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Author
Goldhaber, G.

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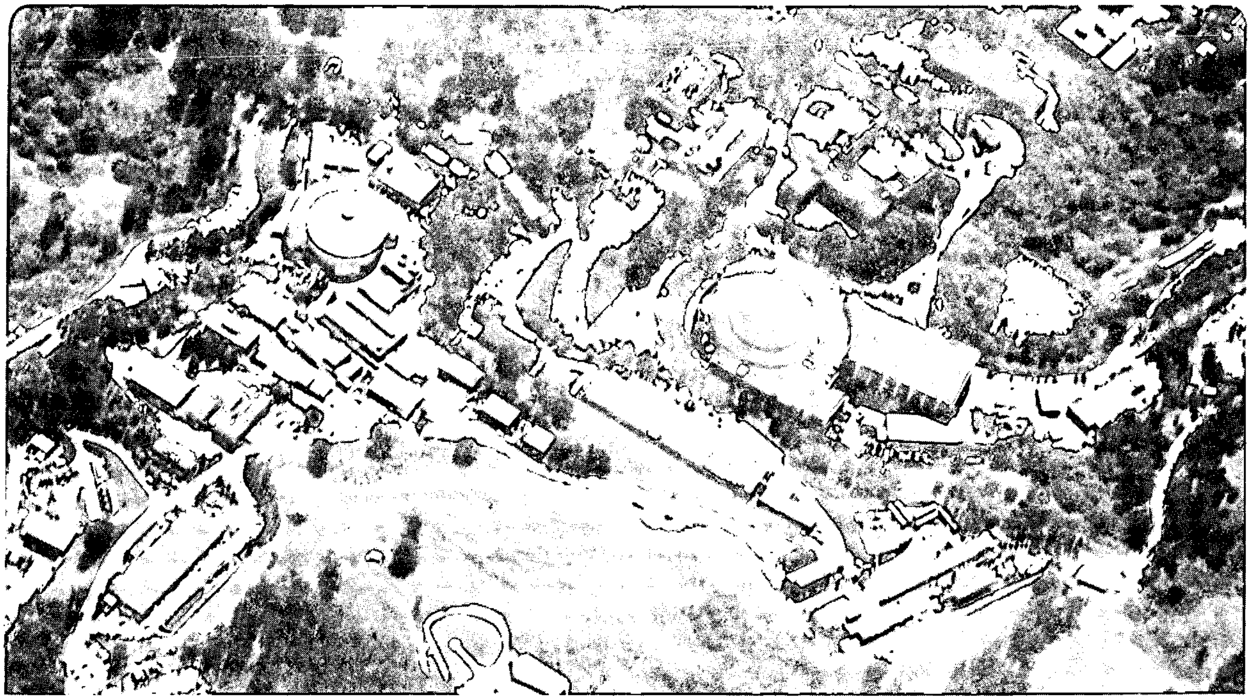

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Gerson Goldhaber

Physics Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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FROM THE ψ TO CHARMED MESONS[*][†]

Gerson Goldhaber

Lawrence Berkeley Laboratory
& Center for Particle Astrophysics
University of California at Berkeley

Abstract

This talk deals with my recollections about the discoveries of the J/ψ the $\psi\prime$ as well as psion spectroscopy and charmed mesons. I give a chronology for the ψ and $\psi\prime$ discoveries. I also discuss the events which led to the charmed meson discovery as well as detailed discussions on the proof that the resonance we observed in the $K^-\pi^+$ system, at 1865 MeV, was indeed the predicted charmed meson.

As I look back at the first three years or so at SPEAR, I consider this one of the most revolutionary or perhaps *the* most revolutionary, experiment in the 60 year history of particle physics. It certainly was the most exciting time — in a laboratory that is — that I have ever experienced.

Most of the discoveries I will mention were made with the SLAC-LBL Solenoidal Magnet Detector or "MARK I" — as it became known later on — which we(1) operated at SPEAR from 1973 to 1976. The groups in this work were those of Martin Perl and Burton Richter of SLAC and William Chinowsky, Gerson Goldhaber and George Trilling of LBL.

The detector was the first of the Solenoidal detectors which have now became ubiquitous. It is interesting to note that this detector — which far from perfect — was adequate for what we needed for our discoveries. It was capable of a reasonable π/K separation by momentum and time of flight, as well as e/μ separation by ionization in shower counters and range. See Fig. 1.

In my talk I will cover the period 1973–1976 which saw the discoveries of the ψ and $\psi\prime$ resonances the χ states and most of the Psion spectroscopy, the D°, D^+ charmed

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[*] Presented at the International Conference on: "The History of Original Ideas and Basic Discoveries in Particle Physics", Erice, Italy, 29 July - 4 August 1994.

[†] This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract Number DE-AC03-76SF00098 and also by the National Science Foundation, under agreement ADT-88909616.

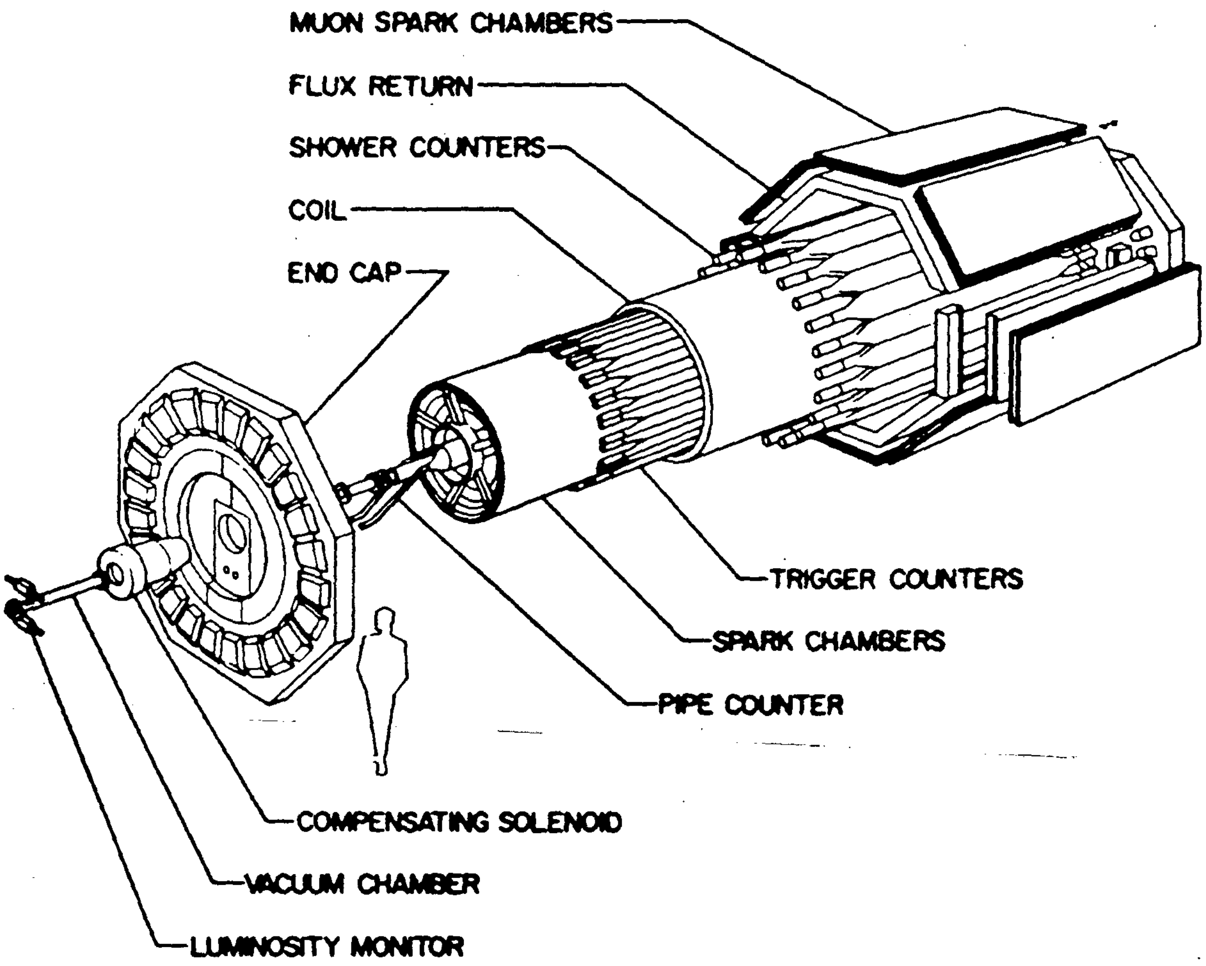

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Fig. 1. The SLAC-LBL Solenoidal Magnetic detector, later known as MARK I.

meson doublet as well as the D^{o*} and D^{+*} doublet. I will also refer briefly to some more recent results. In 1976 the MARK I was modified to include a "Lead Glass Wall" (LGW) for improved photon and electron detection as discussed by Martin in his earlier talk on the study of the anomalous $e\mu$ events which eventually were identified as the signature of the τ lepton.

During the course of the LGW experiment we were engaged in building a new and improved SLAC-LBL Magnetic Detector the "MARK II" which returned to SPEAR in 1978 and was moved to PEP in 1980, and then to the SLC in 1987, each time in an improved and upgraded version. The MARK II detector was decommissioned in 1990.

History of the Discovery of the ψ.

Some of my personal reminiscences regarding the week-end of the ψ discovery have already been published(2) and I will only allude to them briefly here.

Our first task was to learn how our detector behaved in the SPEAR environment. For this purpose we developed two independent analysis systems one at LBL and one at SLAC. The overall data acquisition was due to Marty Breidenbach. The SLAC system for data analysis was under Adam Boyarski while Gerry Abrams was largely responsible for the system we had at LBL. Having recently emerged from Bubble chamber experiments our tendency was to produce visual displays of our data. We thus used track reconstruction based on Bubble Chamber programs. This work was largely done by Willie Chinowsky and his students Bob Hollebeek and John Zipse of LBL as well as Fatim Bulos, Harvey Lynch and Roy Schwitters of SLAC. At a later stage the track fitting routines were revised and improved by George Trilling with the help of Dave Johnson at LBL.

I worked on the Berkeley version of the displays which we recorded on 'microfiche' and then scanned manually. We soon learned how to distinguish cosmic ray events from Bhabhas, mu pairs, beam gas collisions and annihilation into hadrons. At each step, Gerry Abrams, John Kadyk and I as we developed scanning and filtering programs, we compared our results with those of Charles Morehouse who developed similar independent programs at SLAC. With time we were able to incorporate our results into the triggering procedures for the detector. I mention these details because they were important later in following the on-line data acquisition with a 'one event display' on a CRT screen.

Following an engineering run in the Spring of 1973, we started our experiment at SPEAR in late 1973 with an energy scan. At that time we had not expected narrow structures(3) we thus decided to measure the cross section in 100 MeV steps in beam energy, i.e., 200 MeV steps in E_{cm}. Fig. 2 shows our first cross section

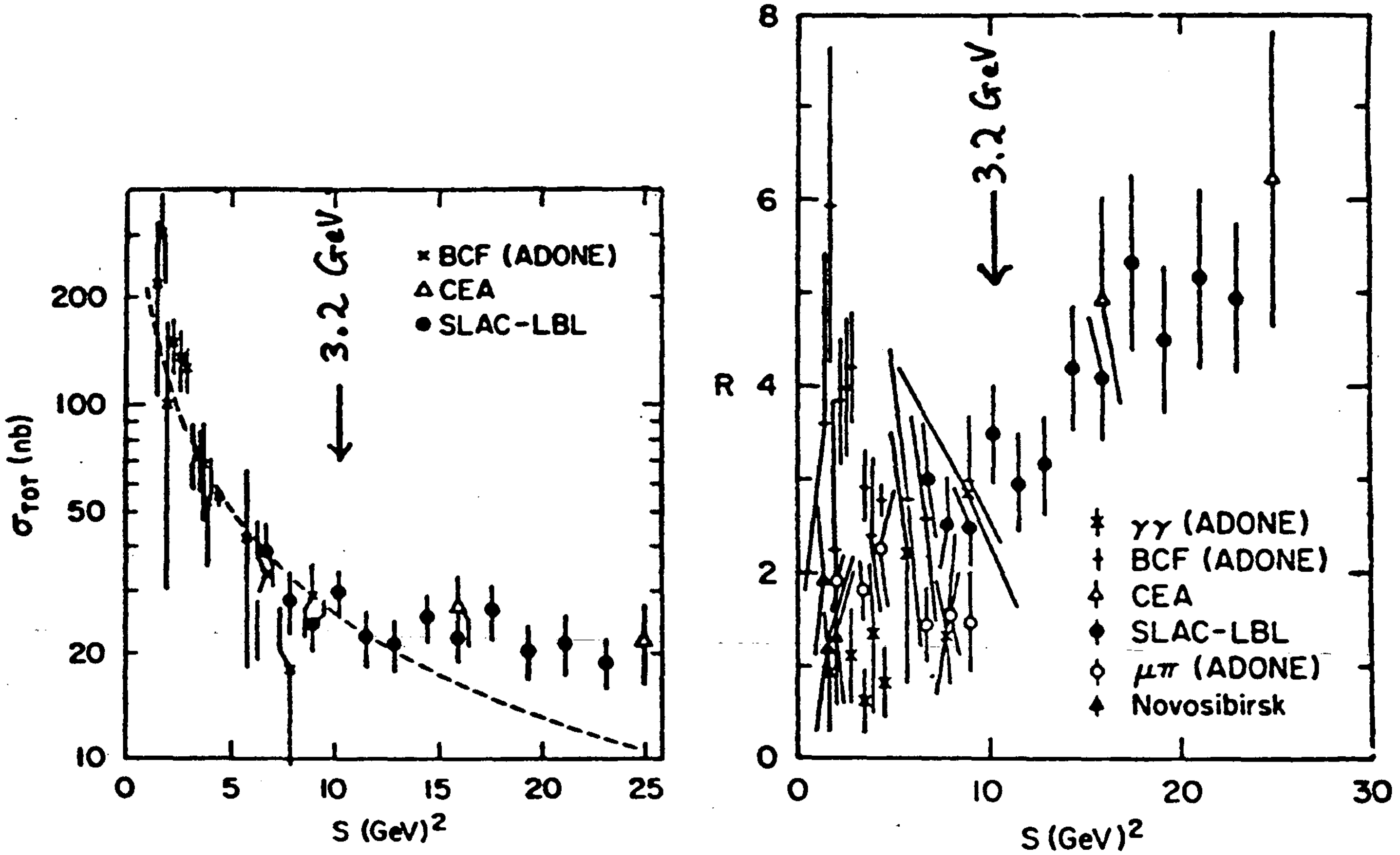

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Fig. 2. The first cross section and $R = \sigma_{\rm Had}/\sigma_{\mu\mu}$ measurements with the SLAC-LBL MARK I detector taken in 200 MeV steps. Earlier data is also shown.

and R results as presented by Burton Richter at the London Conference in June 1974. The data was in good agreement with the earlier CEA and Frascati results$^{(4)}$ and, contrary to QED expectations, showed a roughly constant cross section from 2.5 to 4.8 GeV. And yet—the data was not completely flat, and we were sufficiently intrigued with the high points at 3.2 GeV and 4.2 GeV that we decided to take additional intermediate points in June 1974 at 3.1 and 3.3 GeV as well as around 4.2 GeV. It was an irregularity in the new 3.1 GeV data point—as re-analyzed by Roy Schwitters, with the help of my student Scott Whitaker, in October 1974—which convinced us, in early November 1974 that we had to remeasure this region before we could publish our cross section data. One speculation some of us had was that the SPEAR energy could have drifted upward into a region of higher cross section, for the two anomalous runs at the nominal energy of 3.1 GeV. See the chronology of the ψ discovery below.

In the control room at SPEAR on Saturday, November 9, we realized already that we were on to something momentous. When I came to SLAC in the afternoon we were scanning in small energy steps (at that point we were thinking of 10 MeV as a small step) across the 3.1 GeV region.

At this stage in our experiment the on line event identification methods were still rudimentary. A rapid idea of what types of events were occurring could be obtained by observing events as they occurred on the cathod ray tube (CRT) monitor, the so called "one event display".

As I arrived Rudy Larsen was watching the CRT monitor and recording and classifying the events as they came in for a background run at 2×1.5 GeV $= 3.0$ GeV. The important categories were "E^+E^-" or "BHABHAS", hadronic events called "$> 2P$" or "≥ 3" for 3 or more prongs as well as "2 Prong" which were non-collinear events not identifiable from the CRT monitor alone and "Brodsky" that is 2 photon events named for Stanley Brodsky of SLAC. I took over the CRT watch from Rudy and the next energy was set at 2×1.56 GeV $= 3.12$ GeV. Now the most amazing thing happened before my eyes, see Fig. 3. The ratio hadronic events to Bhabha events went from $10/61 = 0.16$, in the background region, to $55/170 = 0.3$. An increase in this ratio, which is related to the hadronic cross section, by a factor of 2. Little did I know that on the next day this ratio would go up by nearly two orders of magnitude!

Fig. 4 shows the ψ signal which we found on November 10, 1974, by scanning in very small steps. We thus realized that the increase in cross section we first noted at 3.2 GeV and the anomalies at 3.1 GeV were the result of the presence of the radiative tail, and the very sharp rise of this enormous resonance.

Fig. 5 shows a picture taken by Vera Luth who caught us discussing what the possible quantum numbers of this new resonance could be. The next day we learned from Samuel Ting about the MIT BNL results on the J—clearly the same effect.$^{(5)}$

Chronology of ψ Discovery

Jan.,1974

- **John Kadyk** (LBL) noted high σ by $\sim$ 30% at $E_{\text{TOT}} = 3.2$ GeV.
- Confirmed by LBL and SLAC Collaborators.

June, 1974

- Presentation of "flat" σ by **Burton Richter** at the London Conference.
- However: anomalous point at 3.2GeV.

June, 1974

- **Marty Breidenbach** (SLAC) carried out measurements at 3.1, 3.2 and 3.3 GeV to check high point at 3.2 GeV.

Oct., 1974

- **Roy Schwitters** (SLAC) looked at all σ data to prepare for a paper. Found inconsistencies at 3.1 GeV.

6 runs	σ "normal"	$\sigma = \sigma_0$
1 run		$\sigma = 3\ \sigma_0$
1 run		$\sigma = 5\ \sigma_0$

- Finding confirmed by **Gerry Abrams** (LBL).
- Events in the 3.1 GeV data checked in detail independently by **Scott Whitaker** and **Gerson Goldhaber** (LBL).
- All looked normal only apparent increase of $K^{\pm}$ and K° observed in high σ runs (partly statistical fluctuation).

Week of
Nov. 4, 1974

- Discussions with **Burton Richter** leading to decision to study 3.1 GeV data in detail to explain inconsistencies.

Nov. 9, 10 1974

- The week-end discovery. Paper written "on-line".

Nov. 11, 1974

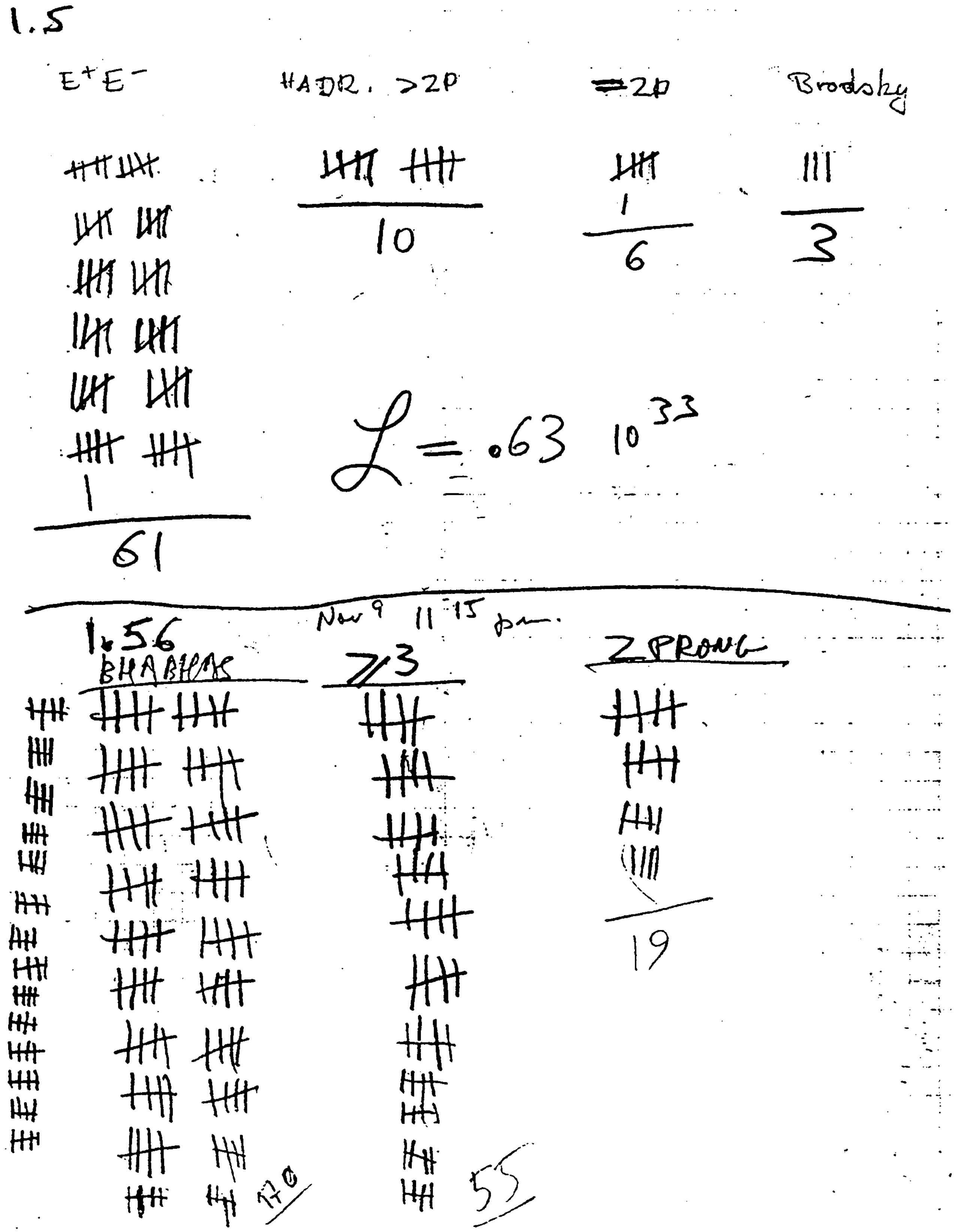
- Reports on our result to our respective laboratories: **Roy Schwitters** at SLAC and **Gerson Goldhaber** at LBL.
- Heard from **Sam Ting** about discovery of the J.

Nov. 15, 1974

- News picked up from my talk by Daily Cal the Berkeley Student newspaper breaking the Phys. Rev. Lett. news embargo.
- Frantic scrambling for Joint press release of J and ψ.
- The J/ψ confirmed at Frascati.

Nov. 21, 1974

- The discovery of the ψ'



1.5

E⁺E⁻ 61

HADR. >2P 10

=2P 1 6

Brodsky 3

$\mathcal{L} = .63\ 10^{33}$

Nov 9 11:15 pm.

1.56

BHABHAS 170

>3 55

2 PRONG 19

Fig. 3. The "score sheet" for incoming events as recorded by Rudy Larsen and later Gerson Goldhaber at the CRT on November 9, 1974.

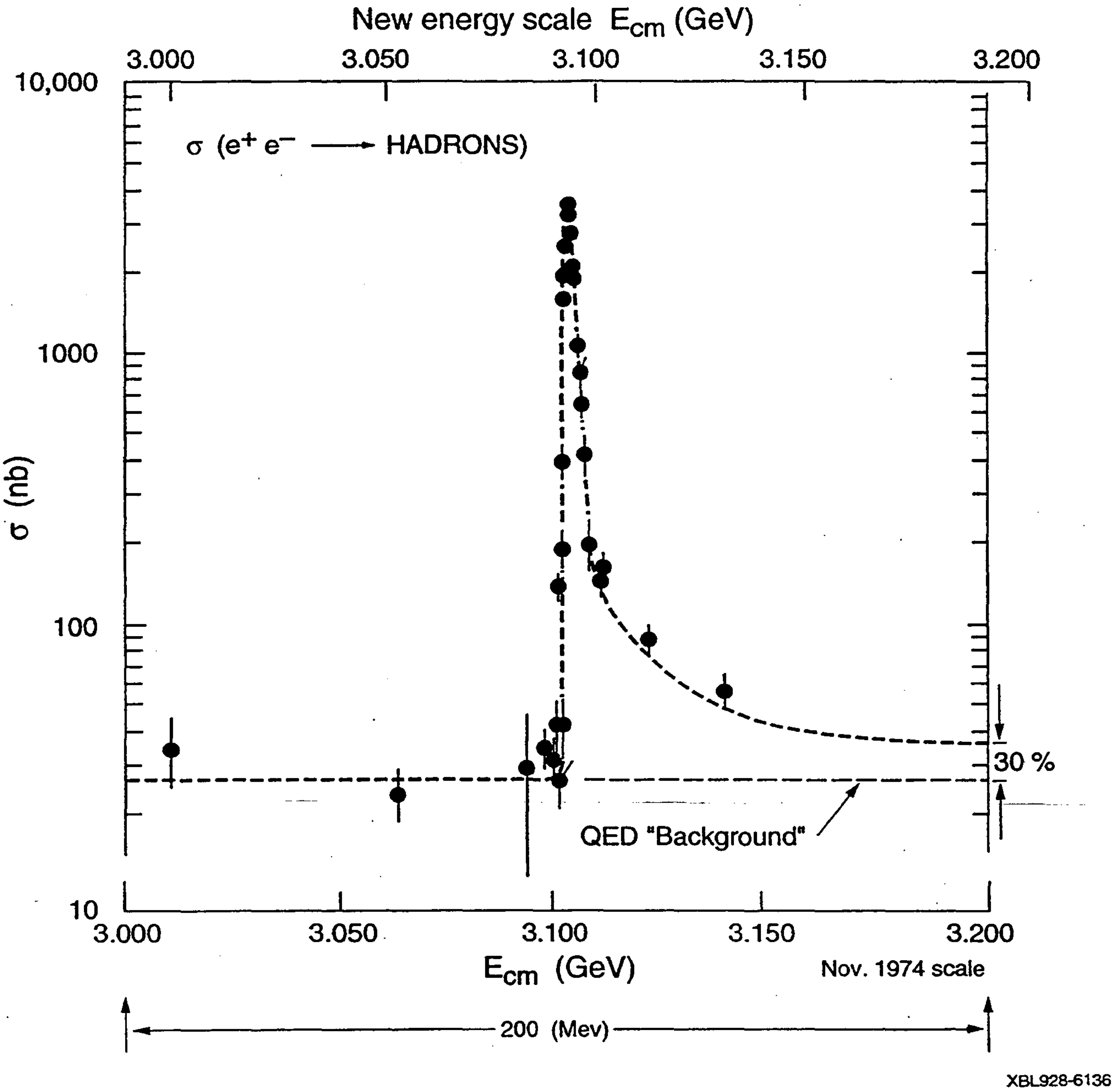


Fig. 4. The discovery of the ψ as observed on November 10, 1974. The lower energy scale was the one used at the time of discovery. The upper "New" energy scale is based on a recalibration of the orbits at SPEAR a few months later. The original 200 MeV energy step as well as the ~30% high value of σ at 3.2 GeV is also shown.

Fig 5. **November 10, 1974** **SPEAR Control Room**
Photo: Vera Luth

Willie Chinowsky, Martin Perl, Francois Vannucci, and Gerson Goldhaber.

We asked each other what could be the quantum number of this new beast. I even consulted the "blue book", Particle Data booklet.

As the messages about these results reverberated around the world we got a rapid confirmation of the J/ψ from the groups at Frascati who managed to push the energy of their e^+e^- ring, by running all their magnets hot, from the maximum design value of 3.0 GeV up to 3.1 GeV! This is illustrated in Fig. 6, and, in fact, all 3 papers were published in the same issue of Physical Review Letters.(6,7,8)

The Physical Review Letters News Embargo Edict.

Like good citizens of the physics community we were going to wait with a press release on our momentous discovery until the Phys. Rev. Letter appeared in print. However, with the entire physics community in a super excited state, this turned out to be impossible.

As it happened, it was my talk at LBL that opened the flood gates, see Fig. 2. The gist of my talk was given by someone in the audience to a reporter of "The Daily Californian", the Berkeley student newspaper. The reporter called me up, and I made a valiant attempt to have him wait until the Phys. Rev. Letter appeared in print. But all he wanted to know was, had I given a talk and did we really discover a new particle. The article he wrote is reproduced in Fig. 7. This started a chain-reaction. We next heard from the New York Times. Why did we give this news to the Daily Californian and not to them as well?

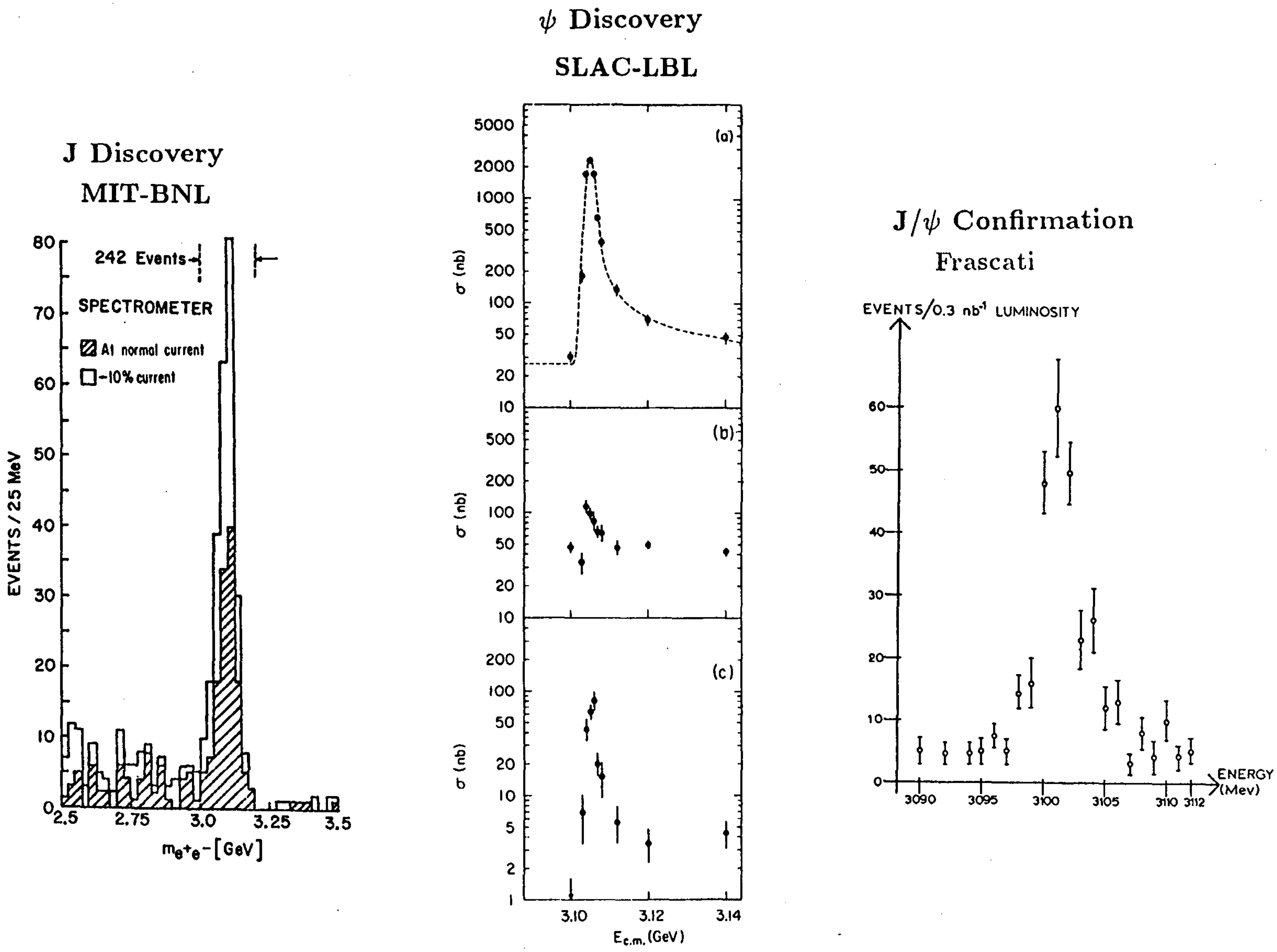
There followed on this same day, November 15, a mad scramble to coordinate a joint press release for the J and the ψ discoveries. Pief Panofsky and Burton Richter at SLAC, Martin Deutch and Sam Ting at MIT as well as many others worked on this far into the night. Fig. 8 gives the Editorial response by the Phys. Rev. Letters Editors to our breaking of the embargo.

The Energy Scale that Shaped History.

As we found out after the discovery of the ψ our energy scale at SPEAR was off by 10 MeV. Thus the ψ, which was at first measured as 3105 MeV, was actually at 3095 MeV. This is shown in Fig. 4 which gives both the old and the new energy scales. Had we had the correct energy scale when the measurements were made by Breidenbach in June 1974 at 3.100 GeV we would have seen all eight runs at about six times the normal cross section instead of just two anomalous runs with cross sections three and five times "normal" respectively! This would certainly have led to the ψ discovery right then and there.

Alternately had the energy scale been off by say another 5 MeV we would not have discovered the ψ at all!

NOVEMBER 10, 1974



ψ Discovery

SLAC-LBL

J Discovery

MIT-BNL

J/ψ Confirmation

Frascati

XBL 7510-8476

Fig. 6. The discovery of the J by the MIT-BNL group, the ψ by the SLAC-LBL group and the confirmation of the J/ψ by the Frascati groups.

Daily Californian

FIVE CENTS at some off-campus locations

BERKELEY, CALIFORNIA News 548-8300 FRIDAY, NOVEMBER 15, 1974

UC-Stanford Physics Team Produces 'Psi': New Atomic Particle

By WILLIAM LINK

Berkeley and Stanford scientists have succeded in producing what they believe to be a particle previously unknown to modern physics.

The particle, named the psi particle by its discoverers, caused great excitement in scientists working at the Stanford Linear Accelerator and at the Lawrence Berkeley Laboratory over the weekend.

The discovery was revealed by graduate students of a researcher involved in the experiment.

What is it?

A member of the team, Dr. Gerson Goldhaber, confirmed that the scientists had indeed discovered something unusual. "We don't even know what it is," Goldhaber said.

Stanford researcher James Paterson said, "It is something very new. Existing theories cannot explain the particle's characteristics." The particle's existence, Paterson said, may shed some light on previously unexplained discrepancies in other phsyical theories.

In an experiment at the Massachusetts Institute of Technology, other researchers believe they have discovered the same particle almost simultaneously. Patterson said the MIT scientists were working independently of the Berkeley-Stanford team, arriving at their finding through a different experiment.

Unusual Data

The discovery was made when researchers noticed unusual results on an energy graph. When electrons and positrons (positive electrons) collide, the energy released can be plotted on a graph. On Sunday the graph showed unusual energy peaks 100 times greater than the baseline measurements, indicating the presence of the particle.

The discovery is significant, Goldhaber said, because the particle appears to have a very high mass, and occurs in an extremely narrow energy band width.

Paterson said "it is the narrowest elementary particle we have yet observed." He also confirmed reports that the particle had an unusually long life-span compared to other subatomic particles.

Since June

The psi particle's life span is approximately 10^{-19} seconds, compared to other elementary particles which may have a life span of only 10^{-24} seconds.

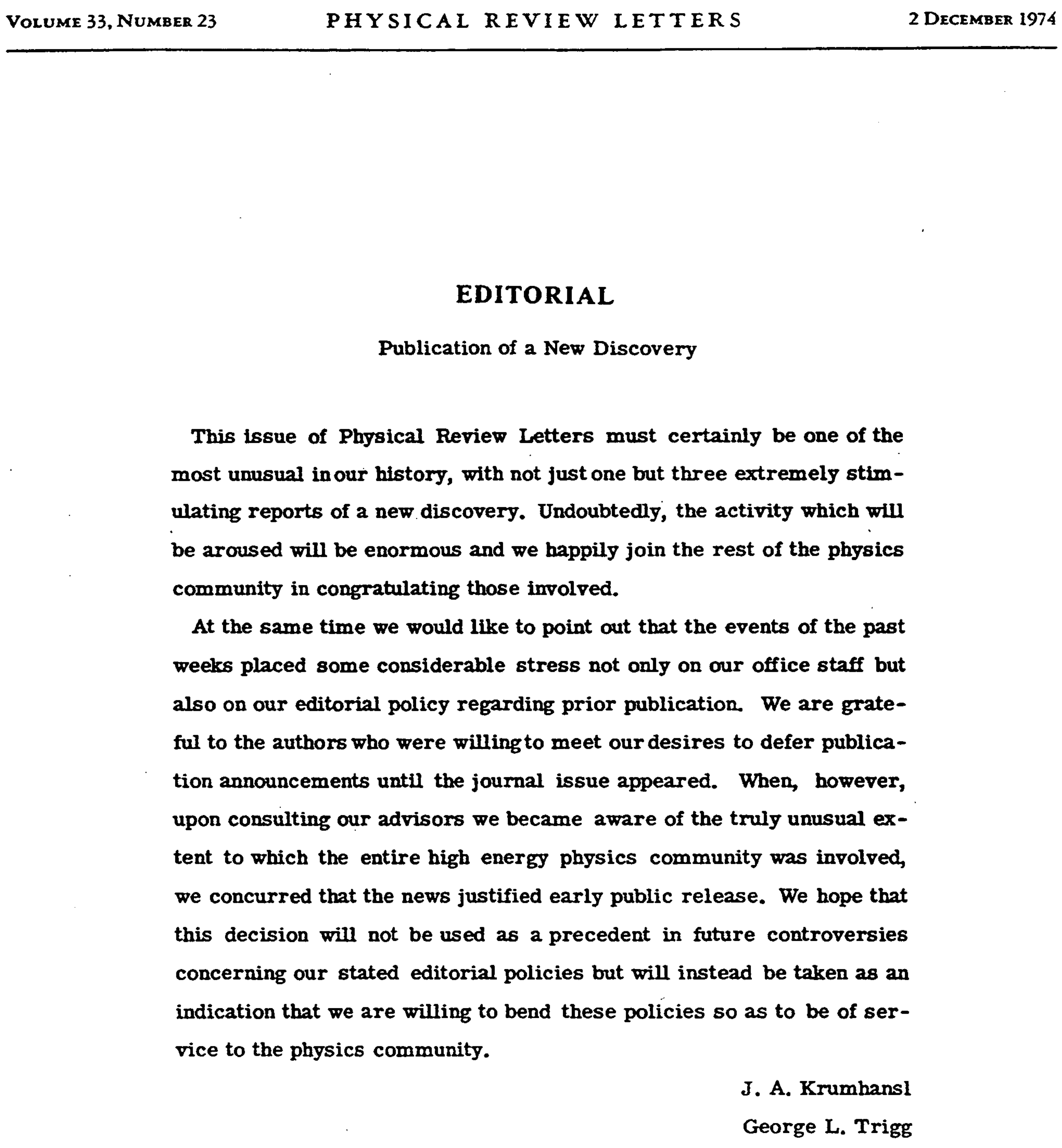
Paterson said the particle decays into several other kinds of particles, including positrons; electrons and, most frequently, hadrons.

This weekend's discovery culminated very careful research which has been going on since June. At that time, "incongruencies" in a number of experiments dealing with elementary particles were noticed.

Over the summer, Paterson said, the scientists painstakingly checked their calculations and found that they had made no errors. That was when they suspected the existence of an unknown factor (possibly the particle) which could account for the discrepancies.

The researchers from both the Berkeley-Stanford experiment and the MIT experiment are expected to make a more formal public announcement on Monday, Dec. 2.

Fig. 7. Excerpt from the "Daily Californian" of November 15, 1974.



VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

EDITORIAL

Publication of a New Discovery

This issue of Physical Review Letters must certainly be one of the most unusual in our history, with not just one but three extremely stimulating reports of a new discovery. Undoubtedly, the activity which will be aroused will be enormous and we happily join the rest of the physics community in congratulating those involved.

At the same time we would like to point out that the events of the past weeks placed some considerable stress not only on our office staff but also on our editorial policy regarding prior publication. We are grateful to the authors who were willing to meet our desires to defer publication announcements until the journal issue appeared. When, however, upon consulting our advisors we became aware of the truly unusual extent to which the entire high energy physics community was involved, we concurred that the news justified early public release. We hope that this decision will not be used as a precedent in future controversies concerning our stated editorial policies but will instead be taken as an indication that we are willing to bend these policies so as to be of service to the physics community.

J. A. Krumhansl
George L. Trigg

Fig. 8. Editorial in *Phys. Rev. Lett.* of December 2, 1974.

The Discovery of the $\psi\prime$.

Encouraged by our remarkable result we decided to look for more sharp peaks! Burton Richter(9) together with Ewan Paterson and Robert Melen was able to modify the SPEAR operation so as to run in a mode in which the energy was stepped up by 1 MeV every 3 minutes while Martin Breidenbach was able to modify our analysis system so that the resulting cross section points could be calculated *on-line*. Fig. 9 from our Phys. Rev. Letter illustrates a real time test of this new setup by scanning the ψ mass region.(10) This shows clearly that in this mode of operation a resonance, like the ψ, can be readily discovered. Indeed 10 days later during the early morning of November 21 we discovered a second narrow resonance: the $\psi\prime$.

The Properties of the J/ψ and $\psi\prime$, and Psion Spectroscopy.

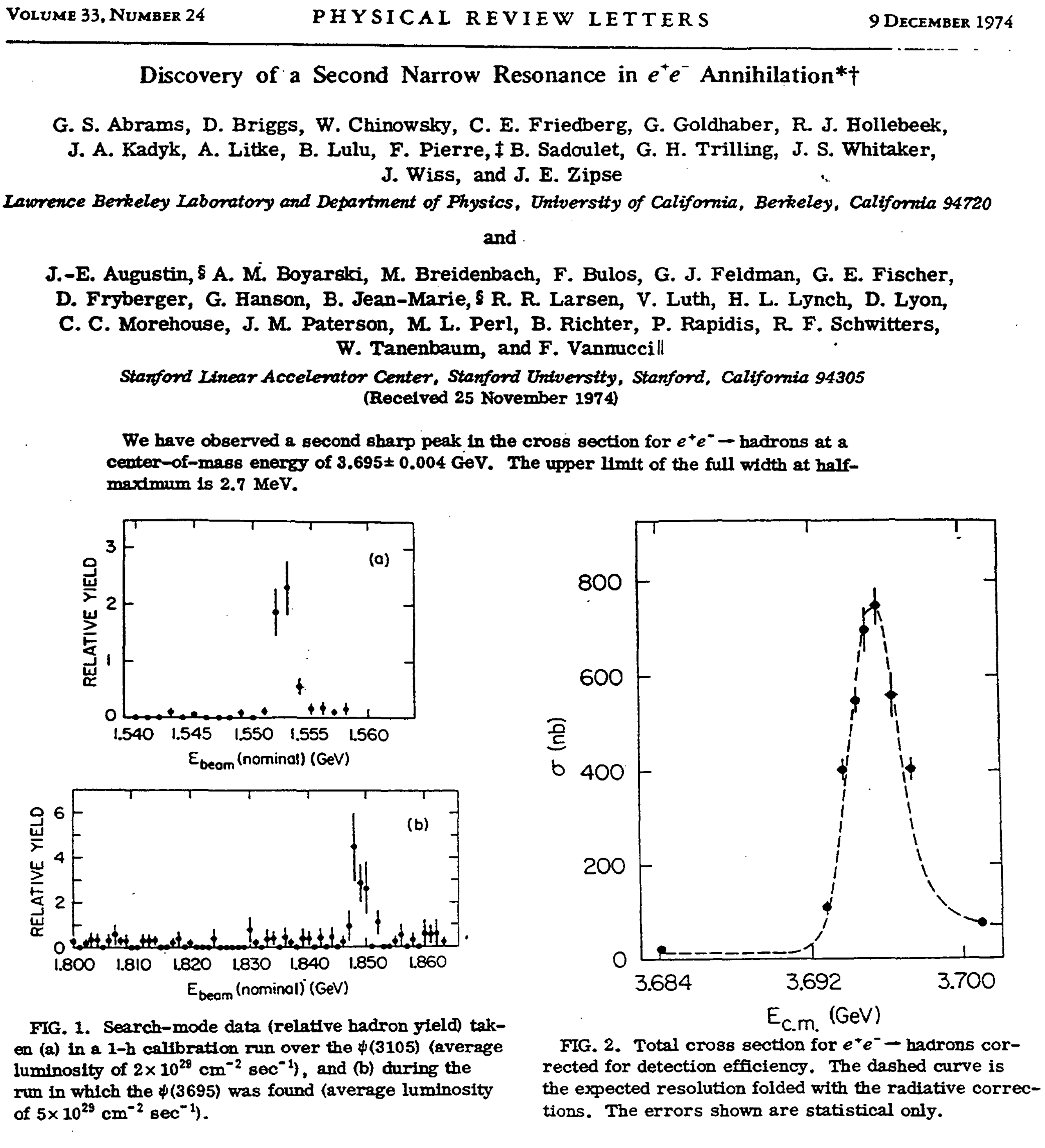
Emboldened by this success, after taking a day or two off to write the $\psi\prime$ paper,(10) we continued our scan and scanned on and on and on ... Fig. 10 gives the results of this scan and illustrates clearly that no other narrow resonance showed up, since, unfortunately, SPEAR was not designed to reach 10 GeV! We did however find a broad resonance at 4.4 GeV and considerable structure near 4.03 GeV. In Fig. 11 I show a later plot (1977) which shows this structure as well as the $\psi\prime\prime(3770)$ discovered by the LGW collaboration.(11)

During the period November 1974 to May 1976 enormous progress was made in understanding the properties of the ψ and $\psi\prime$ and in unraveling the entire Psion spectroscopy.

Thus for the ψ and $\psi\prime$ we measured the spin, parity and charge conjugation in interference experiments with Bhabha scattering at the leading edge of the resonances. We found that $J^{PC} = 1^{-\,-}$— the quantum numbers of the photon and vector mesons. From final state studies in ψ decay we determined that G = $(-)$ from a predominance of an odd number of pions, and that I = 0 from the decay $\psi \rightarrow \Lambda\overline{\Lambda}$ among others. We observed the transitions $\psi\prime \rightarrow \psi\pi^+\pi^-$ the major decay mode of the $\psi\prime$, and $\psi\prime \rightarrow \psi\eta^o$ which showed that if the ψ consisted of a combination of two quarks $Q\overline{Q}$ these quarks passed on to the final state. Following a DASP discovery(12) of a P state intermediate between ψ and $\psi\prime$, we observed the χ states ^3P_o, $^3P_1$ and $^3P_2$ obtained from

$$\begin{aligned} \psi\prime &\rightarrow \chi\gamma \\ &\rightarrow \gamma\psi \end{aligned}$$

and also from $\psi\prime \rightarrow \chi\gamma$ followed by direct hadronic χ decays. The detailed studies of the transitions between these states came later from work by the MPPSSD collaboration(13) and the Crystal Ball collaboration.(14) See Fig. 12 for the more recent results from the Crystal Ball experiment.



VOLUME 33, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1974

Discovery of a Second Narrow Resonance in e^+e^- Annihilation*†

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek,
J. A. Kadyk, A. Litke, B. Lulu, F. Pierre,‡ B. Sadoulet, G. H. Trilling, J. S. Whitaker,
J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

and

J.-E. Augustin,§ A. M. Boyarski, M. Breidenbach, F. Bulos, G. J. Feldman, G. E. Fischer,
D. Fryberger, G. Hanson, B. Jean-Marie,§ R. R. Larsen, V. Luth, H. L. Lynch, D. Lyon,
C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters,
W. Tanenbaum, and F. Vannucci‖
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 November 1974)

We have observed a second sharp peak in the cross section for $e^+e^- \to$ hadrons at a center-of-mass energy of 3.695 ± 0.004 GeV. The upper limit of the full width at half-maximum is 2.7 MeV.

FIG. 1. Search-mode data (relative hadron yield) taken (a) in a 1-h calibration run over the ψ(3105) (average luminosity of 2×10^{29} cm^{-2} sec^{-1}), and (b) during the run in which the ψ(3695) was found (average luminosity of 5×10^{29} cm^{-2} sec^{-1}).

FIG. 2. Total cross section for $e^+e^- \to$ hadrons corrected for detection efficiency. The dashed curve is the expected resolution folded with the radiative corrections. The errors shown are statistical only.

Fig. 9. Announcement of the ψ′ discovery in *Phys. Rev. Lett.*

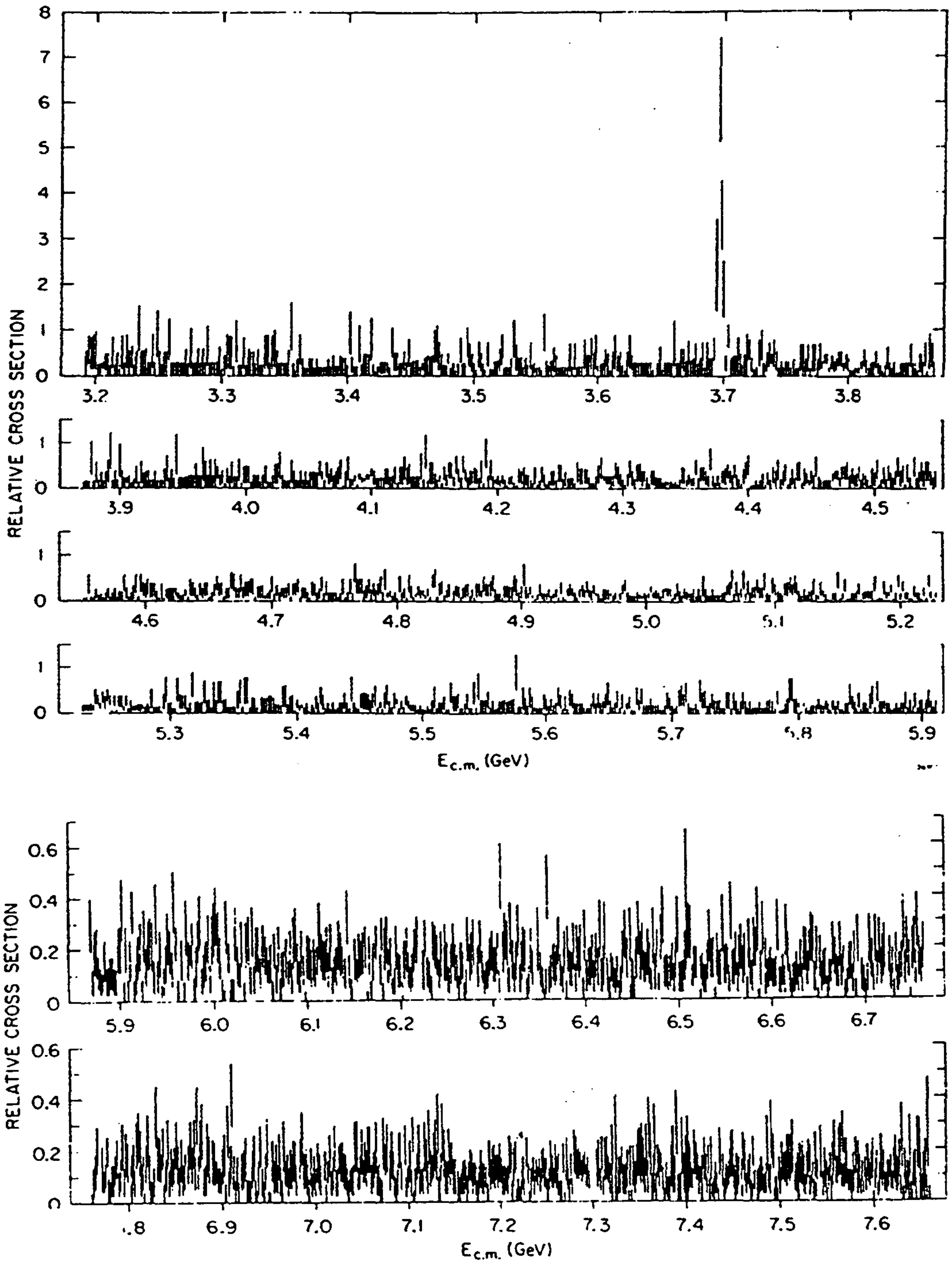


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Fig. 10. Search for additional narrow resonances up to 7.7 Gev. SLAC-LBL MARK I and MARK II data taken over several running periods.

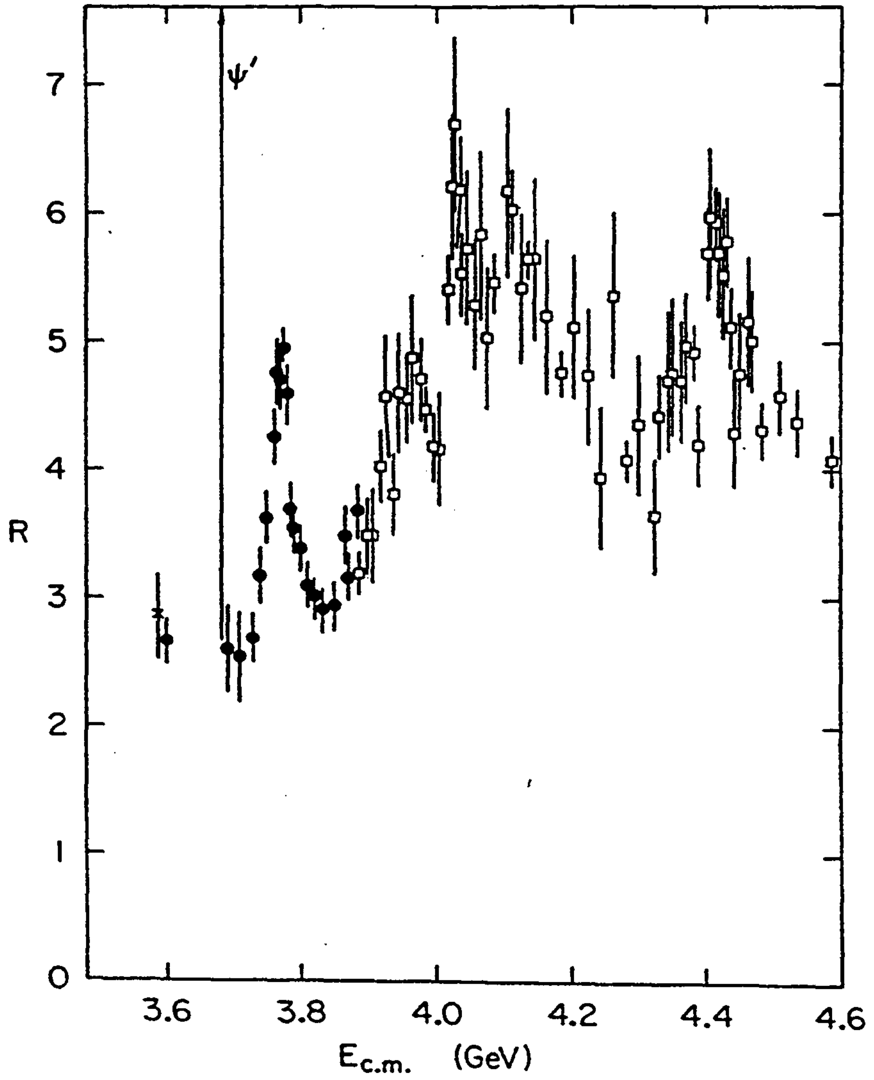

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Fig. 11. Open squares represent R measurements in the SLAC-LBL MARK I detector at SPEAR. Closed circles represent measurements by the LGW-MARK I experiment.

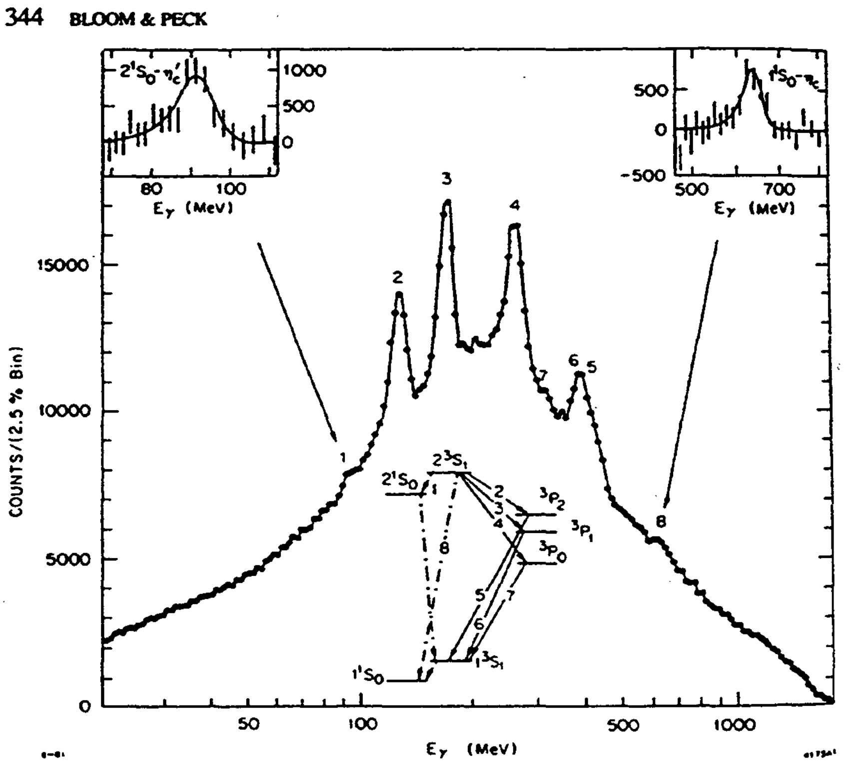

Fig. 12. Inclusive γ spectrum at the ψ'. Note that the spectrum is $\Delta N/\Delta(\log E) \cong E\, dN/dE$. The upper inserts show the background-subtracted signals for the η_c and η_c' candidate states. The numbers over the spectrum key the observed spectral features with the expected radiative transittions in the charmonium spectrum inset. Crystal Ball Experiment at SPEAR.

During this period also, Martin Perl discovered the τ-lepton(15), Gail Hanson demonstrated that Jets are produced in the e^+e^- annihilation process(15) and Roy Schwitters observed transverse beam polarization in SPEAR and demonstrated that the final state particles followed the distribution expected for the spin $\frac{1}{2}$ partons(15)

Where Does the Name ψ Come From?

We started out(2) calling the resonance SP (3105) for about 1 day where SP stood for SPEAR, however, we soon realized that a 2 letter name was unsuitable. The name ψ came from a cursory look I made through the Particle Data Group booklet for an unused, yet pronounceable, Greek letter—while on the phone to George Trilling and then to Burton Richter. In addition "PS" in "PSI" is "SP" spelled backward. Little did we know that the resonance would end up with 2 letters, J/ψ anyhow! all the same—we evidently "got a sign" later, from the reaction:

$$\begin{aligned} \psi' &\rightarrow \psi\pi^+\pi^- \\ &\quad\;\, \rightarrow e^+e- \end{aligned}$$

that our choice of the Greek letter ψ was an auspicious one! See Fig. 13.

What Does All This Have to Do With Charm?

The discovery of the ψ and ψ' was purely an experimental achievement. Within weeks there came a ground swell of theoretical papers interpreting the effects we were observing (see Fig. 14)—the front runners among these theories was the one suggesting that the J/ψ contained "hidden charm" namely, that is was a bound state of $c\bar{c}$ quarks, which had been predicted earlier.(16) while the narrowness of the ψ was explained by the Okubo-Zweig-Iizuka or OZI rule. On the other hand once one had settled on a front runner the theoretical predictions for psion spectroscopy and for particles with "naked charm" become crucial to our progress(17). Yet it took from November 1974 to May 1976 to find a clear peak(18) in the $K^-\pi^+$ and $K^-\pi^+\pi^-\pi^+$ mass distributions(19,20) at a mass of 1865 MeV/c^2.

Why Could We Not Find Charmed Mesons?

This was a major theme of a meeting on "Particles With New Quantum Numbers" held April 22–24, 1976 at the University of Wisconsin at Madison my old alma mater. I talked on various aspects of the ψ, ψ' and χ studies involving baryonic final states(28). Harvey Lynch talked on cross section measurements and in particular about our inability to observe naked charm signals.(29)

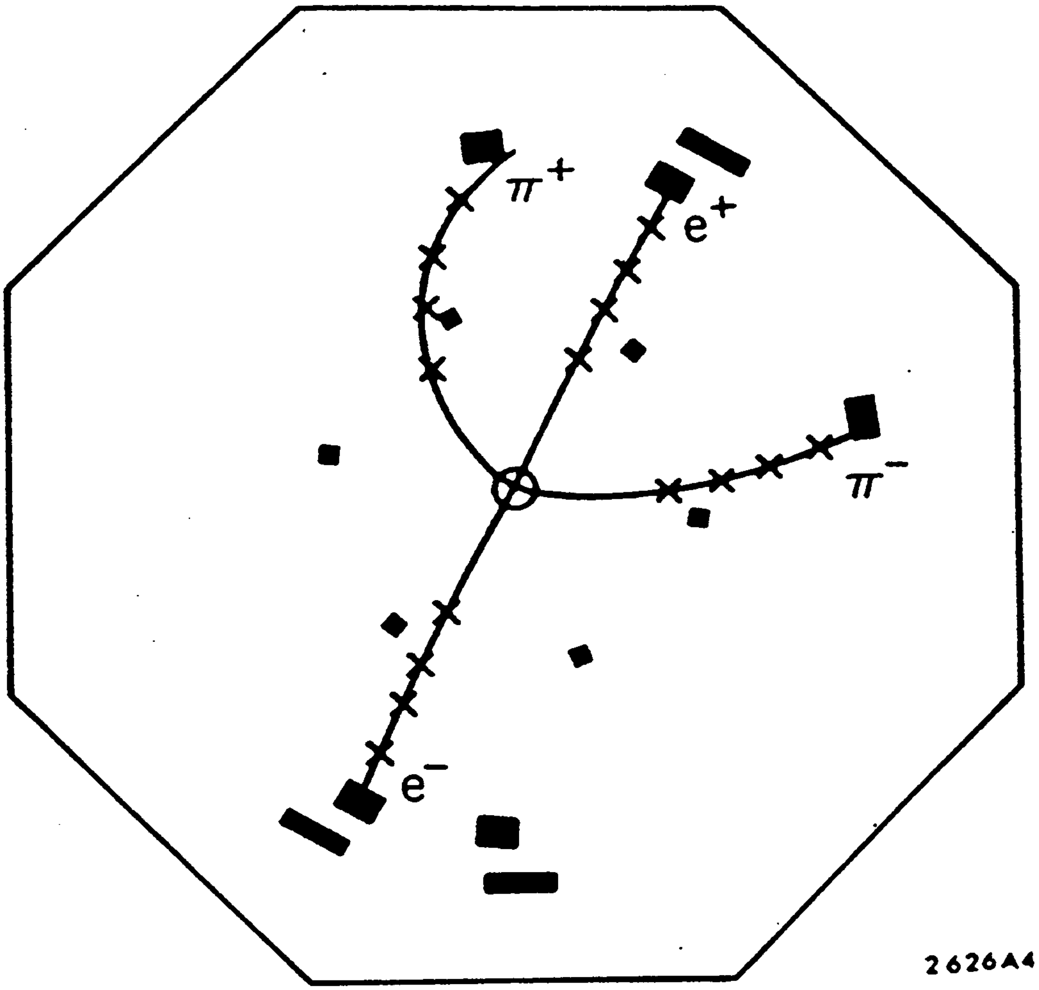

Fig. 13. Example of the decay $\psi' \to \pi^+\pi^-\psi, \psi \to e^+e^-$.

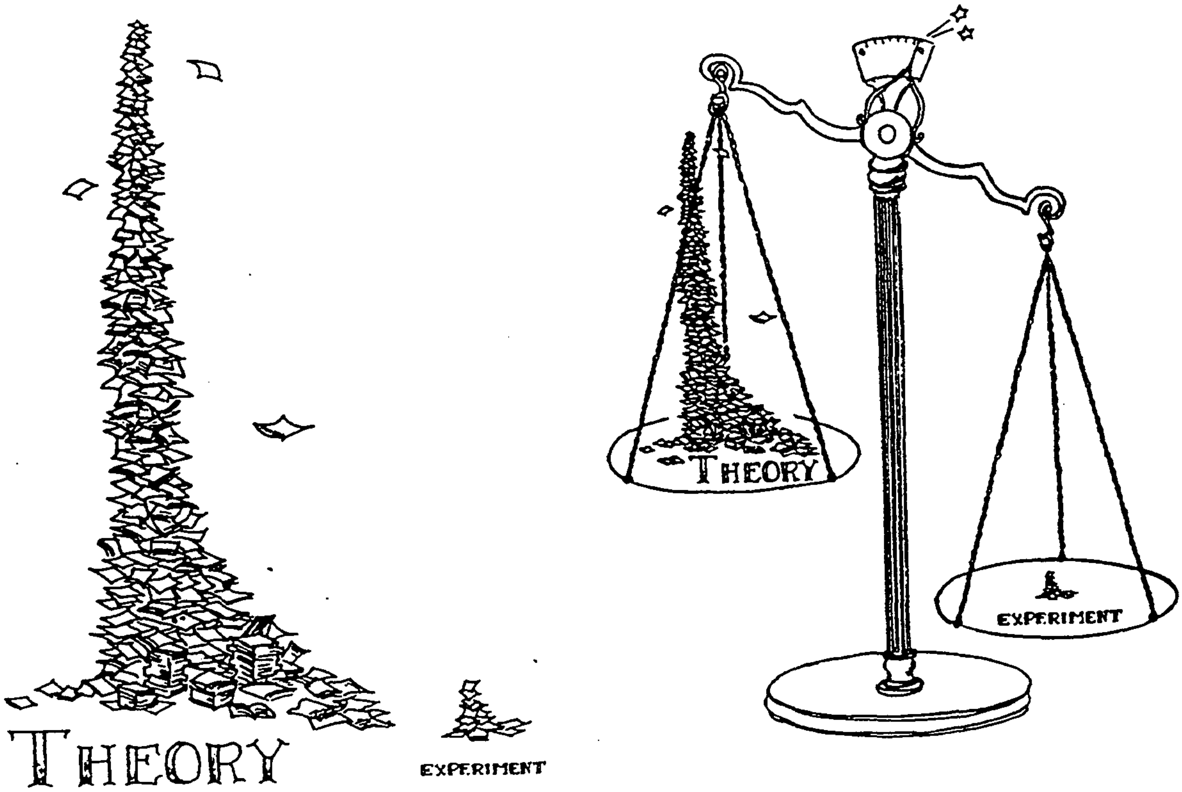

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Fig. 14. Cartoon by J.D. Jackson indicating the status of experimental and theoretical papers on the J/ψ within weeks of the discovery. Also shown is an addition by Roy Schwitters (right hand side) sketched by Bob Gould.

I decided at the meeting that when I got back to Berkeley I would spend a month to carefully sift through our data and try to find charmed particles or to find out why charmed particles did not occur in our experiment. At the airport, on the way home, I met up with Shelly Glashow and we shared a plane ride to Chicago. Shelly was particularly persistent that charmed particles just had to be there. Why were we incapable of finding them? I told him that I had resolved to spend at least a month re-analyzing the data to find the answer.

When I got back to Berkeley I spent the rest of the week and week-end at the lab. We had just taken some more data at SPEAR in the 3.9 GeV to 4.6 GeV region. Previously in various analyses I had carried out I had always been careful to use strict criteria for K and π identification, we used time of flight and momentum measurements to determine the masses of the particles produced in the e^+e^- annihilation. I decided to change my strategy and make very loose cuts. The thought was that I would not have a pure sample but rather a sample enriched in K mesons.

I thus studied $K^\mp\pi^\pm$ mass distributions correlated with recoil mass distributions. To my surprise and delight I did not have to wait a month. By Sunday, I had obtained a clear signal—a peak in the $K^\mp\pi^\pm$ mass distribution at about 1870 MeV associated with an equal or larger recoil mass peak. See Fig. 15.

On Monday and Tuesday I was looking for my colleague Francois Pierre—a visitor with our group at LBL from Saclay, France—to show him my result. Finally I met up with him on Wednesday for lunch. The reason I could not find him was that on Monday and Tuesday he had gone to SLAC. As I found out, he had also observed a $K\pi$ as well as a $K\pi\pi\pi$ signal. Right after lunch we compared distributions and realized we had each independently and with different criteria found the same mass peaks. We spent the next two hours writing a joint note to our collaboration showing our data. I called Roy Schwitters at SLAC, our spokesman at that time, to tell him about our results. There was much excitement both at LBL and SLAC. After our colleagues had a chance to check our results and convince themselves that we were right, a paper was sent off to Phys. Rev. Lett. One question came up. How could we prove that we had really identified K's? Jonathan Dorfan who had just recently joined our collaboration came up with the suggestion that we weight each track according to the probability that it be a K or a π and then plot the weighted $K\pi$ mass distribution. This is shown in our paper.(19)

On May 8 I called Shelly Glashow to tell him about our finding. He was extremely excited and happy. His long standing predictions had finally come true! Shelly of course "knew" it all along. But now the rest of the world knew it as well! We were duly cautious in our paper and only used the word "charm" as the last word in the last sentence:

"..., the narrow width of this state, its production in association with systems

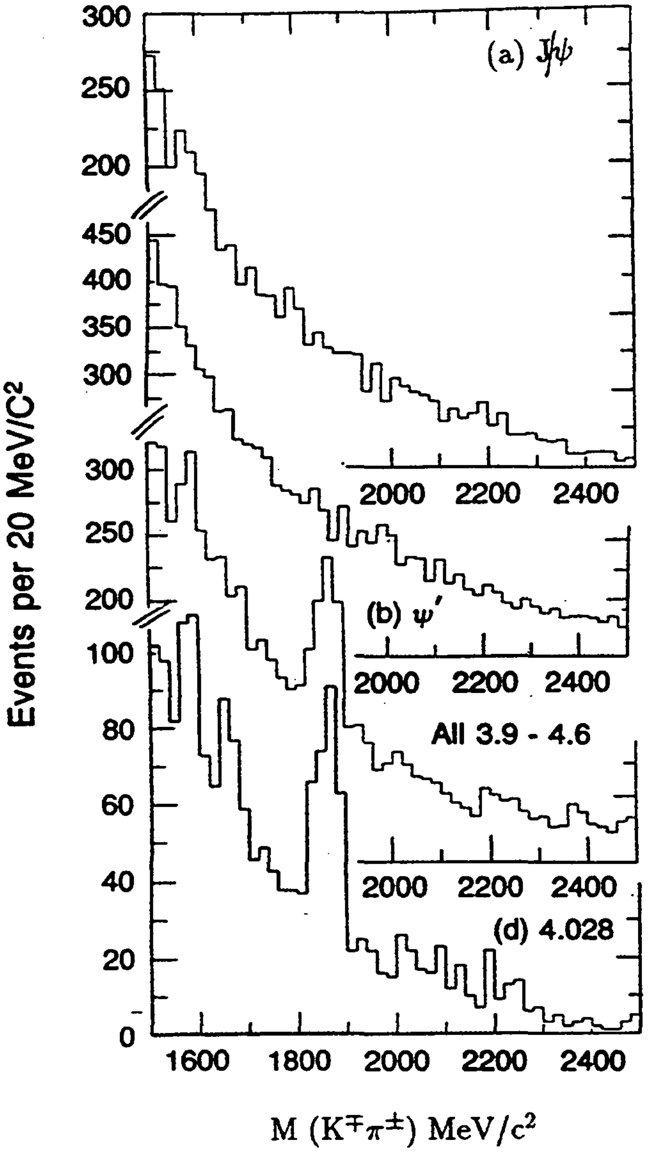

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Fig. 15. A composite of the $K\pi$ mass distribution for the J/ψ region, the ψ' region and the $E_{cm} = 3.9 - 4.6$ GeV region as well as the $E_{cm} = 4.028$ Gev data separately. SLAC-LBL MARK I data.

of even greater mass, and the fact that the decays we observe involve kaons form a pattern of observation that would be expected for a state possessing the proposed new quantum number charm."

When I told my friend Goesta Ekspong about our findings he challenged me to prove that these data indeed represented charmed mesons and not just another $K^{*o} \rightarrow K^-\pi^+$ decay. In the course of the next two years this proof became definitive.

The Case for Charmed Mesons.

(*i*) *Threshold.* For a new K*(1865) we also expect a threshold. But that is expected at ~2.360 GeV [K*(1865) + K] or even ~2.755 GeV [K*(1865) + K*(890)]. However the experimental threshold lies above 3.7 GeV (see Fig. 15). In the charm theory a threshold is expected at $E_{cm} = 2\ E_D \simeq 3.7$ GeV, corresponding to $e^+e^- \rightarrow D^0\overline{D}^0$. In fact, the $\psi''(3770)$ discovered later,(11) is a resonance just above threshold which decays predominately into $D^0\overline{D}^0$ and D^+D^-.

(*ii*) *Associated production.* For a new K*(1865) we expect associated production with K or perhaps with K*(890) but there is no known reason to expect $K^*(1865) + \overline{K}^*(1865)$ associated production. Experimentally we find that all observed events corresponding to the 1865 MeV/c^2 peak occur in associated production with either equal or higher mass objects. Figure 16 shows the experimental recoil mass spectrum in which we use the measured momentum of the $K\pi$ system together with the measured $K\pi$ invariant mass as well as a fixed mass with the nominal value M = 1865 MeV/c^2.

(*iii*) *The charged decay mode.* For a K* with $I = \frac{1}{2}$ we also expect a charged decay mode. For three-body decays this would have to be the non-exotic[†] mode $K^{\mp}\pi^+\pi^-$. Experimentally we observe the exotic decay mode $K^{\mp}\pi^{\pm}\pi^{\pm}$ but do not observe the non-exotic decay mode (see Figure 17); neither do we observe the I = 5/2 triply-charged $K^{\mp}\pi^{\mp}\pi^{\mp}$ decay mode (not shown here). Thus if the peak corresponds to a K* it must have I = 3/2; i.e., an exotic K*, which (incidentally) would be the first clear case of an exotic meson state. If we adopt the point of view that we are dealing with an exotic K*, we would still have to invent an explanation for the peculiar fact that the $I_z = \pm\frac{1}{2}$ states (the non-exotic combinations $K^{\mp}\pi^+\pi^-$) are suppressed.

On the other hand our observations are in good agreement with charm theory in which Cabibbo-enhanced hadronic weak decays obey a $\Delta\ C = \Delta S$ rule, that is the charmed quark c decays weakly to $s\overline{d}u$. Thus in $D^+(C = 1, S = 0)$ decay,

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[†] Here exotic refers to the fact that the strangeness is opposite the charge of the $K^{\mp}\pi^{\pm}\pi^{\pm}$ object, an impossibility for a quark-antiquark combination of the conventional quarks.

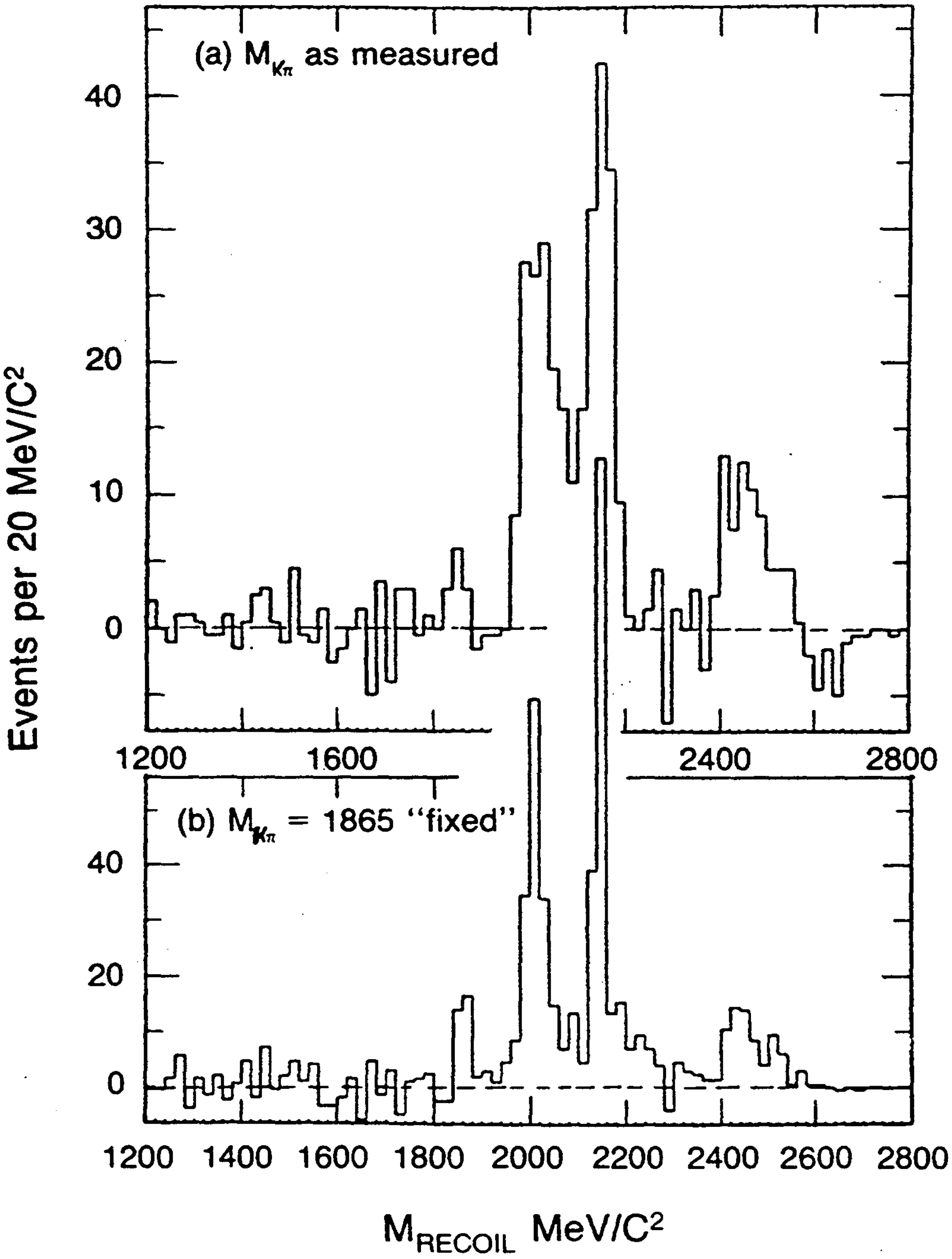

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Fig. 16. (a) M_{recoil} distribution against the $K\pi$ signal as measured. (b) M_{recoil} distribution against the $K\pi$ signal for fixed $M_{K\pi} = 1865$ MeV/c². Each distribution is background subtracted. It is noteworthy that the recoil sharpens up considerbly when $M_{K\pi}$ is taken as a unique mass. SLAC-LBL MARK I and MARK II data.

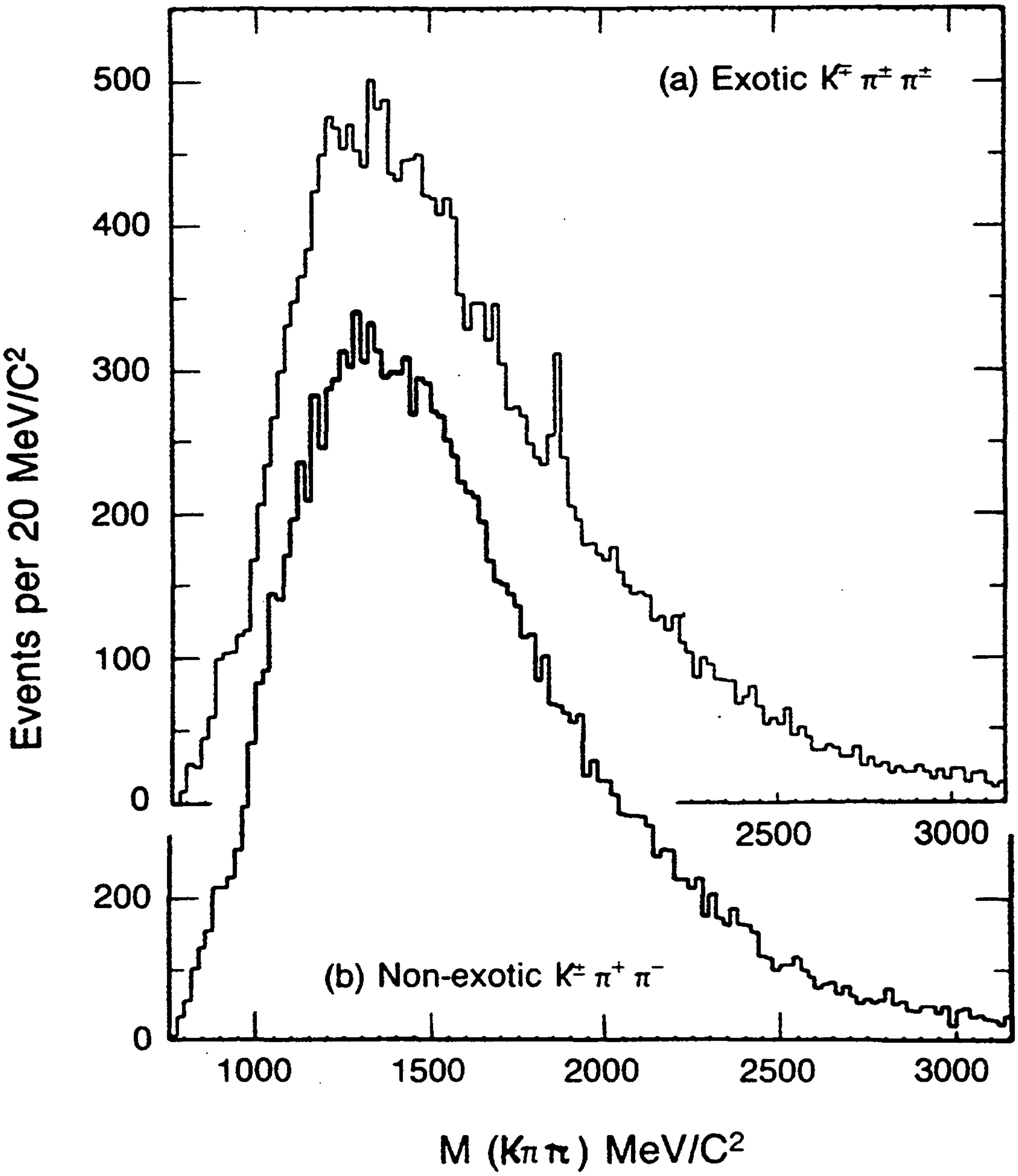

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Fig. 17. (a) Mass distribution for the exotic Kππ combination showing the D^+ peak. (b) Mass distribution for the non-exotic Kππ combination. SLAC-LBL MARK I data.

for example, the final state has $C = 0, \mathrm{S} = -1$ together with charge $Q = +1$; i.e., the charged final state is predicted to be exotic. This point holds explicitly for the charm model and would not necessarily be true for other new types of mesons M composed of $\overline{\mathrm{q}}\mathrm{Q}$.

(*iv*) *Experimental width.* For a K^* of mass 1865 $\mathrm{MeV/c^2}$ we might expect a width $\Gamma \approx 50 - 200\ \mathrm{MeV/c^2}$, although admittedly for an exotic K^* we have no clear prediction. Experimentally, we find $\Gamma < 40\ \mathrm{MeV/c^2}$ from the mass spectrum; however, by making use of the information from the recoil spectrum as well, this limit becomes $\Gamma < 2\ \mathrm{MeV/c^2}$.

Charm theory predicts that the decays we are dealing with are weak decays and estimates are: $\tau \sim 10^{-13}$sec. or roughly $\Gamma \sim 10^{-2}$ eV.

(*v*) *Evidence for parity nonconservation or the "$\tau - \theta$ puzzle" revisited.* For a K^* we expect parity conservation in the decay; this should hold even for an exotic K^*. Experimentally we find evidence for parity nonconservation. This is based on a study of the Dalitz plot for $\mathrm{K}^{\mp}\pi^{\pm}\pi^{\pm}$ decay and the assumption that the charged and neutral states are an I-spin multiplet. If parity is conserved in the $\mathrm{K}^{\mp}\pi^{\pm}$ decay we must have the natural spin parity series $\mathrm{J^P} = 0^+, 1^-, 2^+$, etc. For the $\mathrm{K}^{\mp}\pi^{\pm}\pi^{\pm}$ decay mode: $\mathrm{J^P} = 0^+$ is ruled out for three psedudosclars in the final state by angular momentum and parity consideration.

$\mathrm{J^P} = 1^-, 2^+$, give Dalitz plot distributions which vanish on the boundary. Our data rule this out clearly.(21) Thus we have strong evidence for parity nonconservation and hence a weak decay, consistent with the charm theory predictions.

(*vi*) *Higher mass states.* For a $\mathrm{K}^*(1865)$ there is no specific prediction for a next higher mass state. Experimentally we find from the recoil mass spectrum (see Figure 16) a next higher mass state at 2.006 $\mathrm{GeV/c^2}$. From charm theory a state D^* is predicted with mass $\mathrm{M_D^*} \sim 2\ \mathrm{GeV/c^2}$. If, without prejudicing the case, we use the nomenclature of charm theory, the observed three peaks in the recoil spectrum can be interpreted as:

$$\begin{aligned} \mathrm{e^+e^-} &\rightarrow \mathrm{D^0\overline{D}^0} && (1)\\ &\rightarrow \mathrm{D\overline{D}^*} \text{ and } \mathrm{\overline{D}D^*} && (2)\\ &\rightarrow \mathrm{D^*\overline{D}^*} && (3) \end{aligned}$$

although the detailed structure is complicated (24), the identity of the possible fourth peak in the recoil mass spectrum near 2.43 $\mathrm{GeV/c^2}$ was only recently established by the ARGUS experiment at DESY.

Furthermore, the decay modes

$$\mathrm{D^{*0}} \rightarrow \mathrm{D^0}\pi^0 \qquad (4)$$

$$\rightarrow D^0\gamma \tag{5}$$

have been identified and proceed with comparable rates. These two are the only important D^{*0} decay modes. The fact that D^{*0} has a large radiative decay indicates that it must be narrow and chooses to decay into a D^0 rather than directly into a $K^-\pi^+$ as might be expected for K*(2006). We must conclude that a special quantum number (presumably charm) is conserved in D^{*0} decay to the D^0.

Similar arguments can also be given for the decays(25)

$$D^{*+} \rightarrow D^0\pi^+ \tag{6}$$
$$\rightarrow D^+\pi^0 \tag{7}$$
$$\rightarrow D^+\gamma \tag{8}$$

(*vii*) *Spin.* For a K*(1865) one might expect spin values of $J = 3-4$, although again for an exotic K* all bets are off. An analysis of the events represented by reaction (2) given above can rule out simultaneous spin assignments for the states at 1865 and 2006, respectively, of 0 and 0 as well as 1 and 0, while the assignments 0 and 1 are consistent with the data.(22) Charm theory predicts $J^P = 0^-$ and 1^- for the D and D*, respectively. These values had been confirmed in more recent measurements.(23)

(*viii*) *Lifetime.* For a K* the lifetime is that typical of strong interaction viz. $10^{-23}-10^{-24}$sec. Charm theory predicts weak decay lifetimes in the 10^{-13} sec. region.

Emulsion measurements in cosmic rays(18) and in neutrino beams had observed neutral and charged decays occurring ~10–200μ from the parent interaction. Recently the lifetimes of the D^0 as well as the D^+ have been directly measured for identified decays in emulsions, high resolution Bubble Chambers, and electronic detectors with Vertex chambers-such as the SLAC-LBL MARK II detector. The present best average values are(26)

$$\tau_{D^0} = 4.20 \pm 0.08 \times 10^{-13} \text{ sec.}$$
$$\tau_{D^+} = 10.66 \pm 0.23 \times 10^{-13} \text{ sec.}$$

(*ix*) *Semileptonic decays.* The DASP experiment at DESY has identified electrons in multiprong events ($N > 3$) with a maximum signal observed in the $E_{cm} = 4.0-4.2$ GeV region. They have also observed K^+-e correlations which peak in the same E_{cm} region. Furthermore the PLUTO group at DESY have observed

K_s^0 − e correlations also peaked in the $E_{cm} = 4.05$ GeV region. More recently the decay modes

$$\begin{aligned} D^0 &\rightarrow K^- e^+ \nu \\ &\rightarrow K^{*-} e^+ \nu \end{aligned}$$

have been identified and the decay spectrum measured in the LGW and DELCO experiments at SPEAR(23) as well as in the DESY experiments. The existence of semileptonic decays is further proof for the weak interaction being responsible for D decays as predicted for charmed quarks.

(*x*) *The Cabibbo-suppressed decay modes.* The charm model also predicts a specific ratio between Cabibbo enhanced and suppressed decay modes. For example,

$$(D^0 \rightarrow \pi^- \pi^+)/D^0 \rightarrow K^- \pi^+) = \tan^2\theta_c$$

where θ_c is the Cabibbo angle. The decay modes

$$D^0 \rightarrow \pi^+ \pi^-$$

and

$$D^0 \rightarrow K^+ K^-$$

were later observed in the SLAC-LBL MARK II detector.(23) The average value for the two decay modes is indeed consistent with the above relation.

Establishment of the Cabibbo suppressed decay modes is another characteristic requirement of charmed quarks. The Mark III detector at SPEAR has in the 1980's identified many more Cabibbo suppressed decay modes.

(*xi*) *The F-meson.* In addition to the D^0 and D^+, the isodoublet of the charm model, which correspond to $\bar{u}c$ and $\bar{d}c$, the singlet $\bar{s}c$ is also predicted. This object was expected to have decay modes into two strange particles, $F^+ \rightarrow K^+K^-\pi^+$, for example. This state was hard to find, at first. Early indications were observed at a mass of 2040 MeV, but later the clear observation has been made in the CLEO experiment at CESR, the ARGUS experiment at DORIS and the TASSO experiment at PETRA.(27) These experiments observe the decay $F^+ \rightarrow \phi\pi^+$ at a mass of $M_F = 1970$ MeV/c^2.

These observations together with evidence for an F* from ARGUS and the TPC at PEP, complete the picture, and give us an unambiguous identification of the charmed mesons.

Charmed Mesons as a Tool for the Identification of B Mesons.

Yesterdays discovery becomes today's tool. There are two aspects of charmed mesons which have proved invaluable in the intense study of B mesons occurring at this time.

(*i*) *The decay mode* $D^{*+} \to \pi^+ D^0$. As first noted by Gary Feldman(25) the very low Q value of this strong decay, Q = 5.7 MeV, is a characteristic feature of charmed mesons. This feature is being utilized for identifying charmed meson and in particular distinguishing D^0 and $\overline{D}^0$ mesons. Fig 18 shows a 1993 mass difference distribution from the ALEPH collaboration at LEP.(30)

(*ii*) *The "Satellite" peak associated with* D^0 *decay.* After finishing our runs at SPEAR in 1980, when all the data tapes were available, I noticed that associated with the decay $D^0 \to K^-\pi^+$ there was a second "satellite" peak at a mass of ~ 1600 MeV. This was clearly charm associated — I checked that it did not occur below charm threshold, and yet occurred at all energies above that threshold. See Fig. 19.

I offered a prize of a nickel (5 cents) to some of my theoretical colleagues to find an explanation for this effect. Indeed, Bob Cahn and Mike Chanowitz together with consultations by Dave Jackson came up with the interpretation. The prize was then duly divided up and presented to them with a ceremonial scroll. The explanation is that the peak comes from the copius decay $D^0 \to K^-\pi^+\pi^0$.

This comparatively sharp S° enhancement arises as illustrated in Fig. 20 which gives the features of the Dalitz plot for the decay $D^\circ \to K^-\pi^+\pi^\circ$. We note that this decay mode proceeds via the two intermediate state (pseudo scalar meson + vector meson) channels:

$$D^\circ \to K^-\rho^+ \text{ and } D^\circ \to K^{*-}\pi^+ \text{ as well as a third channel } D^\circ \to K^{*\circ}\pi^\circ$$
$$\lfloor\!\!\to \pi^+\pi^\circ \qquad \lfloor\!\!\to K^-\pi^\circ \qquad\qquad\qquad \lfloor\!\!\to K^-\pi^+$$

which is of no relevance here and is not shown on the Dalitz plot. In view of the fact that we have the decay of $J^p = 0^-$ (the D°) to a $J^p = 0^-$ and $J^p = 1^-$ state, it must proceed via $L^p = 1^-$ in relative orbital angular momentum between the pseudo scalar and vector meson. As a consequence of the angular momentum addition $\vec{L} + \vec{J}(V) = 0$ the vector meson is produced fully aligned and hence with a $\cos^2\theta$ distribution in the vector meson c.m. This expresses itself as a mass-squared distribution along the ρ^+ and K^{*-} bands which peak at the ends of these bands. Fig. 21 shows these as reflected into $M(K^-\pi^+)$ evaluated by a Monte Carlo calculation. Fig. 22 shows a possible fit to the S° peak with 2/3 of the intensity ascribed to the ρ^+ band and 1/3 to the K^{*-}

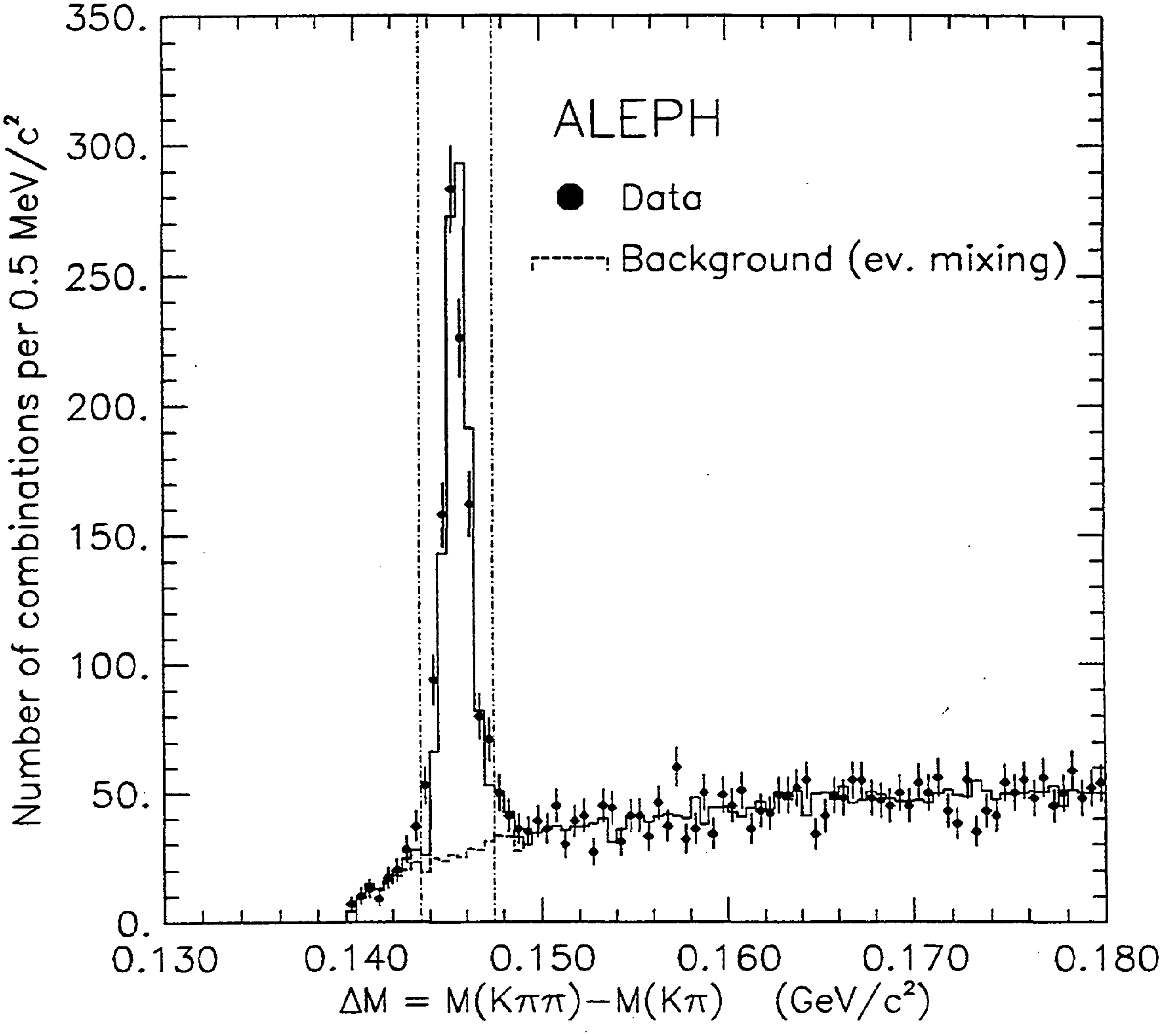

Fig. 18. Recent results from the ALEPH Collaboration(30) at LEP showing the application of the D^{*+} decay method in B identification.

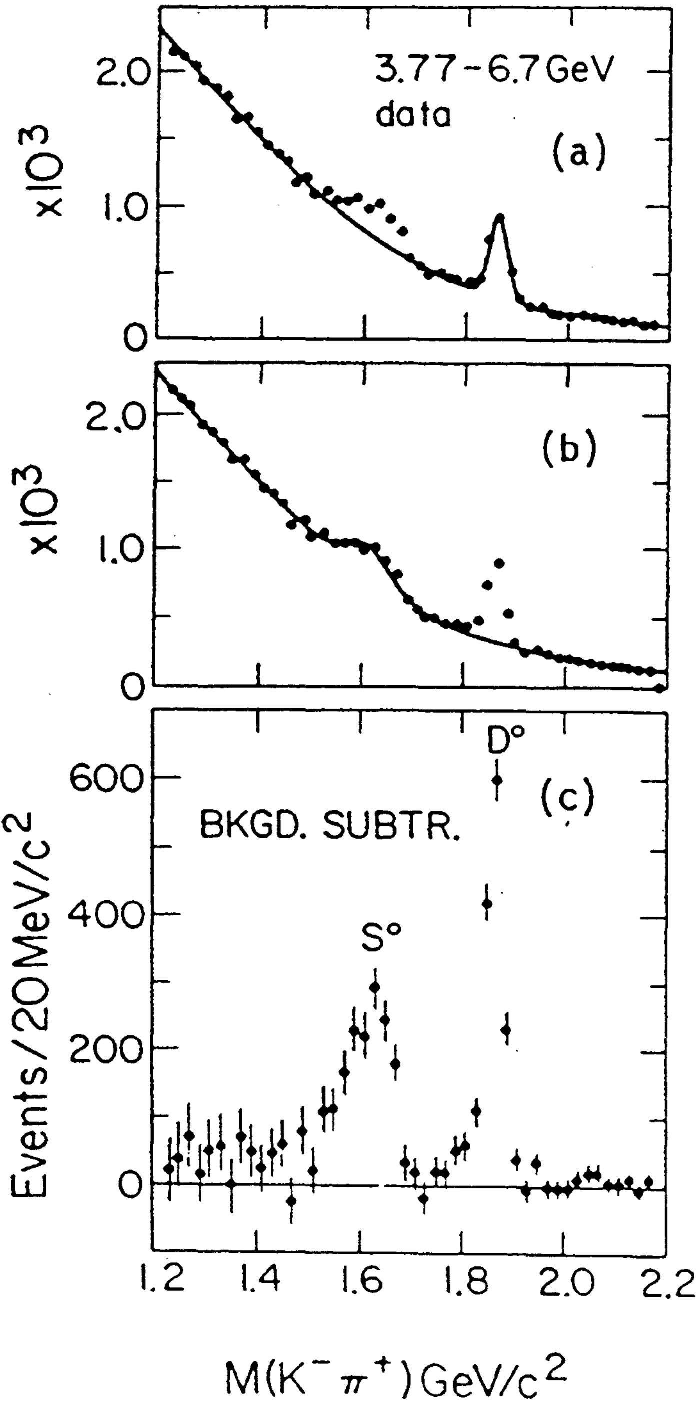

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Fig. 19. The D° resonance and S° enhancement. The signals correspond to 1340 D° events and 1470 S° events. The S° signal thus more than doubles the number of charm tags for the $K^-\pi^+$ decay mode. (a) The curves is a fit to background and the D° signal. (b) The curve is a fit to background and the S° signal. (c) The data with background (as determined from the above fits) subtracted. Mark II at SPEAR.

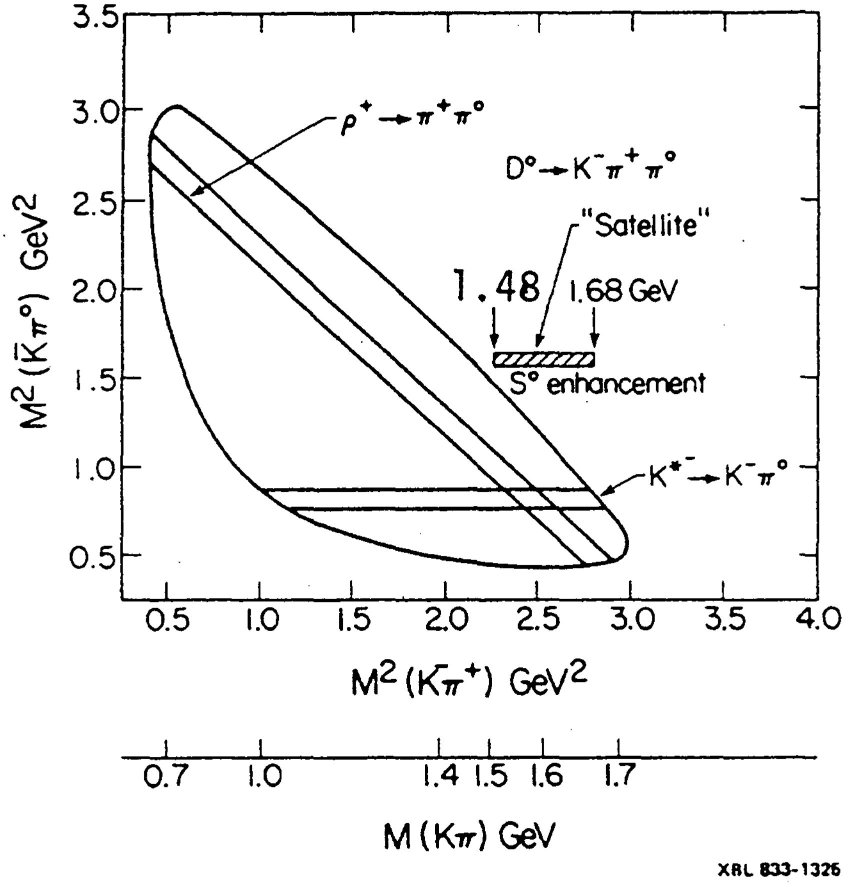

Fig. 20. The Dalitz plot boundary for the reaction $D^\circ \rightarrow K^-\pi^+\pi^\circ$ showing the ρ^+ and K^{*-} bands. The S° enhancement corresponds to the high $K^-\pi^+$ mass end of the resonance bands. Both M^2 and M scales are shown.

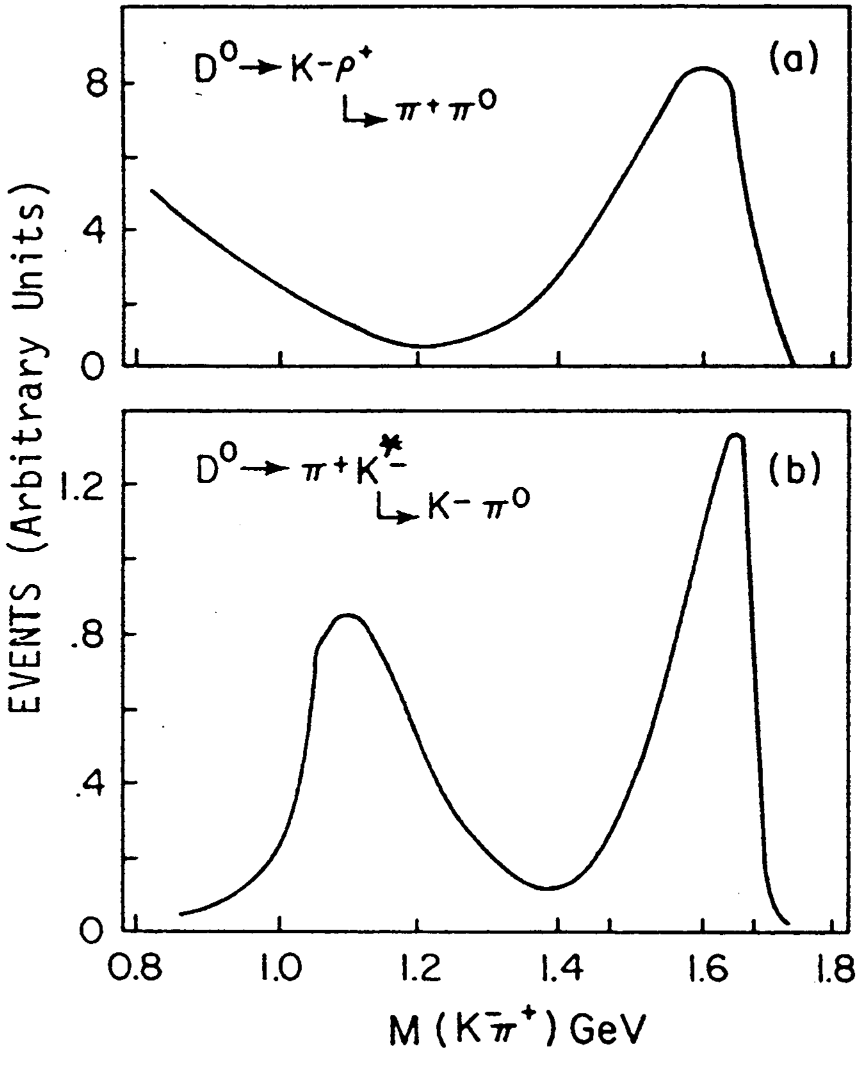

Fig. 21. The calculated shapes of the $K^-\pi^+$ mass projections of the ρ^+ and K^{*-} bands. The observed enhancements are the result of the vector meson alignment from D^0 decay.

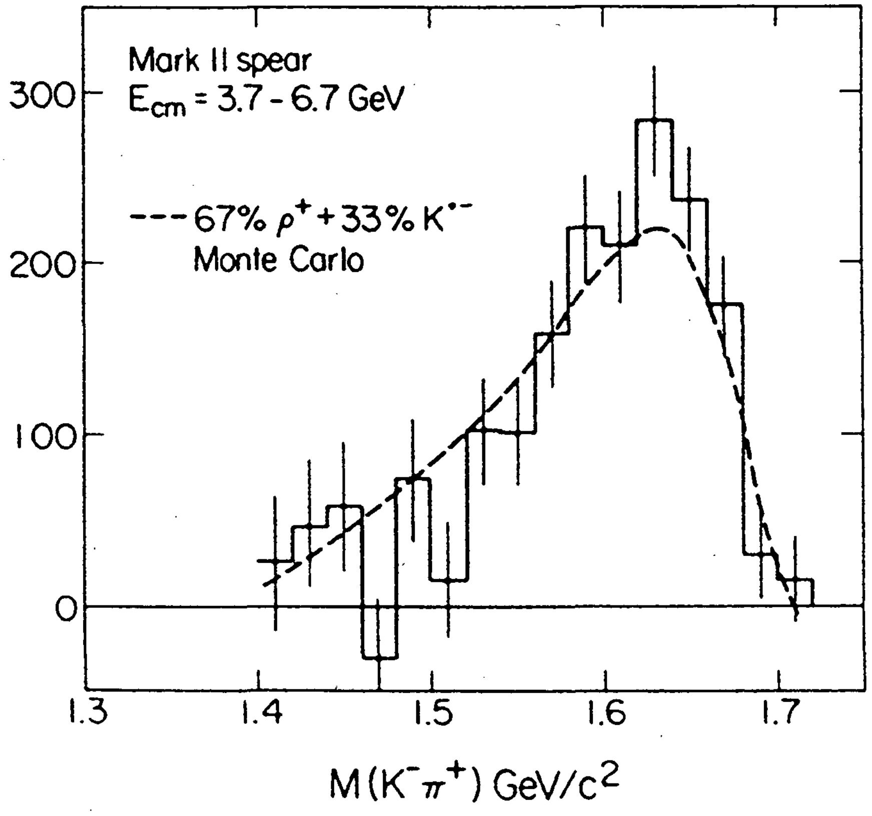

Fig. 22. The S° signal fitted by a combination of the ρ^+ and K^{*-} distributions. Mark II at SPEAR.

band with no account taken of possible interference between the two bands. Thus the S° peak is explained as an enhancement in $M(K^-\pi^+)$, primarily due to the D° $\rightarrow K^-\pi^+\pi^\circ$ decay mode. The Satellite peak $S^0 \rightarrow K^-\pi^+$ which I named after my daughter Shaya, contains about as many charmed mesons at the direct decay $D^0 \rightarrow K^-\pi^+$. The importance of this effect, which I have so far only mentioned at conferences,(31) is that it doubles the number of available identifiable charmed mesons. Fig. 23 shows recent data from the OPAL collaboration at LEP utilizing the satellite peak for this purpose.

The LBL-SLAC Collaboration at SPEAR.

Not only were we lucky in that we were sitting on a "gold mine" at SPEAR, we also had a very congenial group of people.

Since we had so much new data, a new discovery came up every few weeks, there was very little infighting. There was plenty of data to go around so that anyone who had something to report could give talks at conferences.

I am very proud of our record. I do not believe that any of the data we published had a serious flaw or was outright wrong. A lot of the credit for this must go to George Trilling, my co-group leader at LBL. George is a very liberal person, but is very conservative when it comes to physics claims. He has personally gone through every word we published with a fine toothed comb and checked the validity of every standard deviation we claimed.

There is of course another side to this coin. To never publish a wrong result we have to set our threshold for acceptance of any given result very high. Thus occasionally we decided not to publish a claim that actually turned out to be correct! I will give three examples:

When we published our paper on the Kπ peak at 1865 MeV the recoil spectrum appeared to have structure—this was later identified as $D\overline{D}^*$ and $D^*\overline{D}^*$ production (see Fig. 16), however we decided not to claim this structure.

When we published this same recoil spectrum (with considerably higher statistics from the Mark II) there was a clear fourth peak at about 2.43 GeV. We never claimed the observation of a D^{o**} which was later clearly identified by ARGUS at DESY.

Finally we had an isolated peak of about a dozen events in the $\phi\pi$ distribution at 1960 MeV. The data was however not completely understood. We thus never claimed the discovery of the F which was later clearly established by the CLEO group at Cornell.

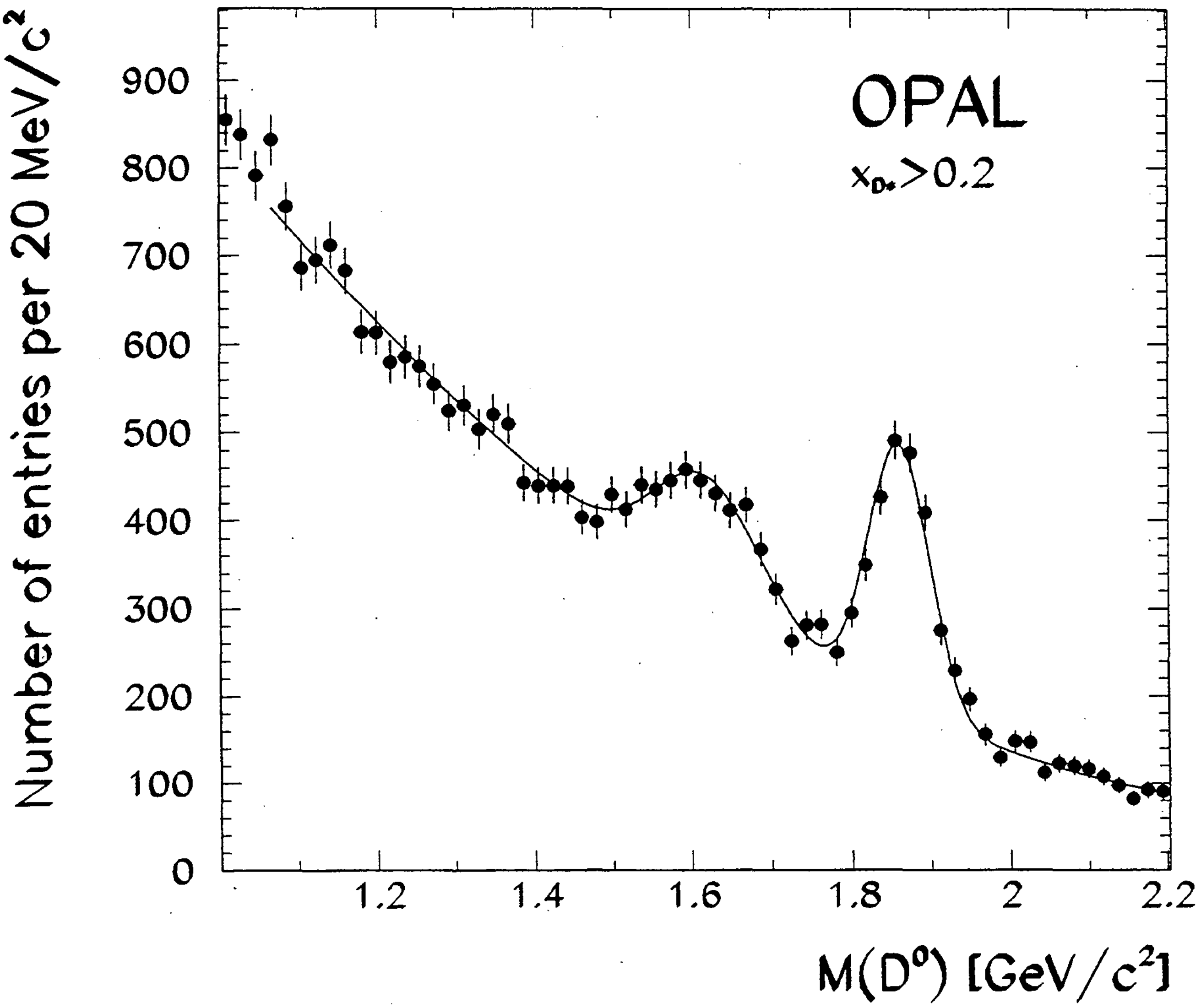

Fig. 23. Recent results from the OPAL collaboration(32) showing the observation of the S° signal which they utilized in B identification.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720