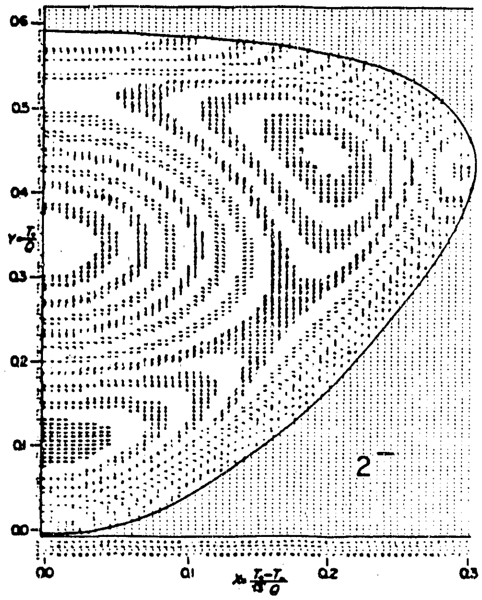
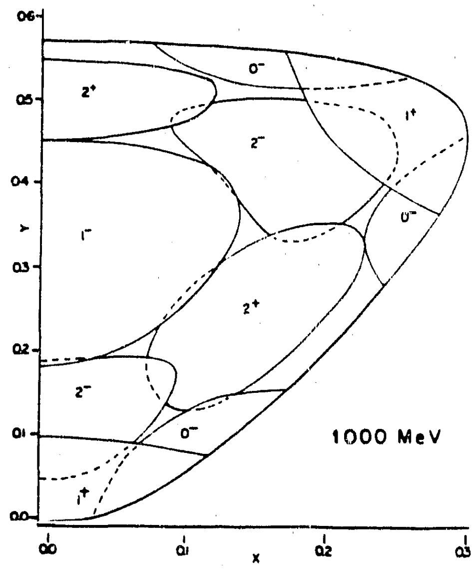
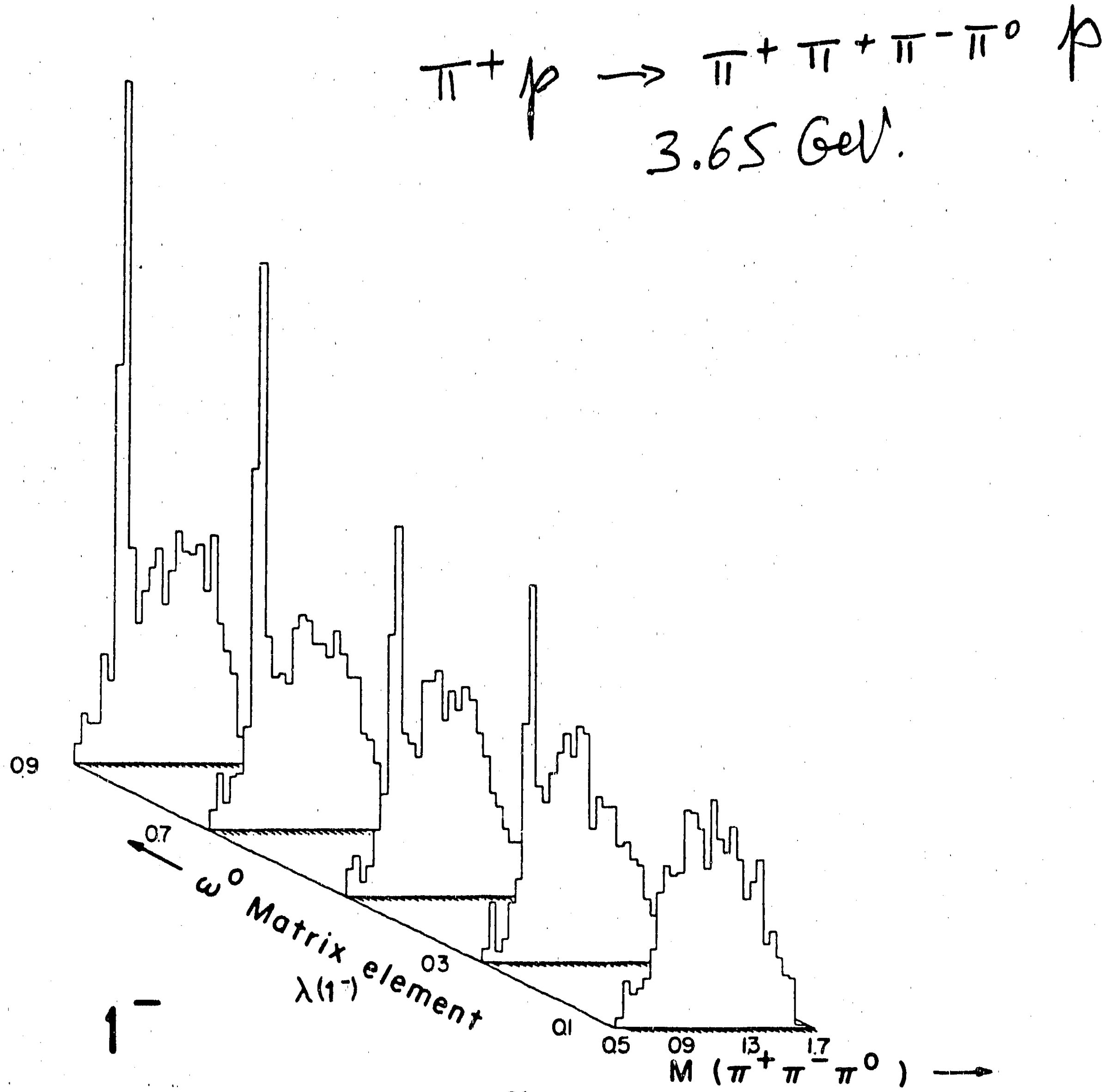


Figure 30



Location of the 50% contours in the Dalitz plot for the preceding matrix elements. For any given J^P value 50% of the events for the corresponding resonance lie inside the contours indicated.



π+ p → π+ π+ π− π0 p
3.65 GeV.
09
07
03
01
ω0 Matrix element
λ(1−)
1−
05
09
13
17
M (π+ π− π0) →

Figure 31

DECAYS OF THE ω AND η MESONS*

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and

H. Brugger, P. Kramer, and R. Plano
Rutgers University, New Brunswick, New Jersey
(Received September 7, 1962)

The experiment described in the previous Letter[1] also yields information on the decay products of the ω and η mesons. We present here studies on correlations among the decay products, and branching ratios of competing decay modes.

(A) Energy correlations in the $\pi^+\pi^-\pi^0$ decay modes.—The Dalitz plot (kinetic energies of the three pions in the center of mass of the decay on a triangular plot) for the ω is given in Fig. 1. This represents 1100 events, of which an estimated 34% are nonresonant background (see Fig. 1 of reference 1.) As was shown already in the original contribution[2] on the ω, this distribution can determine the spin and parity of the ω. For this purpose the dashed lines are drawn in the Dalitz plot of Fig. 1. They divide the plot into regions of equal area along lines of equal matrix elements under the assumption of spin one, parity minus following the model outlined in reference 1. The distribution in this "radius" (also Fig. 1) is in agreement with the 1^- assignment. This only confirms the now well-established 1^{--} quantum numbers of the $T=0$ ω^0. Figure 1 also includes a plot of the distribution in the combined masses of all pairs of pions in the Dalitz plot (3 pairs per event). In this plot the background has been subtracted with the assumption that it follows the phase-space distribution and the matrix element, $|\vec{p}_i\times\vec{p}_j|^2$, has been divided out. The remaining distribution should

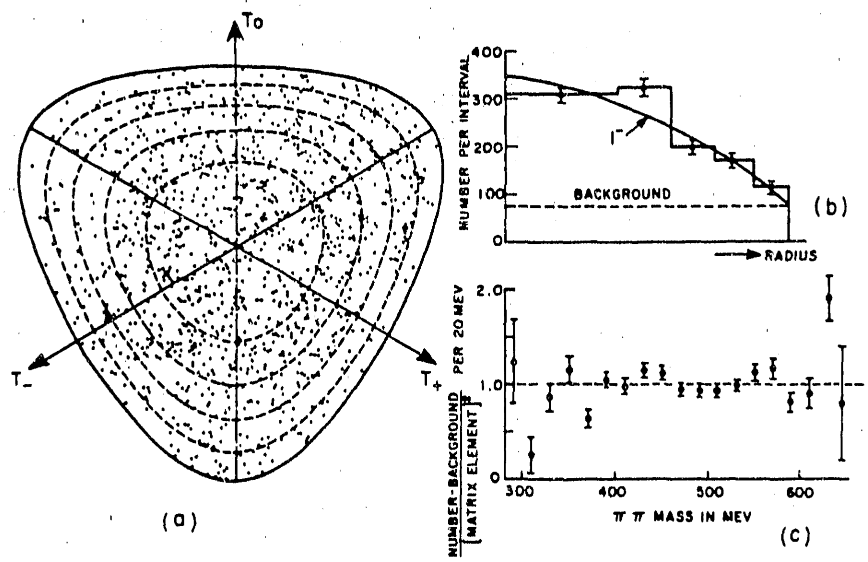
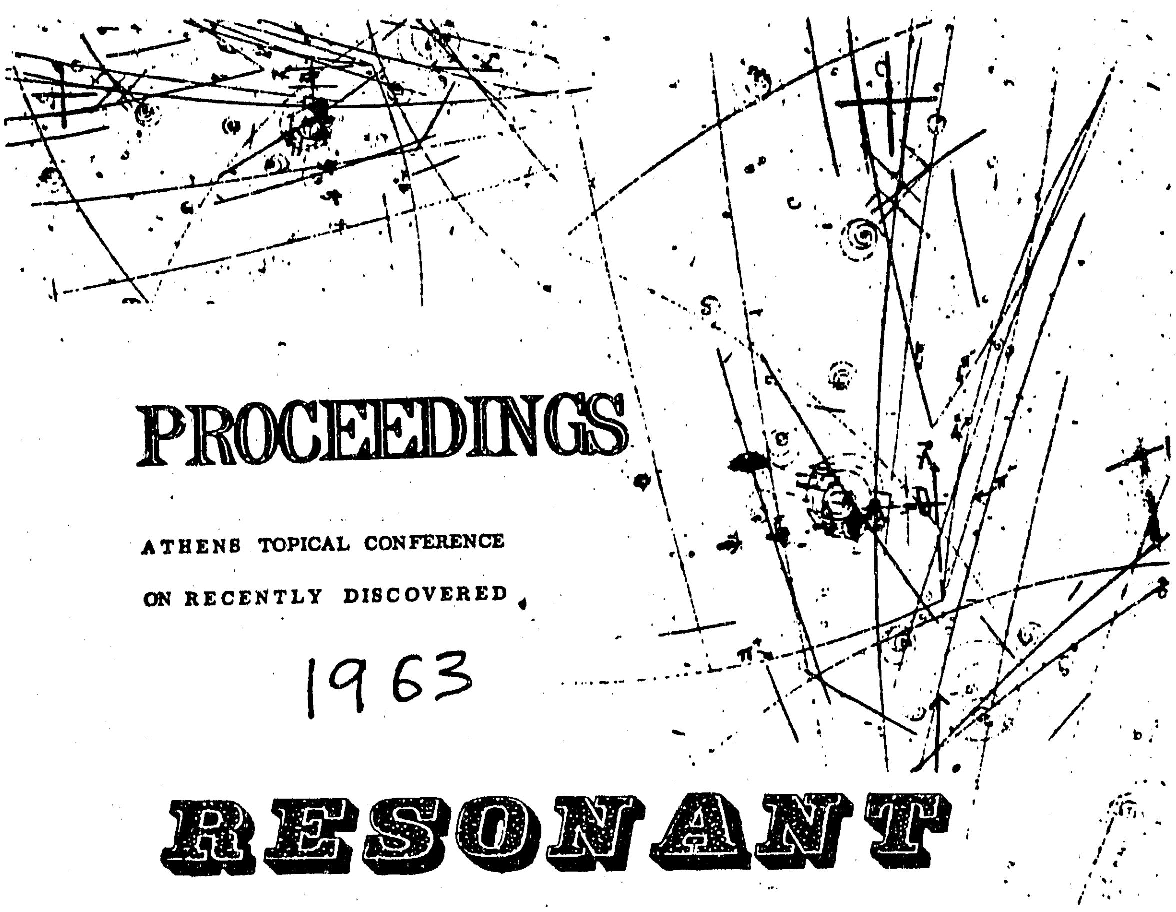


FIG. 1. (a) The Dalitz plot for 1100 omegas (including a background of 375 nonresonant triplets). (b) The density of points on the Dalitz plot compared to the expected density for a 1^- ω plus a uniformly distributed background. (c) The dependence of the $\pi\pi$ interaction in the $T=1$ $J=1$ state as a function of energy. This was obtained by summing the $\pi^+\pi^-$, $\pi^+\pi^0$, and $\pi^-\pi^0$ mass spectra for pion pairs from the ω decays, subtracting a background, and dividing by the distribution expected for 1^- decay into $\pi^+\pi^-\pi^0$. Since two of the three mass combinations are independent, an error corresponding to $(\frac{3}{2}N)^{1/2}$, where N is the number of pairs per interval before background subtraction, was assigned to each piont.

Figure 32



PROCEEDINGS

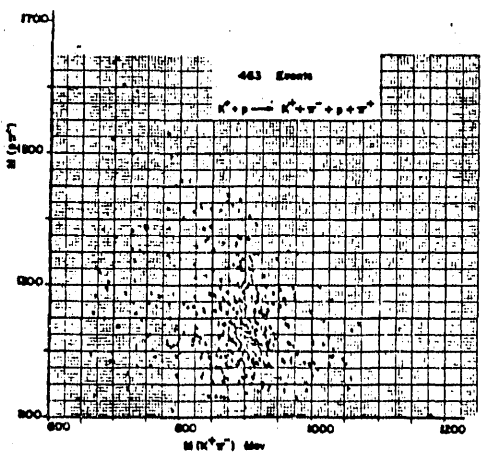
ATHENS TOPICAL CONFERENCE

ON RECENTLY DISCOVERED

1963

RESONANT

PARTICLES



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B. A. MUNIR

L. J. GALLAHER

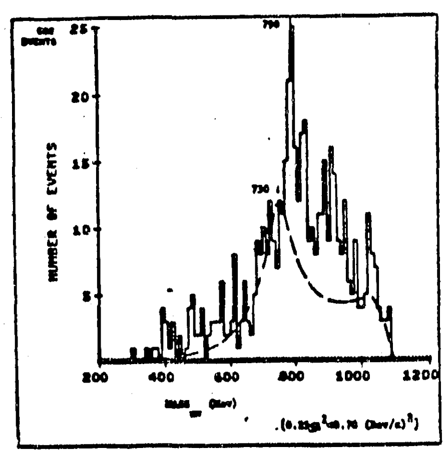
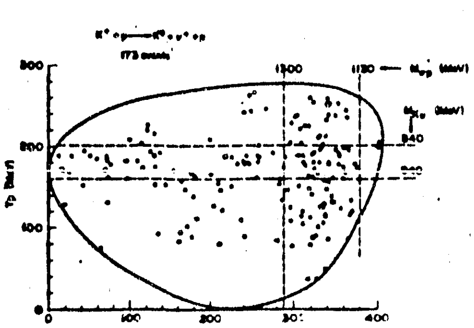
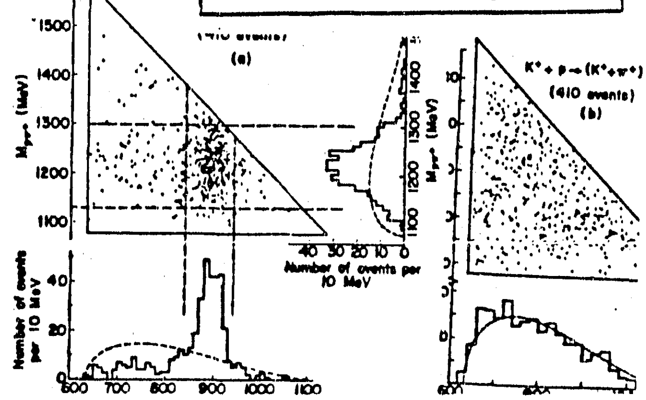


Figure 33





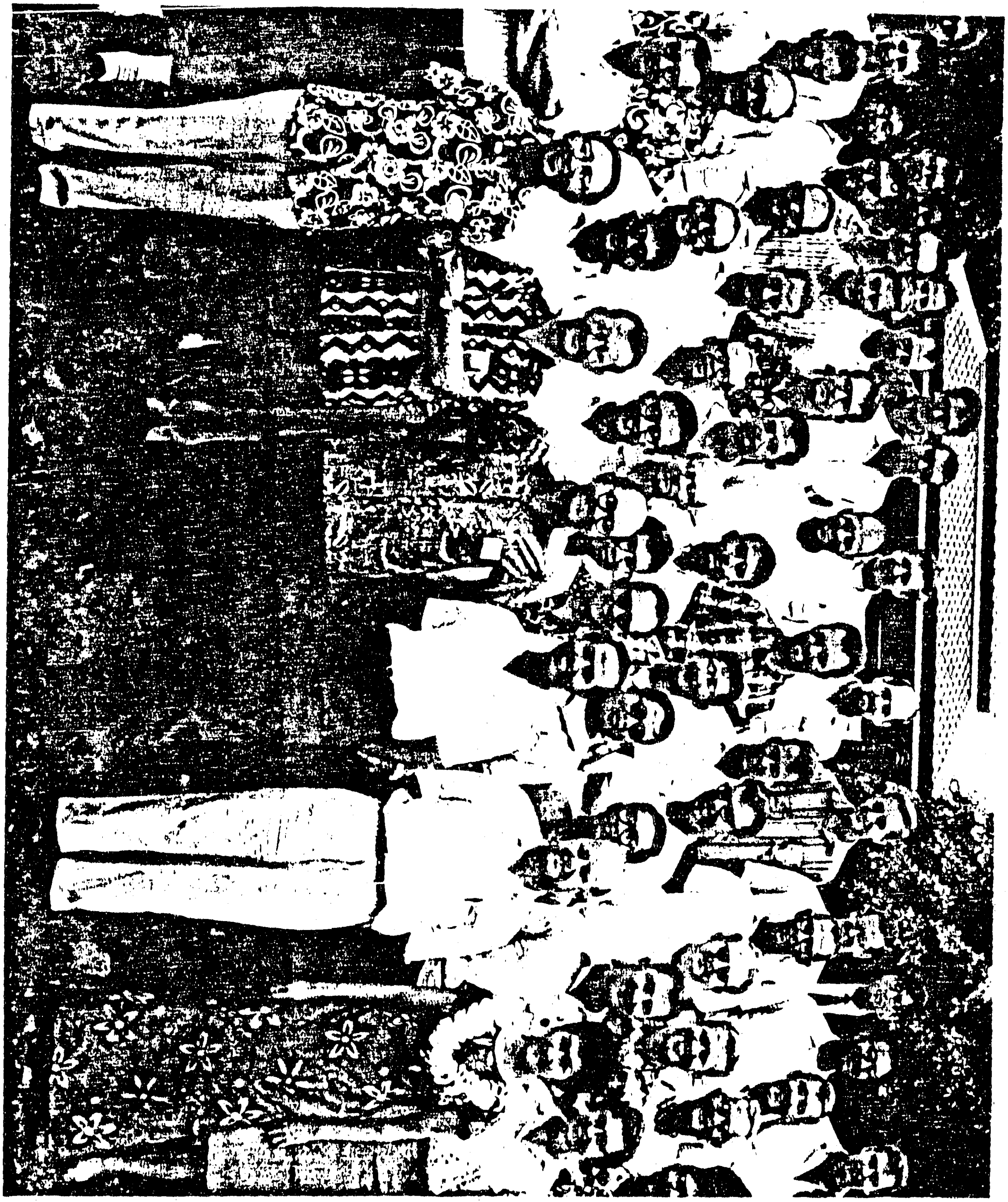


Figure 34

1977

ZEMACH — B. LEE, C. QUIGG, J. ROSNER
DALITZ

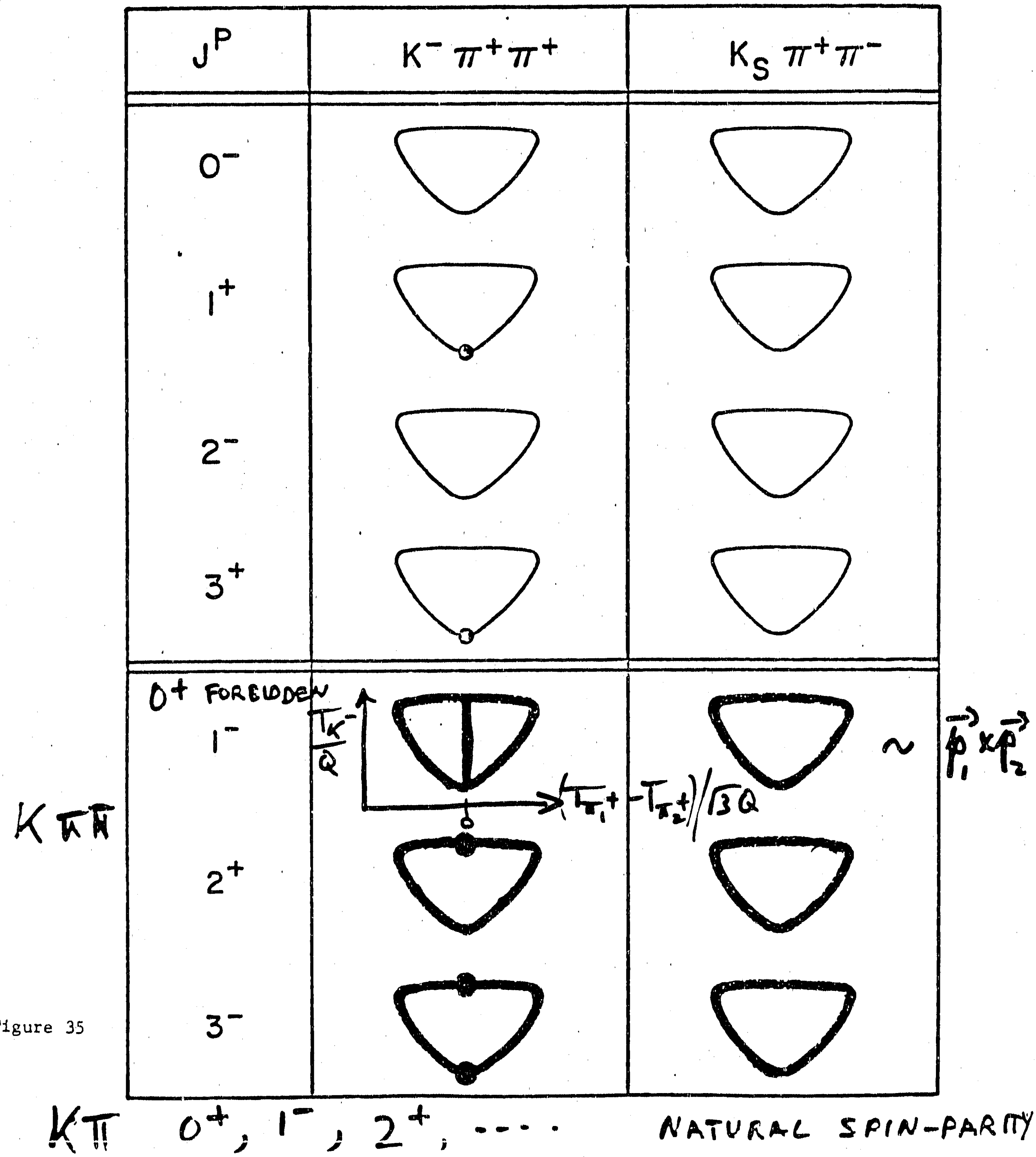


Figure 35

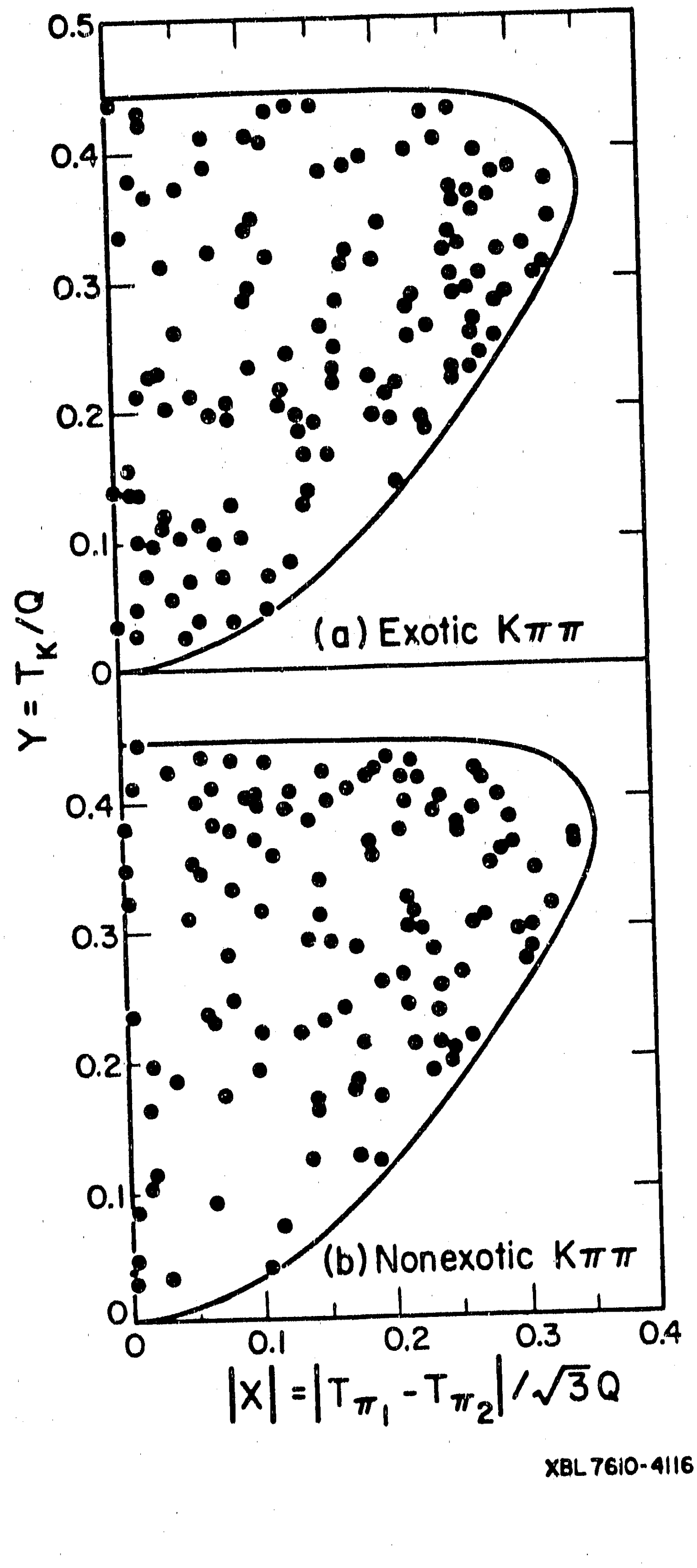
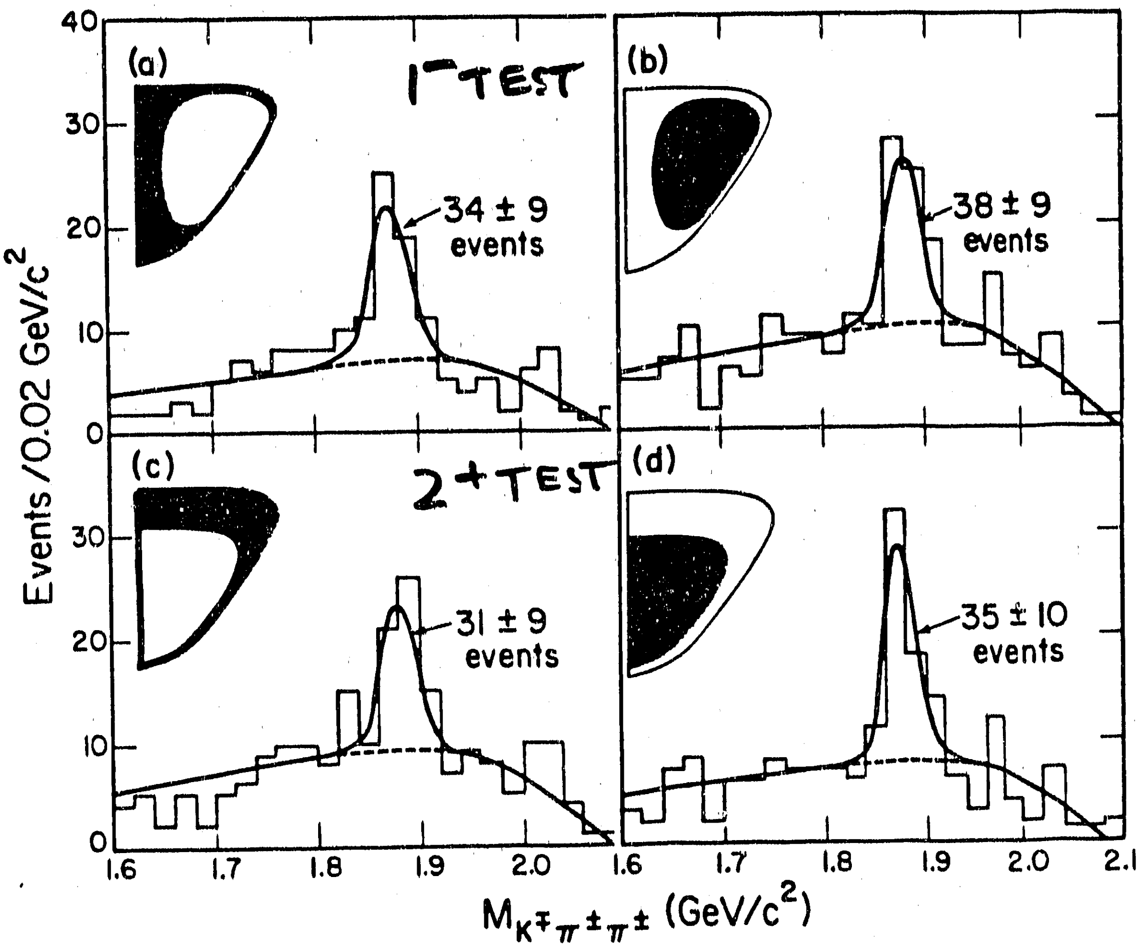

0.5
0.4
0.3
0.2
0.1
0
Y = T_K/Q
(a) Exotic $K\pi\pi$
(b) Nonexotic $K\pi\pi$
0
0.1
0.2
0.3
0.4
$|X| = |T_{\pi_1} - T_{\pi_2}|/\sqrt{3}Q$
XBL 7610-4116

Figure 36

1 : 8.2



1 : 6.5

XBL 7610 4114

MATRIX ELEMENTS:

$$I(1^-) \propto |T_{\pi_1} - T_{\pi_2}|^2 \, |\vec{p}_{\pi_1} \times \vec{p}_{\pi_2}|^2$$

$$I(2^+) \propto |\vec{p}_{\pi_1} - \vec{p}_{\pi_2}|^2 \, |\vec{p}_{\pi_1} \times \vec{p}_{\pi_2}|^2$$

Figure 37

Initial Measurements of Z-Boson Resonance Parameters in e^+e^- Annihilation

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Figure 38

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Figure 39

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Study of Hadronic Decays of the Z^0 Boson

DELPHI collaboration

Abstract

Hadronic decays of Z^0 bosons are studied in the Delphi detector. Global event variables and single particle inclusive distributions are compared with QCD-based predictions. The mean charged multiplicity is found to be 20.6±1.0 (stat+syst). The mean values of the sphericity, aplanarity, thrust, minor value, p_T^{in} and p_T^{out} are compared with values found at lower energy e^+e^- colliders.

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Figure 40

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Figure 41

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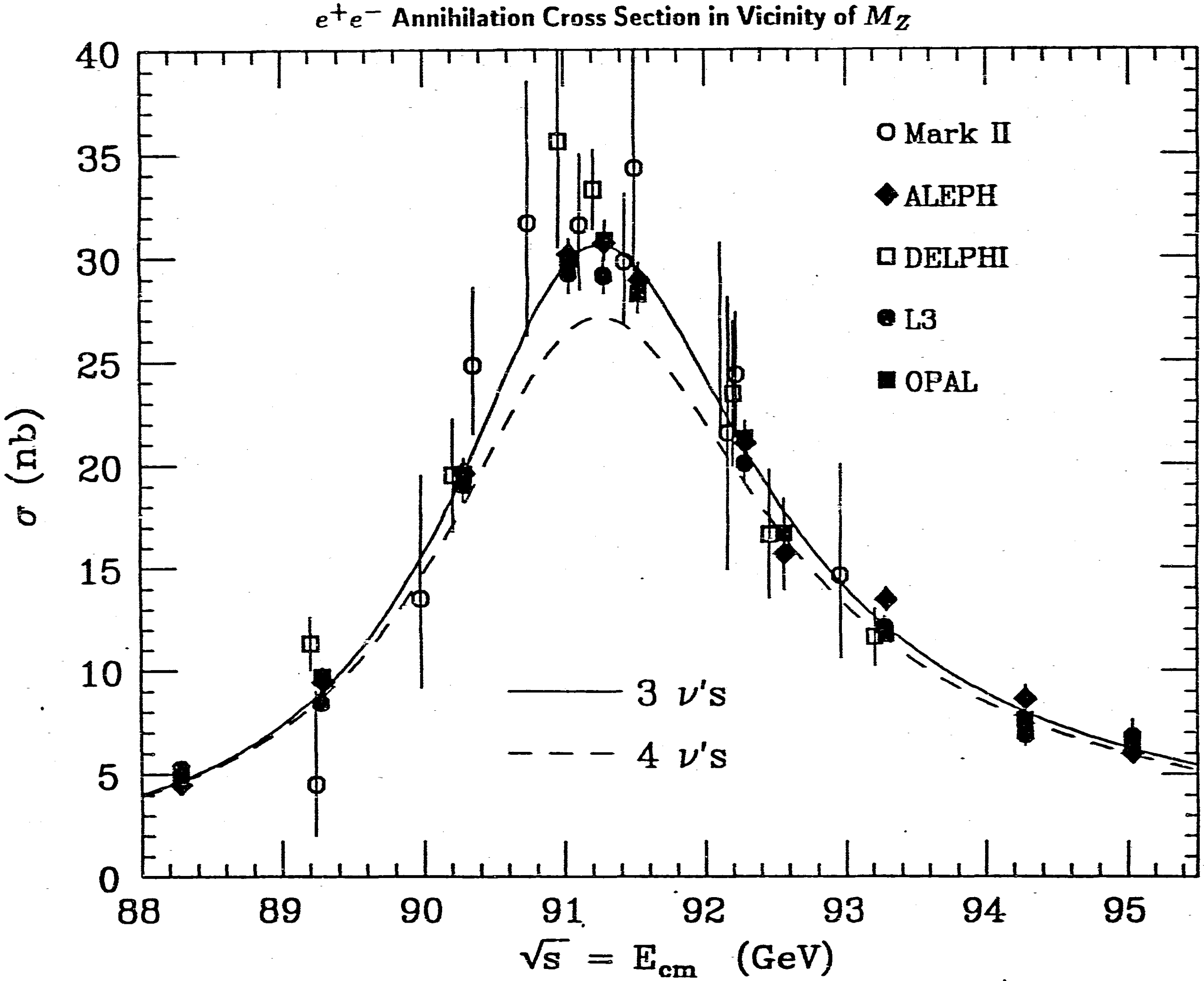
Figure 42



Data from the Mark II, ALEPH, DELPHI, L3, and OPAL Collaborations (Refs. 1–5) for the cross section in e^+e^- annihilation into hadronic final states as a function of c.m. energy near the Z. The curves show the predictions of the Standard Model with three species (solid curve) and four species (dashed curve) of light neutrinos. The mass of the Z was fixed by the data to be 91.157 GeV, and there were no other free parameters. The resulting widths are respectively 2.488 GeV and 2.653 GeV, which include QCD corrections for the hadronic channels and assume no t-quark contribution. The asymmetry of the curves is produced by initial-state radiation.

1. Mark II—G.S. Abrams *et al.*, Phys. Rev. Lett. 63, 2173 (1989).
2. ALEPH—D. Decamp *et al.*, to be published in Phys. Lett. B (1990).
3. DELPHI—P. Aarnio *et al.*, Phys. Lett. B231, 539 (1989).
4. L3—B. Adeva *et al.*, submitted to Phys. Lett. B (1990).
5. OPAL—M.Z. Akrawy *et al.*, to be published in Phys. Lett. B (1990).

Figure 43

Energy Spectrometer

Precise measurements are made of the energy of both e- and e+ bunches every crossing. The bend angle of the beam through a precision magnet is determined using synchrotron radiation.

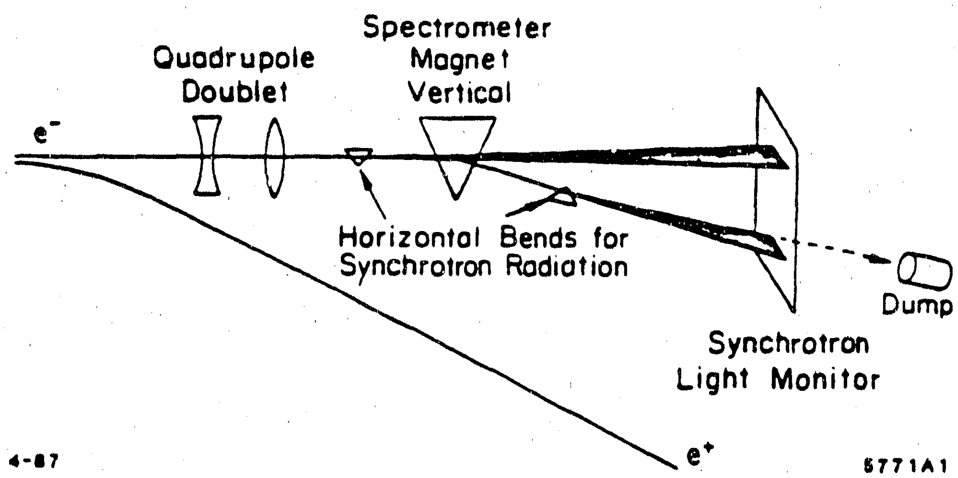


Figure 44

EXPECTED UNCERTAINTY IN M_Z AND Γ_Z FOR THE MARK II

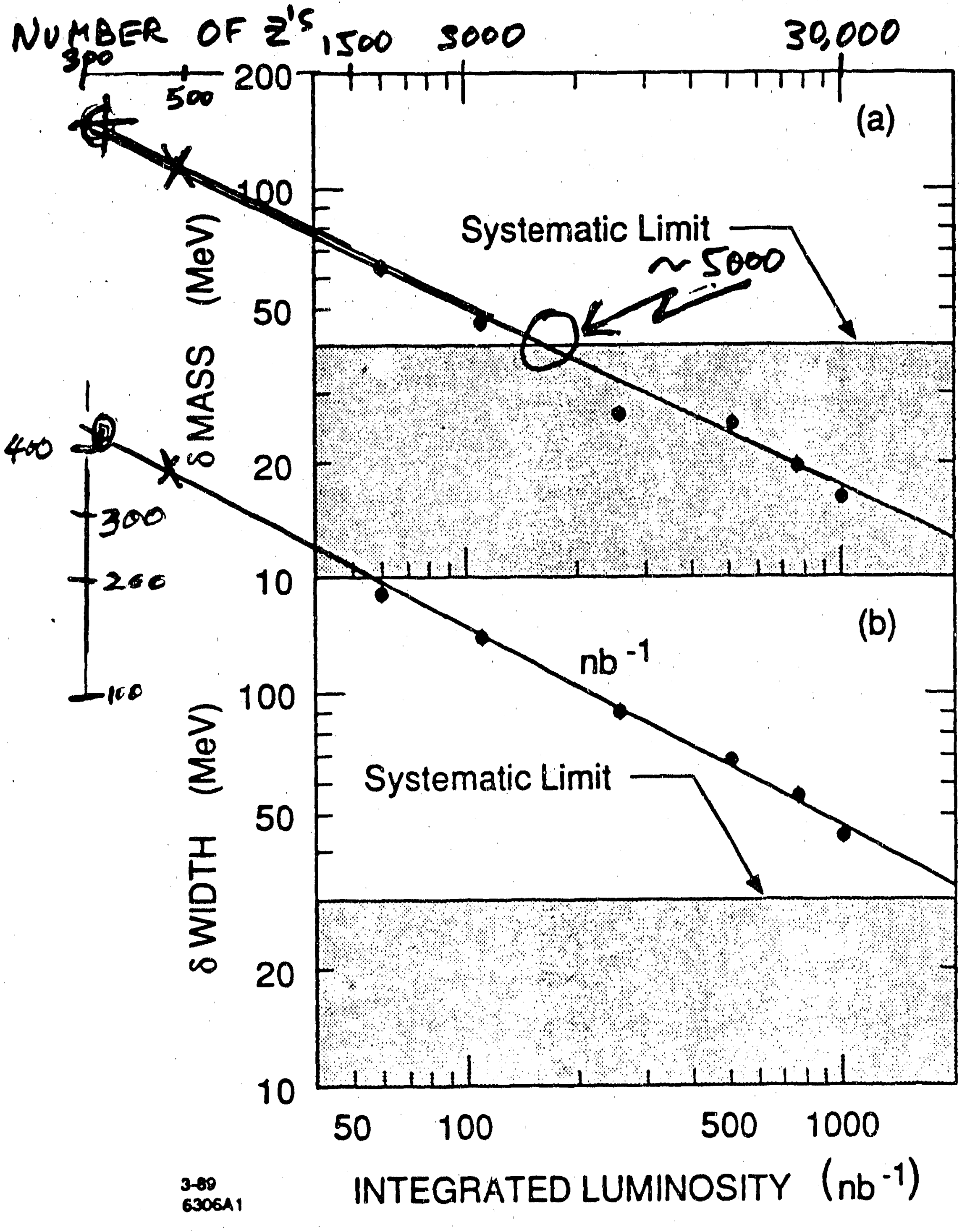


Figure 45

Measuring the Z Resonance

For each scan point (SLC energy setting), measure:

- SLC energy
- Luminosity
- Number of Z's produced

Determine the Z cross section (σ_Z) using:

Number of events = Luminosity $\times$ σ_Z

Then derive resonance parameters by fitting expected shape to data.

Figure 46

Luminosity Measurement

Count Bhabha events ($e^+e^- \longrightarrow e^+e^-$) in two different detector components. (Rate doesn't depend on creating a Z).

$$\text{Number of events} = \text{Luminosity} \times \sigma_B$$

Number of events ↑ count

σ_B ↑ calculate for each energy

Figure 47

Selecting Events

Z events are almost background-free.

It is sufficient to require:

- three charged tracks from the interaction point (average is 20 per event).

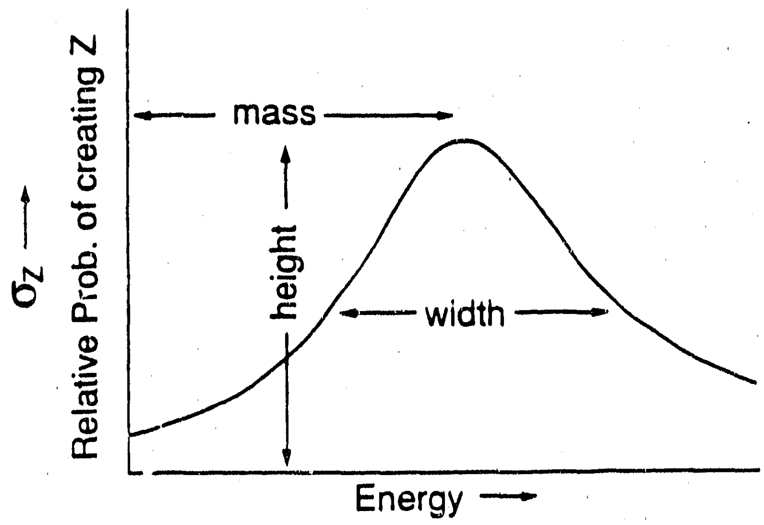
- 5% of the center-of-mass energy in both the forward and backward hemispheres.

  (Background events tend to give energy in only one hemisphere).

Figure 48

Z Resonance Shape

Three parameters of the resonance shape:



- Width increases with the number of different types of particles to which the Z decays.

- Height is interpreted in terms of the number of species of neutrinos.

Figure 49

We perform a maximun-likelihood fit using Poisson statistics to a relativistic Breit-Wigner line shape:

$$\sigma(E) = \frac{12\pi}{m^2} \frac{s\Gamma_{ee}(\Gamma - \Gamma_{inv})}{(s - m^2)^2 + s^2\Gamma^2/m^2} [1 + \delta(E)]$$

$S = E^2$ Γ_{INV} = width leading to "invisible" decays.

Radiative effects, $[1 + \delta(E)]$, are calculated using an analytic form by Cahn.

A Breit-Wigner shape has 3 parameters: position, width, and height. We fit for these as m, Γ, and Γ_{inv} or N_ν.

PEAK cross section:

$$\sigma(m_Z) = \frac{12\pi}{s} \frac{\Gamma_{ee}(\Gamma - \Gamma_{INV})}{\Gamma^2} \cdot (1 + \delta(m_Z))$$

is most sensitive to N_ν

Figure 50

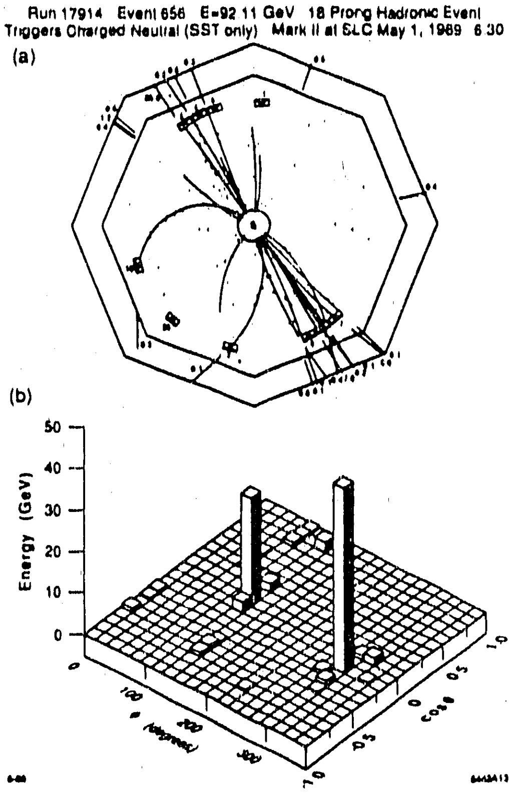

Run 17914 Event 656 E=92.11 GeV 18 Prong Hadronic Event
Triggers Charged Neutral (SST only) Mark II at SLC May 1, 1989 6:30
(a)
(b)
Energy (GeV)
50
40
30
20
10
0
0
100
200
300
φ (degrees)
1.0
0.5
0
-0.5
-1.0
cos θ

Figure 51

Results SLC

mass = 91.14 +/- 0.12 GeV

width = 2.4 +/- 0.4 GeV (Expect 2.45 GeV if no new particles)

N = 2.8 +/- 0.6 ⟹ N < 3.9, 95% CL

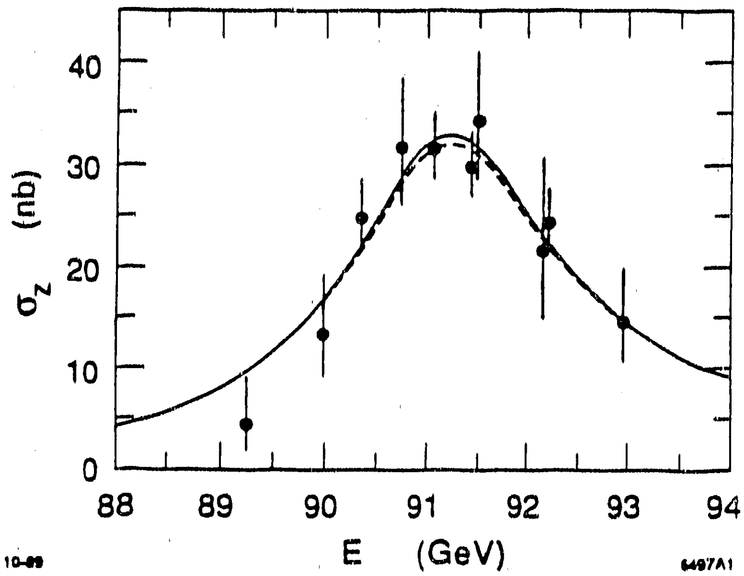


Figure 52

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/89-169
December 19th, 1989

A Precise Determination of the Number of Families with Light Neutrinos and of the Z Boson Partial Widths.

19 December 1989

The ALEPH Collaboration

Abstract

More extensive and precise results are reported on the parameters of Z decay. On the basis of 20 000 Z decays collected with the ALEPH detector at LEP we find:

$M_Z = 91.182 \pm 0.026\ (\mathrm{exp}) \pm 0.030\ (\mathrm{beam})\ \mathrm{GeV}$
$\Gamma_Z = 2.541 \pm 0.056\ \mathrm{GeV}$
and $\sigma^0_{had} = 41.4 \pm 0.8\ \mathrm{nb}.$

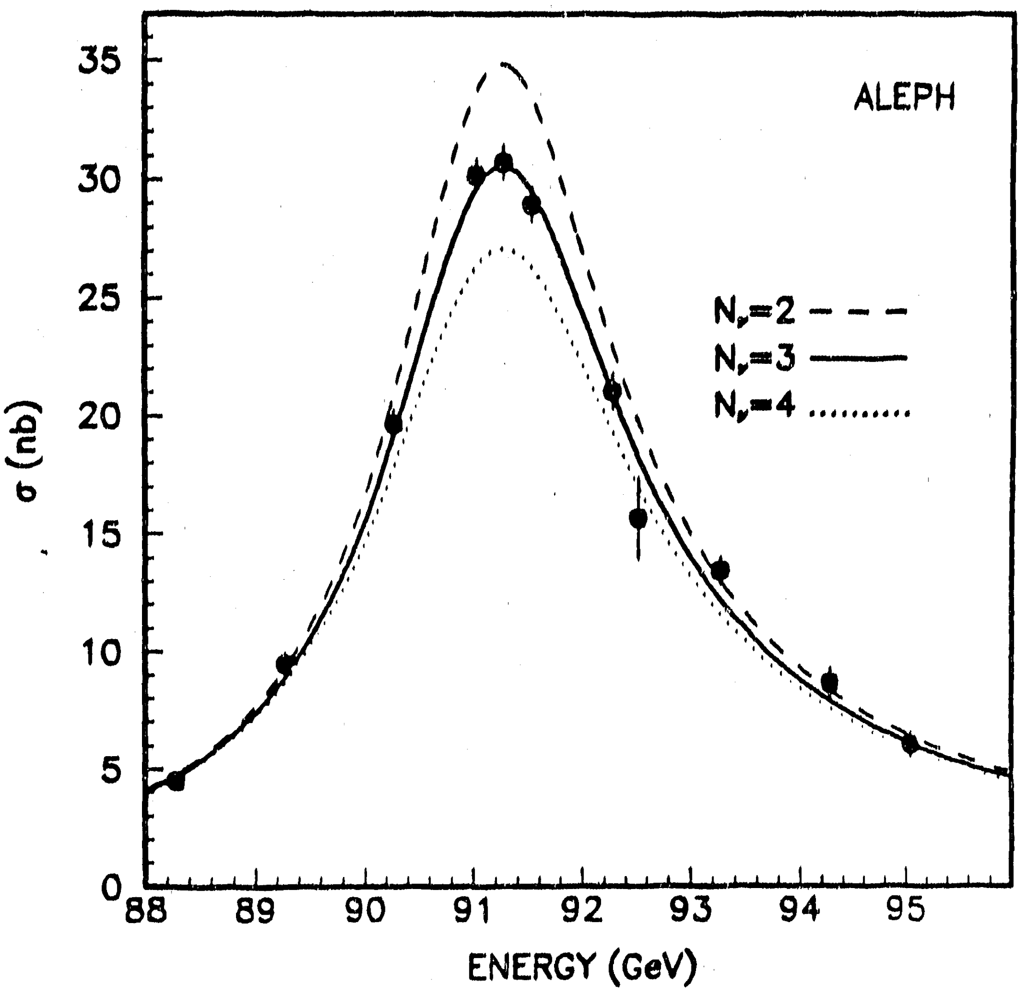
The partial widths for the hadronic and leptonic channels are:

$\Gamma_{had} = 1804 \pm 44\ \mathrm{MeV}$
$\Gamma_{e^+e^-} = 82.1 \pm 3.4\ \mathrm{MeV}$
$\Gamma_{\mu^+\mu^-} = 87.9 \pm 6.0\ \mathrm{MeV}$
and $\Gamma_{\tau^+\tau^-} = 86.1 \pm 5.6\ \mathrm{MeV},$

in good agreement with the standard model. On the basis of the average leptonic width $\Gamma_{l^+l^-} = 83.9 \pm 2.2\ \mathrm{MeV}$, the effective weak mixing angle is found to be $\sin^2\theta_W(M_Z) = 0.231 \pm 0.008$.

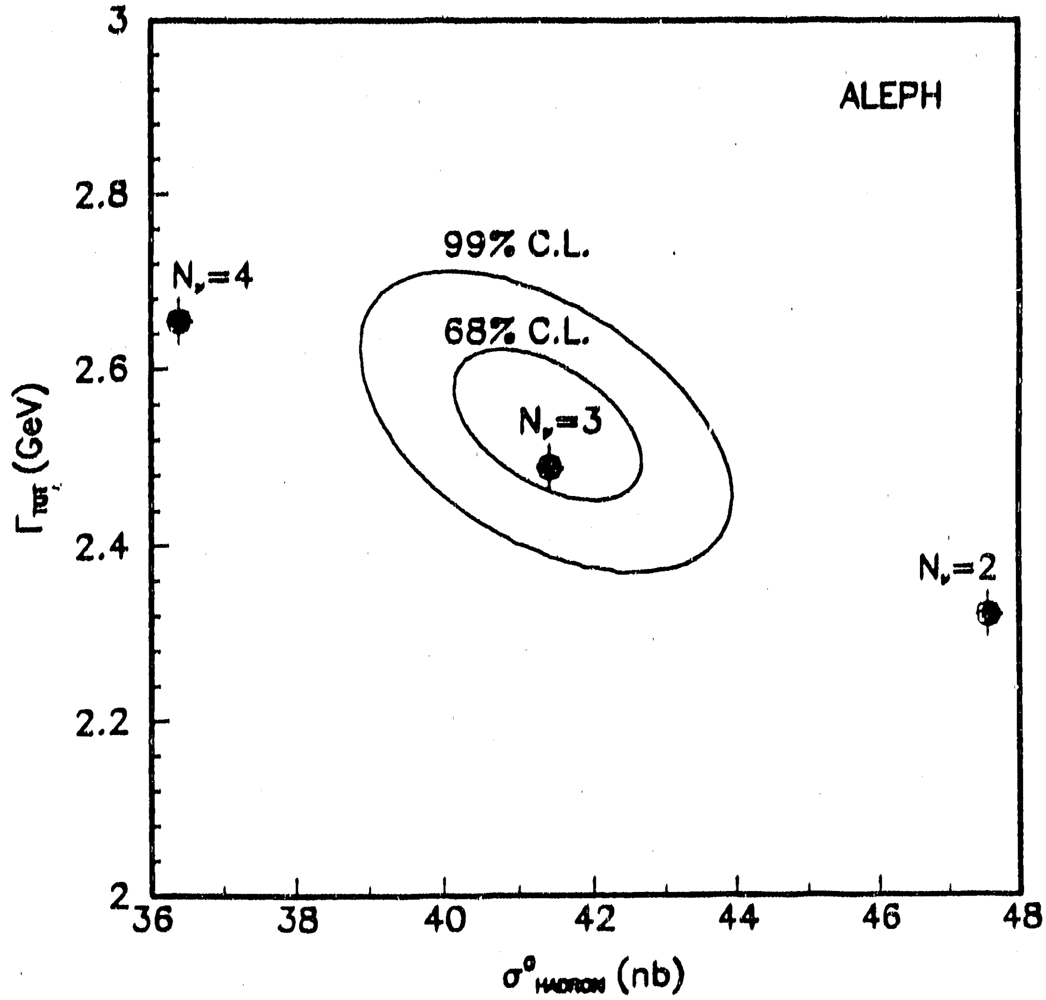
Using the partial widths calculated in the standard model, the number of light neutrino families is $N_\nu = 3.01 \pm 0.15(\mathrm{exp}) \pm 0.05\ (\mathrm{theo})$.

Figure 53



Cross-section for e^+e^- –> hadrons as function of LEP energy. The Standard Model predictions for $N_\nu = 2$, 3 and 4 are shown.

Figure 54



Contours of constant χ^2 in the σ^0_{had} - Γ_Z plane, and the Standard Model predictions for N_ν = 2, 3 and 4.

Figure 55

Measurement of Z^0 Decays to Hadrons, and a Precise Determination of the Number of Neutrino Species

The L3 Collaboration

ABSTRACT

We have made a precise measurement of the cross section for $e^+e^- \rightarrow Z^0 \rightarrow$ hadrons with the L3 detector at LEP, covering the $\sqrt{s}$ range from 88.28 to 95.04 GeV. From a fit to the Z^0 peak, we determined the Z^0 mass, total width, and the hadronic cross section to be $M_{Z^0} = 91.160 \pm 0.024(experiment) \pm 0.030(LEP)$ GeV, $\Gamma_{Z^0} = 2.539 \pm 0.054$ GeV, and $\sigma_h(M_{Z^0}) = 29.5 \pm 0.7$ nb. We also used the fit to the Z^0 peak cross section and the width to determine $\Gamma_{invisible} = 0.548 \pm 0.029$ GeV, which corresponds to 3.29 ± 0.17 species of light neutrinos. The possibility of four or more neutrino flavors is thus ruled out at the 4σ confidence level.

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Figure 56

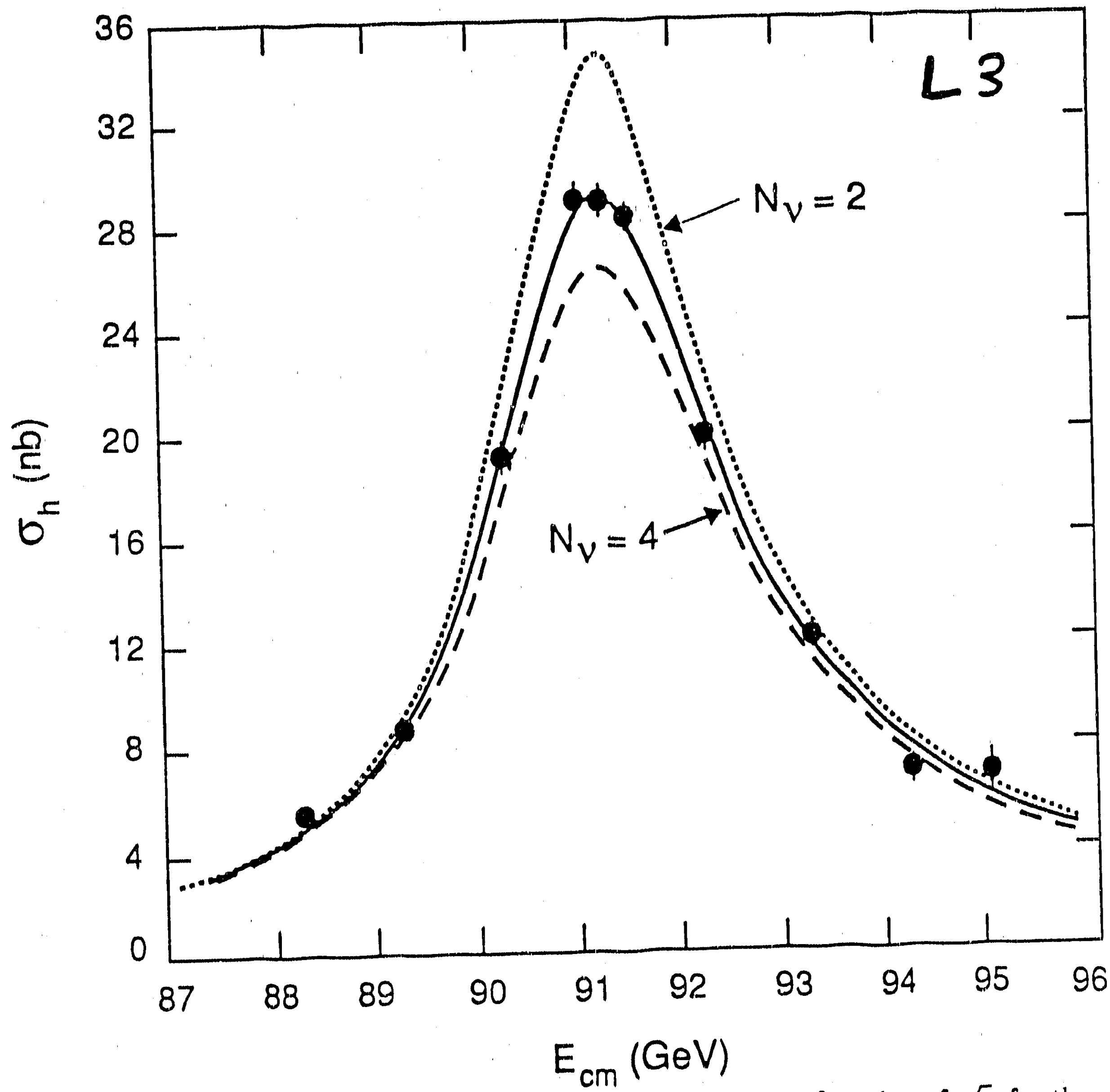

Figure 57 The measured cross section for $e^+e^- \rightarrow hadrons$ as a function of $\sqrt{s}$, for the Run 2 data as described in the text. Data are shown with statistical errors only. The solid curve is a fit to the formula of Borelli *et al.* [17] in which M_{Z^0} and $\Gamma_{invisible}$ were left free. The partial widths Γ_{ee}, $\Gamma_{\mu\mu}$, $\Gamma_{\tau\tau}$, and $\Gamma_{hadrons}$ were taken from the standard model. The dotted and dashed curves are the standard model curves corresponding to $N_\nu = 2$ and 4 respectively. The curve for $N_\nu = 3$ is nearly indistinguishable from the fitted curve in the figure.

LATEST MEASUREMENTS OF NUMBER OF LIGHT ν SPECIES

$N = 2.8 \pm 0.6$ (MARK II)

$N = 3.01 \pm 0.16$ (ALEPH)

$N = 2.97 \pm 0.26$ (DELPHI)

$N = 3.32 \pm 0.17$ (L3)

$N = 3.09 \pm 0.19$ (OPAL)

Figure 58

END

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