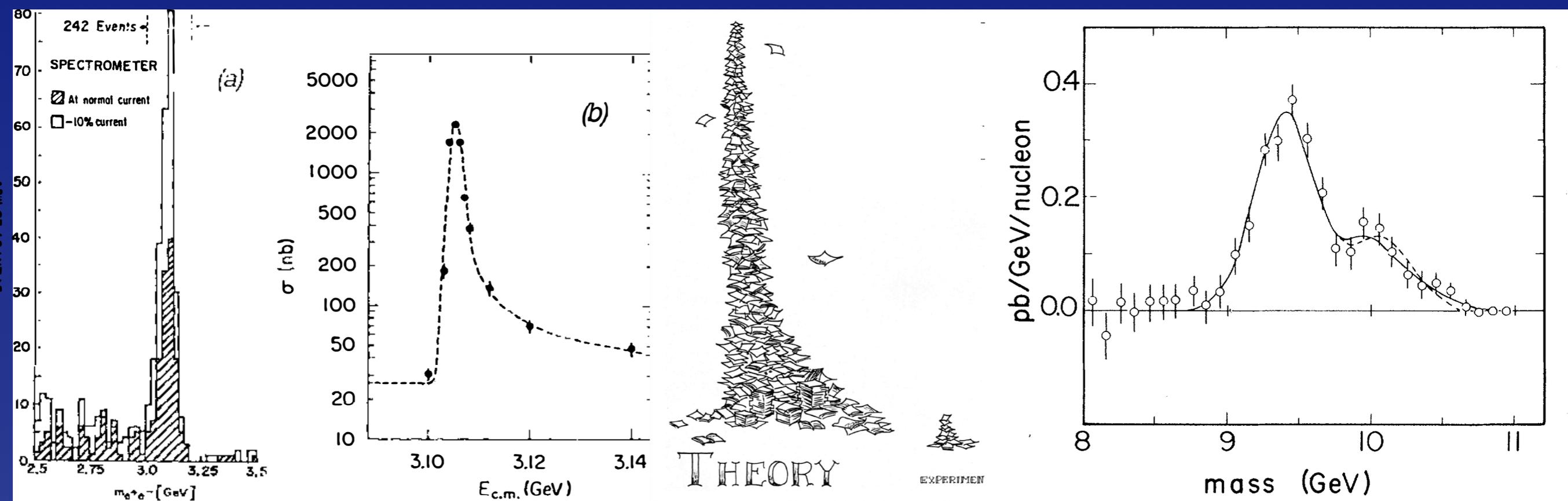


Quarkonium: The First Forty Years

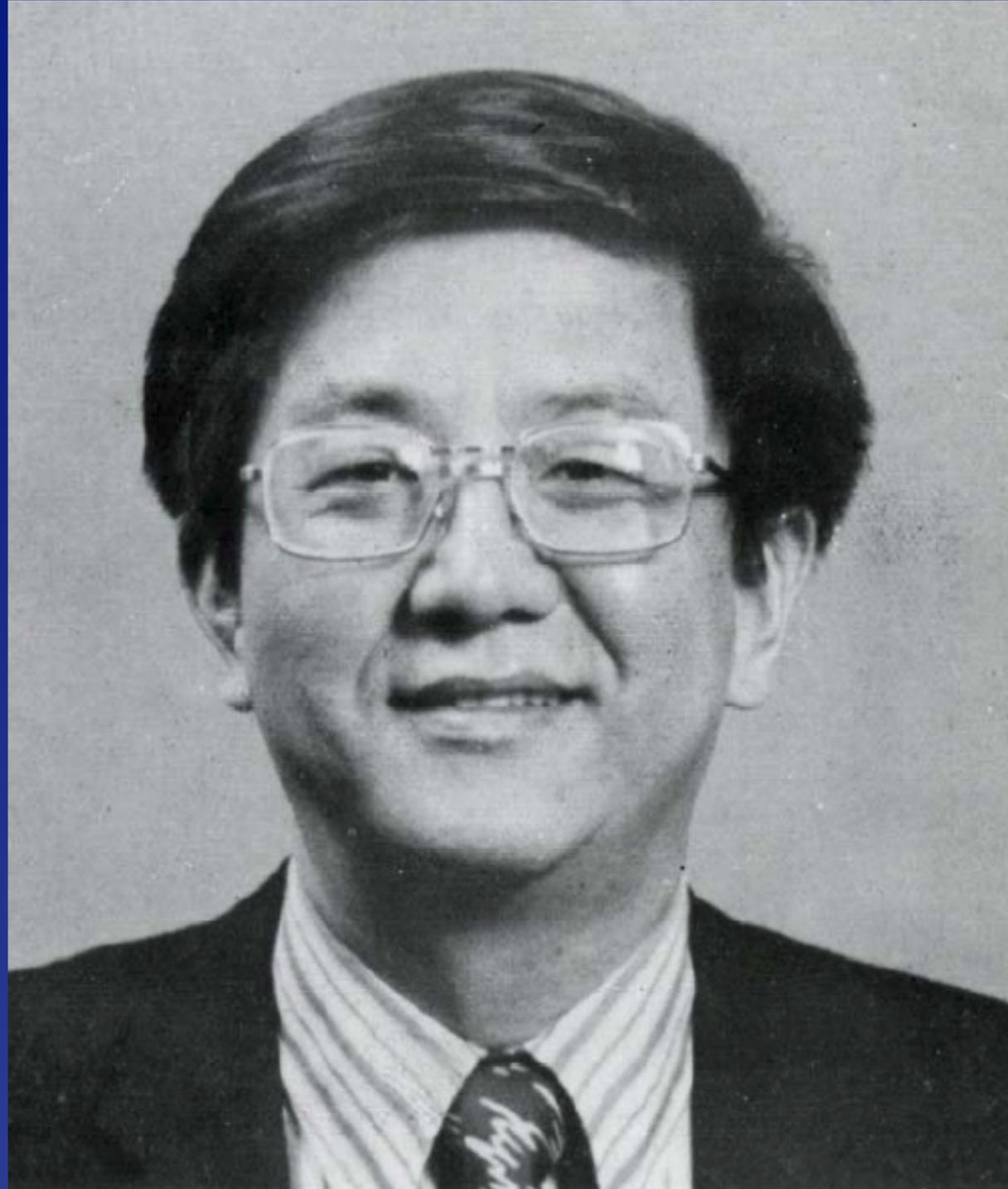
Chris Quigg
Fermilab



La physique valdôtaine · La Thuile · 2 March 2015

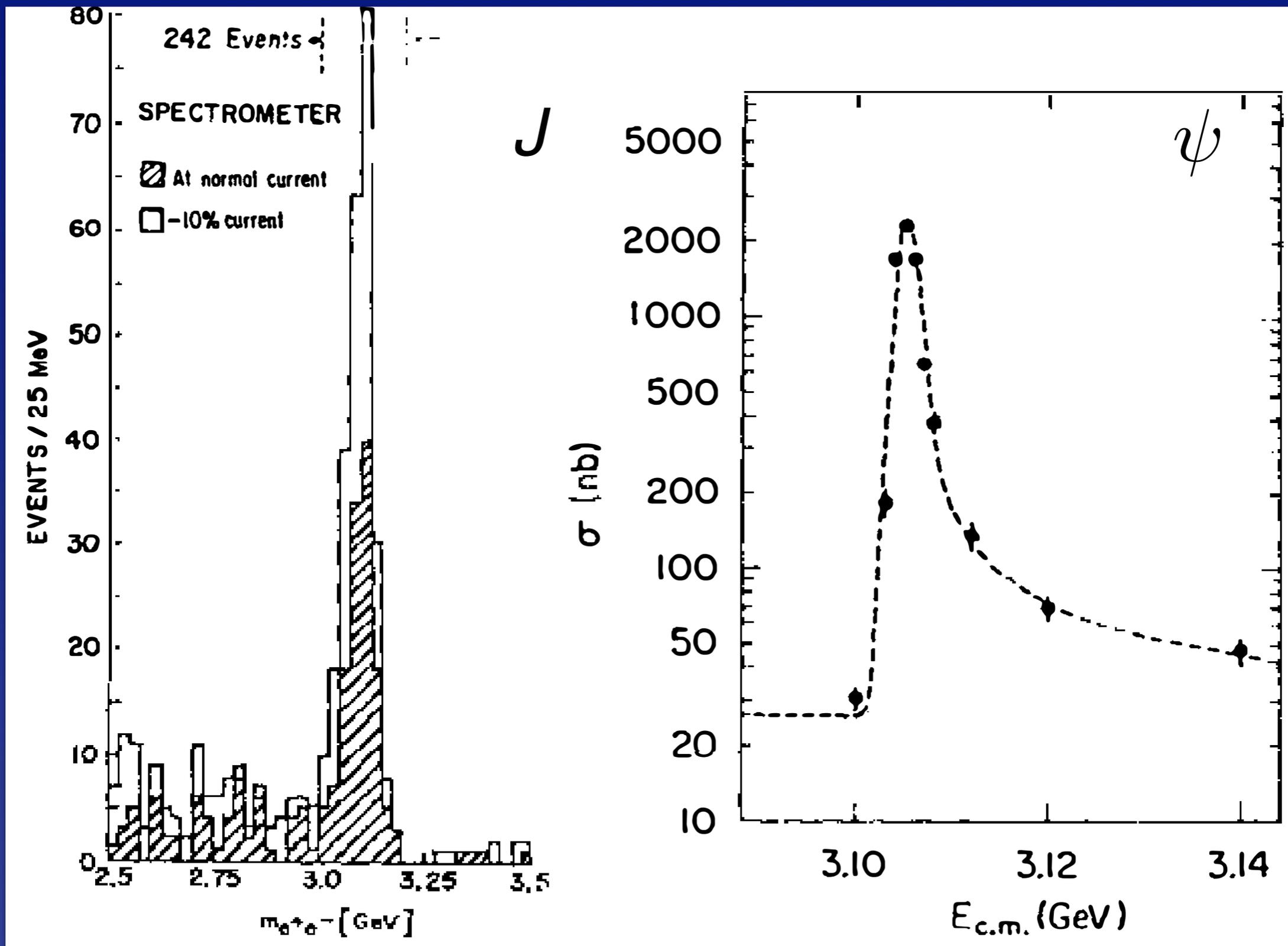
Where were you?

“Looks like charm is found ...”



Ben Lee

11 November 1974



I should have been at SLAC that morning, for my first meeting as a PAC member.

SLAC Director Panofsky advised me:

The meeting will be purely ceremonial; there is no business to decide;

out with the old (members), in with the new.

“If I were you, I would stay home.”

Two life lessons:

You can't always trust a lab director.

Never miss a committee meeting.

Experimental Observation of a Heavy Particle J^\dagger

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

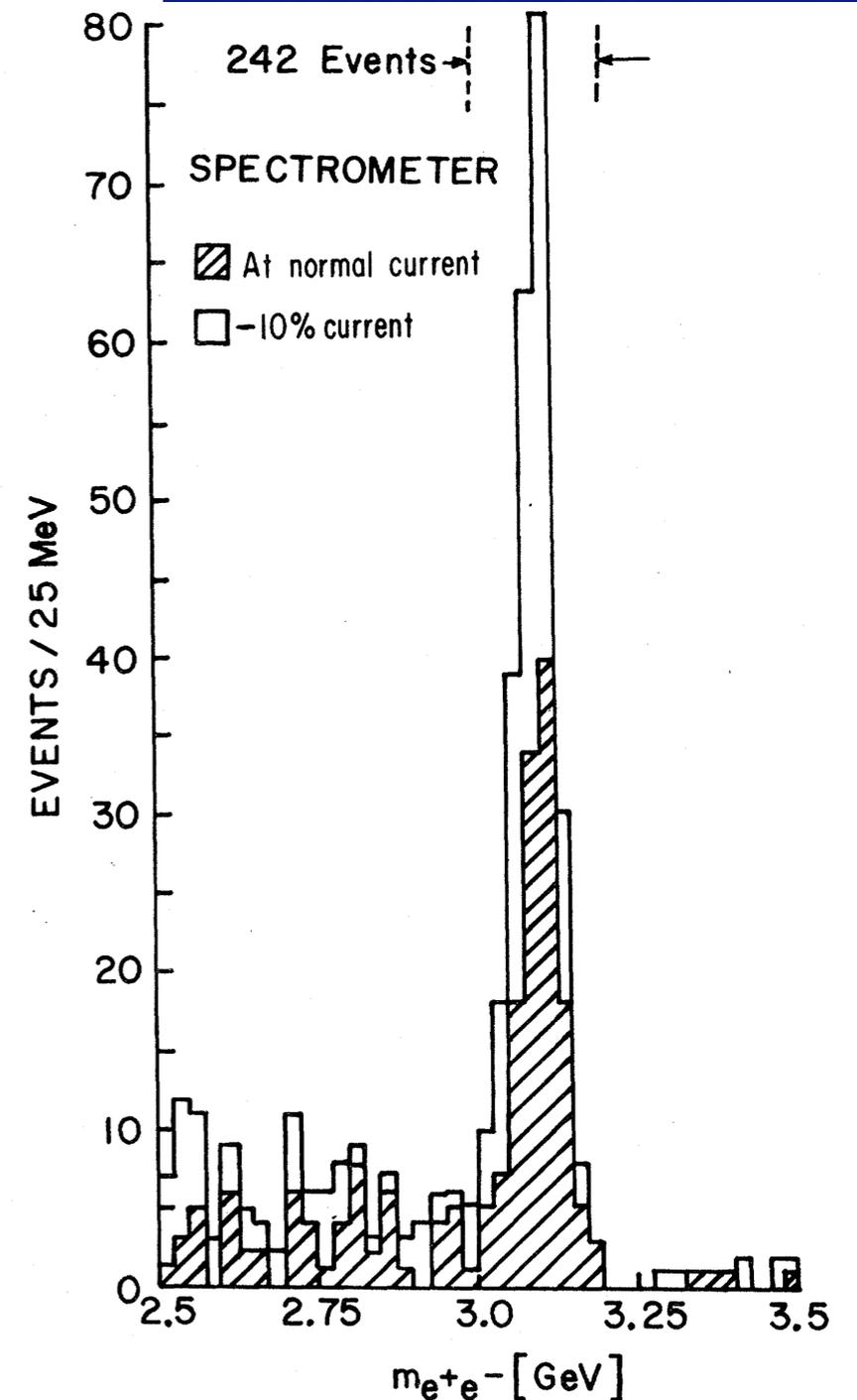
Y. Y. Lee

Brookhaven National Laboratory, Upton, New York 11973

(Received 12 November 1974)

We report the observation of a heavy particle J , with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \text{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Lack of continuum inconsistent with parton model?





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

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman,
G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth,
H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl,
B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum,
and F. Vannucci‡

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek,
J. A. Kadyk, B. Lulu, F. Pierre,§ 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

(Received 13 November 1974)

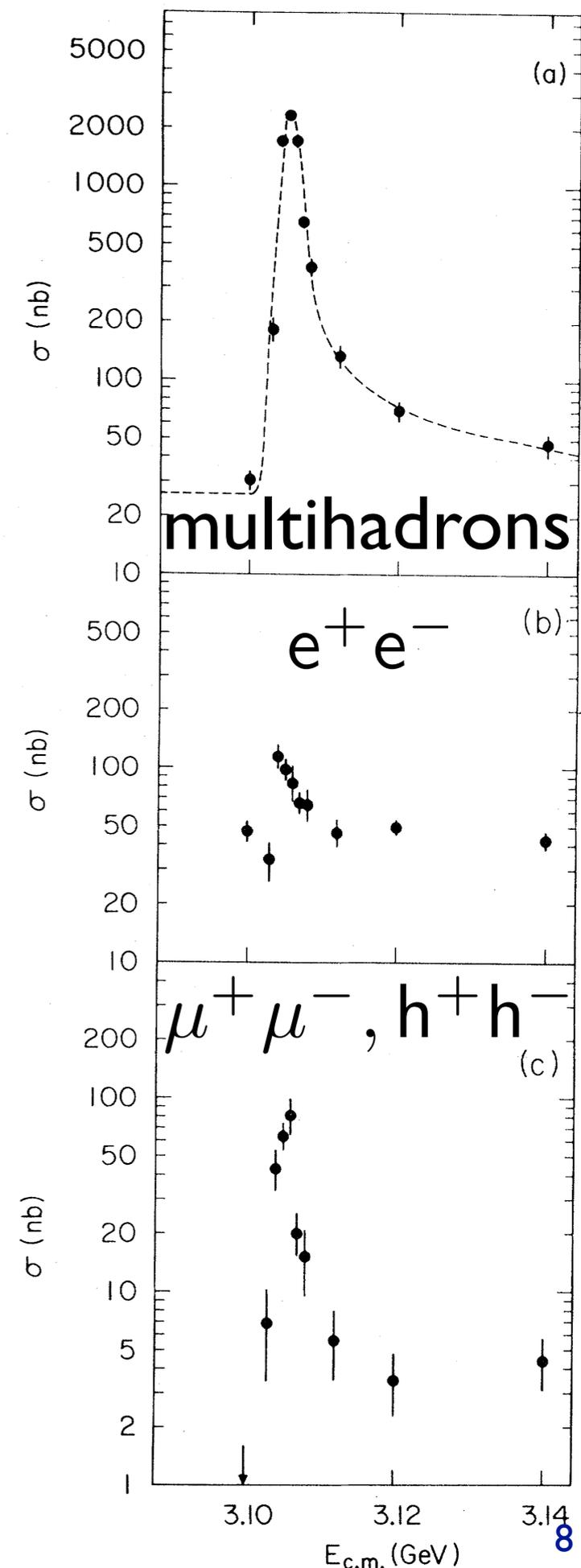
We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow \text{hadrons}$, e^+e^- , and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

Soon known, treating ISR and resolution
à la Jackson & Scharre:

$$\Gamma_e = 4.8 \pm 0.06 \text{ keV} \rightsquigarrow 5.55 \pm 0.14 \text{ keV}$$

$$\Gamma = 69 \pm 15 \text{ keV} \rightsquigarrow 92.9 \pm 2.8 \text{ keV}$$

$$M = 3095 \pm 4 \text{ MeV} \rightsquigarrow 3096.916 \pm 0.011 \text{ MeV}$$





Vera Lüth photo

C. Bacci, R. Balbini Celio, M. Berna-Rodini, G. Caton, R. Del Fabbro, M. Grilli, E. Iarocci,
M. Locci, C. Mencuccini, G. P. Murtas, G. Penso, G. S. M. Spinetti,
M. Spano, B. Stella, and V. Valente

The Gamma-Gamma Group, Laboratori Nazionali di Frascati, Frascati, Italy

and

B. Bartoli, D. Bisello, B. Esposito, F. Felicetti, P. Monacelli, M. Nigro, L. Paolufi, I. Peruzzi,
G. Piano Mortemi, M. Piccolo, F. Ronga, F. Sebastiani, L. Trasatti, and F. Vanoli
The Magnet Experimental Group for ADONE, Laboratori Nazionali di Frascati, Frascati, Italy

and

G. Barbarino, G. Barbiellini, C. Bemporad, R. Biancastelli, F. Cevenini, M. Celveti,
F. Costantini, P. Lariccia, P. Parascandolo, E. Sassi, C. Spencer, L. Tortora,
U. Troya, and S. Vitale

The Baryon-Antibaryon Group, Laboratori Nazionali di Frascati, Frascati, Italy

(Received 18 November 1974)

We report on the results at ADONE to study the properties of the newly found 3.1-BeV particle.

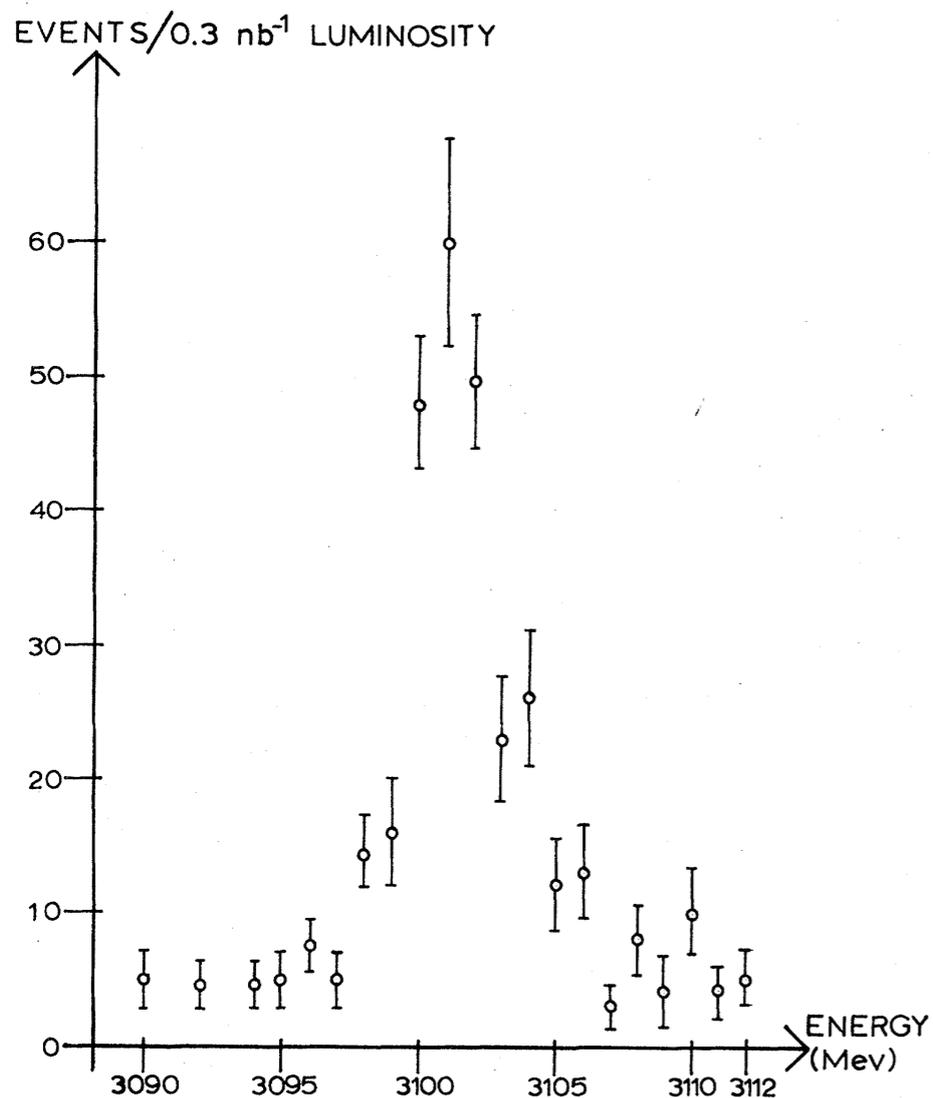


FIG. 1. Result from the Gamma-Gamma Group, total of 446 events. The number of events per 0.3 nb^{-1} luminosity is plotted versus the total c.m. energy of the machine.

A MEASUREMENT OF LARGE ANGLE e^+e^- SCATTERING AT THE
3100 MeV RESONANCE

DASP - Collaboration

W. BRAUNSCHWEIG, C.L. JORDAN, U. MARTYN, H.G. SANDER
D. SCHMITZ, W. STURM, W. WALLRAFF

I. Physikalisches Institut der RWTH Aachen

K. BERKELMAN*, D. CORDS, R. FELST, E. GADERMANN, G. GRINDHAMMER,
H. HULTSCHIG, P. JOOS, W. KOCH, U. KÖTZ, H. KREHBIEL, D. KREINICK, J. LUDWIG,
K.-H. MESS, K.C. MOFFEIT, D. NOTZ**, G. POELZ, K. SAUERBERG, P. SCHMÜSER,
G. VOGEL, B.H. WIJK, G. WOLF

Deutsches Elektronen-Synchrotron DESY and II. Institut für Experimentalphysik der Universität Hamburg, Hamburg

G. BUSCHHORN, R. KOTTHAUS, U.E. KRUSE**, H. LIERL, H. OBERLACK,
S. ORITO, K. PRETZL, M. SCHLIWA

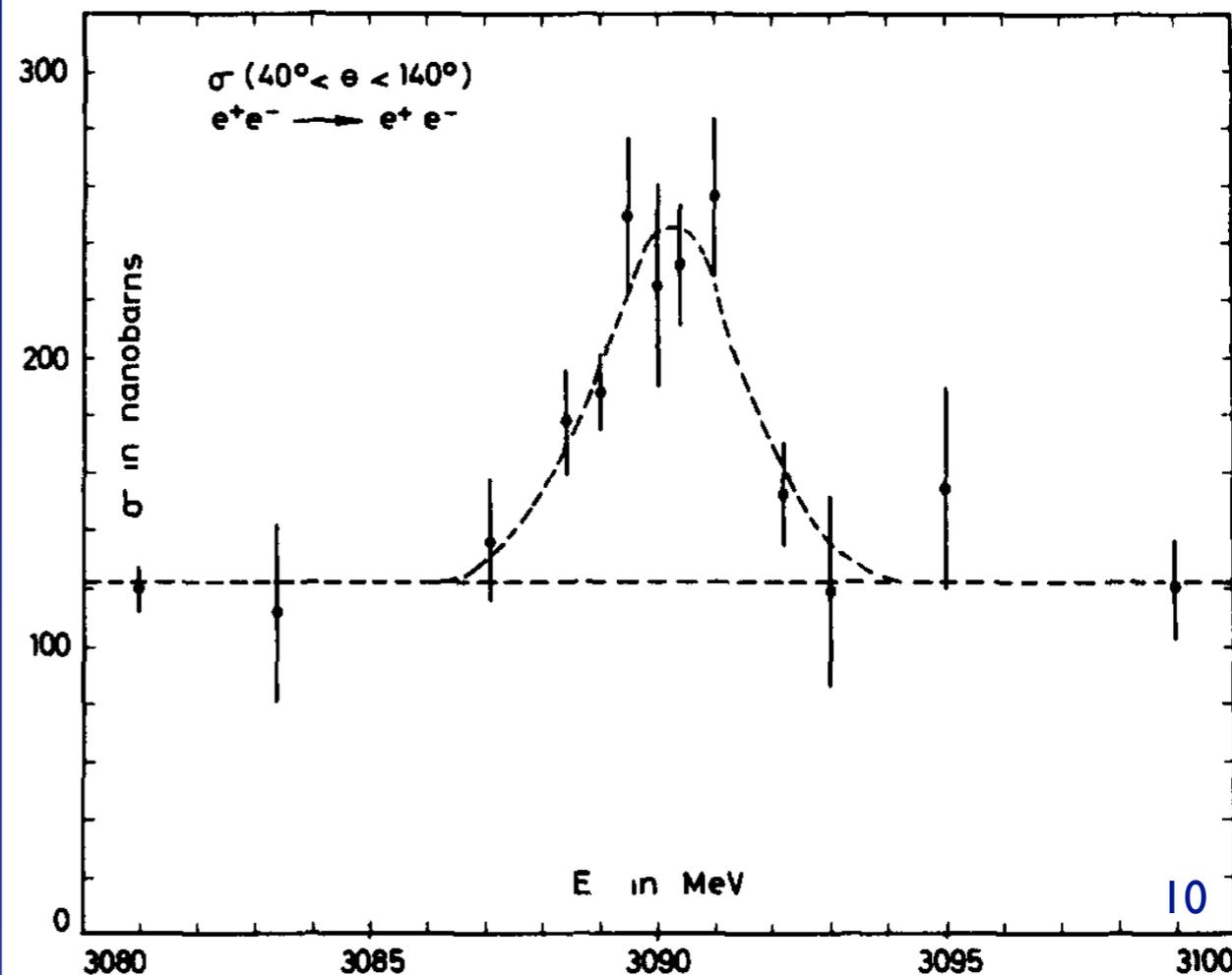
Max-Planck-Institut für Physik und Astrophysik, München

T. SUDA, Y. TOTSUKA and S. YAMADA

University of Tokyo, Tokyo

Received 19 December 1974

Elastic e^+e^- scattering has been measured at total energies covering the newly found resonance at 3100 MeV. The angular distribution is consistent with spin-parity 1^- , and the cross section integrated over energy yields $\Gamma_{ee}^2/\Gamma_{\text{tot}} = 0.23 \pm 0.05 \text{ keV}$ for the resonance.



ICHEP, London: Summer 1974

IV-50

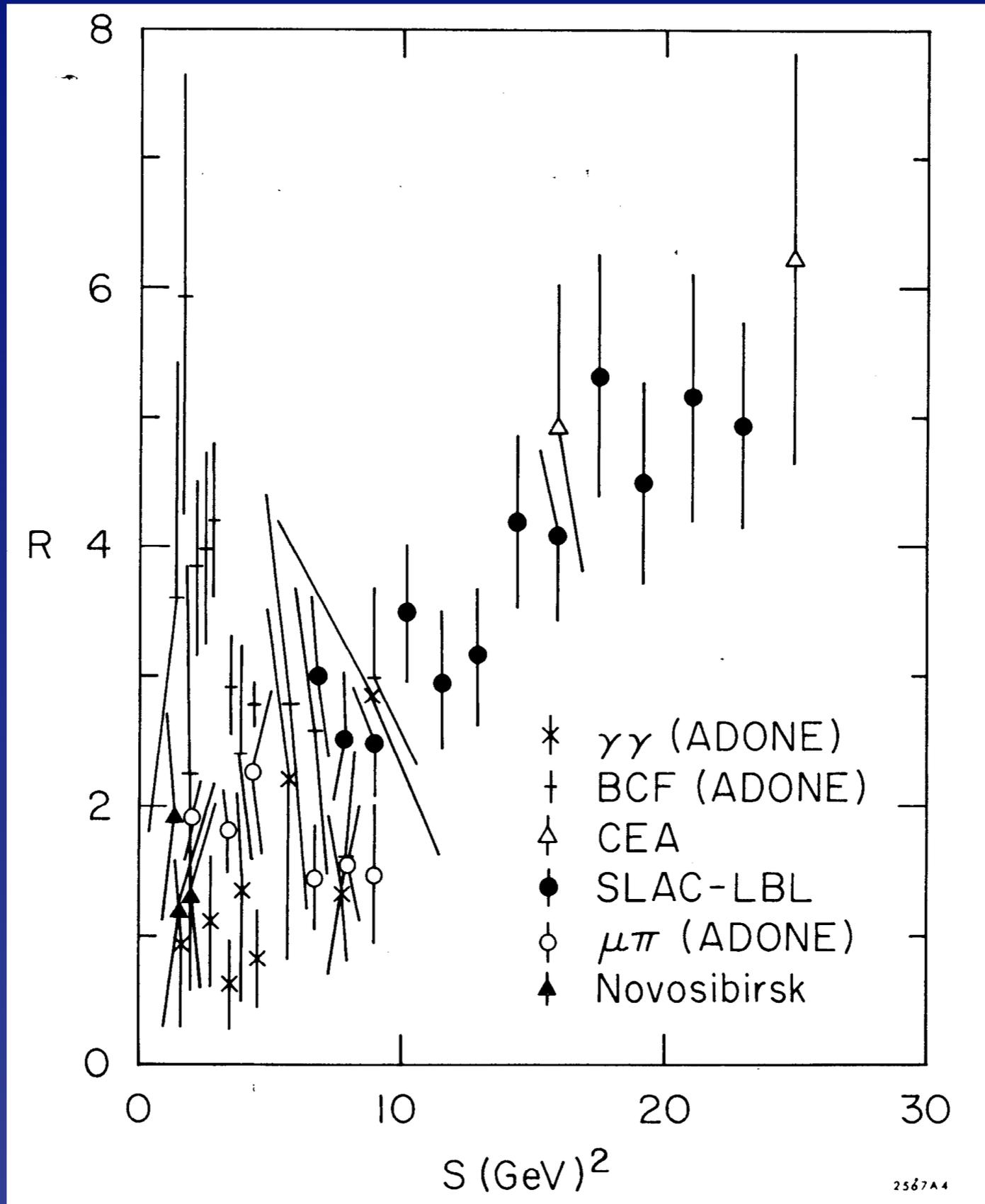
B Richter

X THEORY

The e^+e^- annihilation data contradict both the simple quark-parton model and the Bjorken scaling hypothesis. This has come as a shock for they were both doing so well - giving an understanding of multiplet structure, cross section relationships, decay branching ratios, deep inelastic electron, neutrino, and muon scattering, etc. Indeed, scaling was tested and found to work to 10% to 20 % over three orders of magnitude in the structure functions and for values of momentum transfer ranging up to 60 to 70 $(\text{GeV}/c)^2$ and values of inelasticity out to 100 GeV. Most of the 61 theoretical contributions to this session of the conference, which range from the bizarre to the ordinary, attempt to resolve the contradiction between the success of simple models in the space-like momentum transfer region and their failure in the time-like momentum transfer region.

ICHEP, London: Summer 1974

$$R \equiv \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$$



Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope

Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

E. Zavattini

CERN Laboratory, Geneva, Switzerland

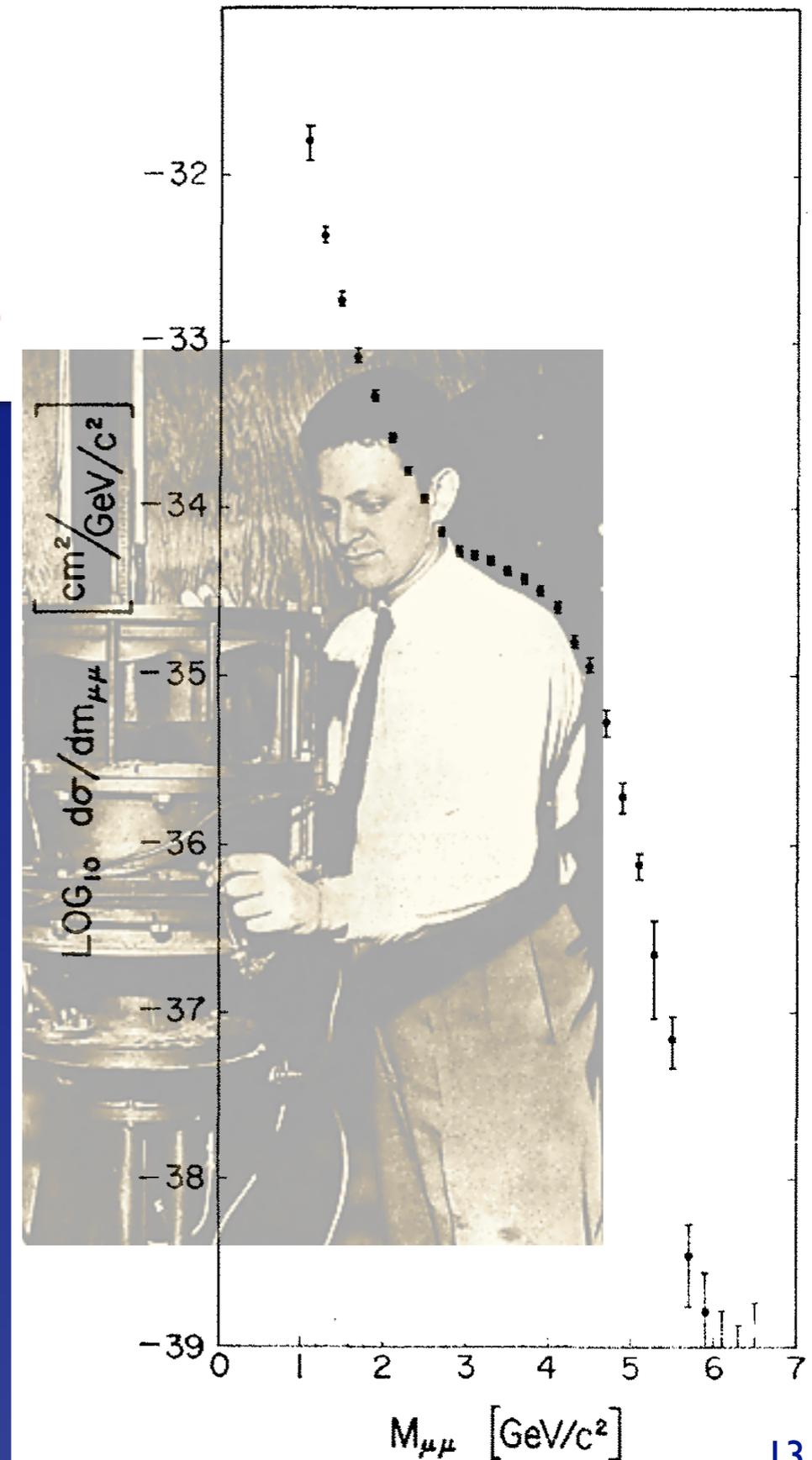
(Received 8 September 1970)

Muon pairs in the mass range $1 < m_{\mu\mu} < 6.7 \text{ GeV}/c^2$ have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}^5 \text{ cm}^2 (\text{GeV}/c)^{-2}$ and exhibits no resonant structure. The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.

Muons penetrated 10 feet of steel

“[I]n the mass region near 3.5 GeV, the observed spectrum may be reproduced by a composite of a resonance and a steeper continuum.”

History: J. Rak & M. Tannenbaum, *High- p_T Physics in the Heavy-Ion Era*, c. 7 & 8



21 NOV 1974

21 NOV 1974

00:30 HONES ALL SEEMS STABLE (FOOK FOR W)

MOON CHAMBERS FOR LOW AND DECREASING EFFICIENCY

Getting 2 spots 2 slots on 13, 14 missing 1st & 2nd side on 16.
The moon chambers are not essential for the beam but are more important for tracking and dipping. Some one ought to look into this thing.

The word signals look OK for moon chambers. All (11, 12, 13, 14, 16) have small 2nd side. Zero X-rays are coming thru 1st side. Trouble is to kill all 5 chambers. 2 ANNA's must go out. Assuming 11, 12, 13, 14, 16 HONES ARE what they need to be (11, 12, 13, 14, 16) at least 11 & 12 show no serious error problems.

70 μ (L. E) looks to be below 20% now. It is as if the μ chamber are now giving my spots near and E is steadily decreasing. No real and more "production" come in.

SOMEONE PLEASE LOOK INTO THIS IN JAN 1975

30 WE SEE A POSSIBLY SIGNIFICANT BUMP AT 1.347, 1.348 (random), LOOKS \approx 6 HON INTIM (steps are 2 HON CM). STOP RUN AT 1.348 (run)

WE WILL GO BACK OVER IT IN 1/4 STEP SIZE

03:00 Start (Hones) Run 1522

21 NOV 1974

Page 001 - 01 1/2

ψ'

47 → 0.2 cm/sec

03:20

SON OF GLORY

Chuck Mariani, Allen Litke, Bob Steg Jo it!

NOTES THE RESCAN (RUN 1522) WAS STARTED AT "1.345" OBTAINED BY RUNNING DOWN FROM 1.363, SO ENERGY OF BALL'S CORRECTED TO WELL AT RUN 1522

04:15 STOP DUMP & RUN

WIB Predicts one at 1.317!

MCC HAS COMPUTED MONITOR → NO FILL. TIME A STARTING AT 1.310.

04:30 DAWN - LMAC BACK UP, DUMP & RUN.

SP-17 DNL RUN 1522 1.35 GEV 3.9 KG CF=XXXXXXXX TL-2 A12

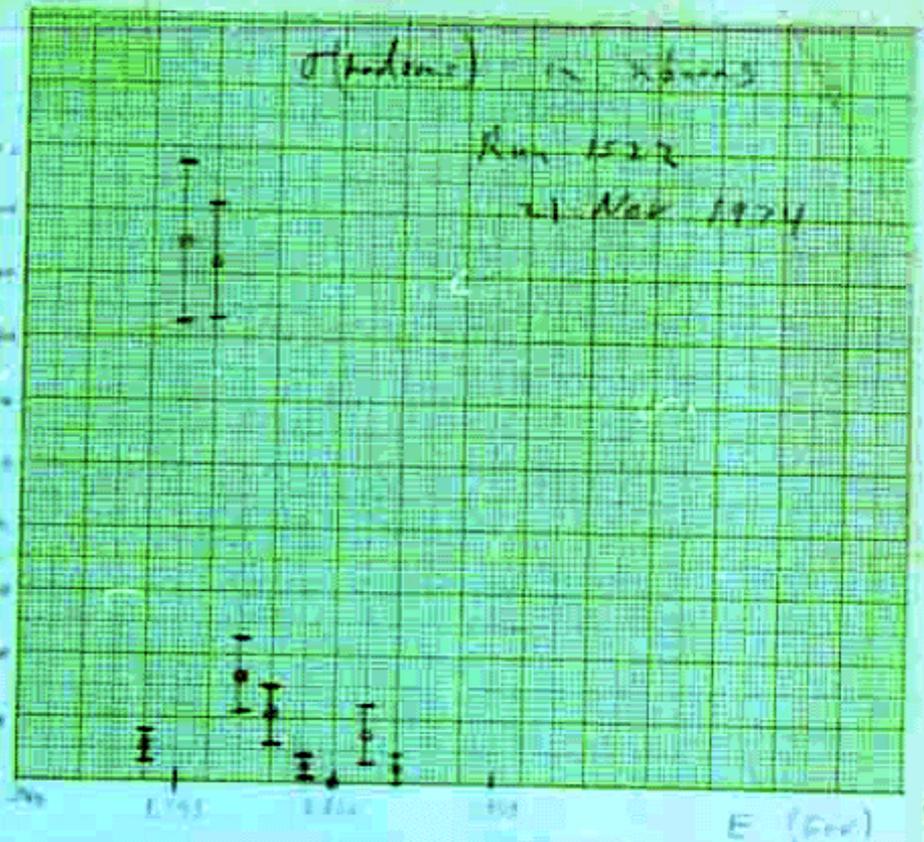
SCALERS			
1	OS TRUE	45378	10
2	OS FLSE	29	11
3	LU NO*SD	19229	12
4	LU NO*SU	26149	13
5	LIVETIME	42903	14
6		0	15
7		0	16
8		0	17
9		0	18
INTEGRATED LUMINOSITY		0	18
PITSORT		*10E 34	

	I	P	PI	MICROPIITS
E=	2.1	*143E-08	*305E-08	15.
E=	2.3	*139E-08	*319E-08	16.

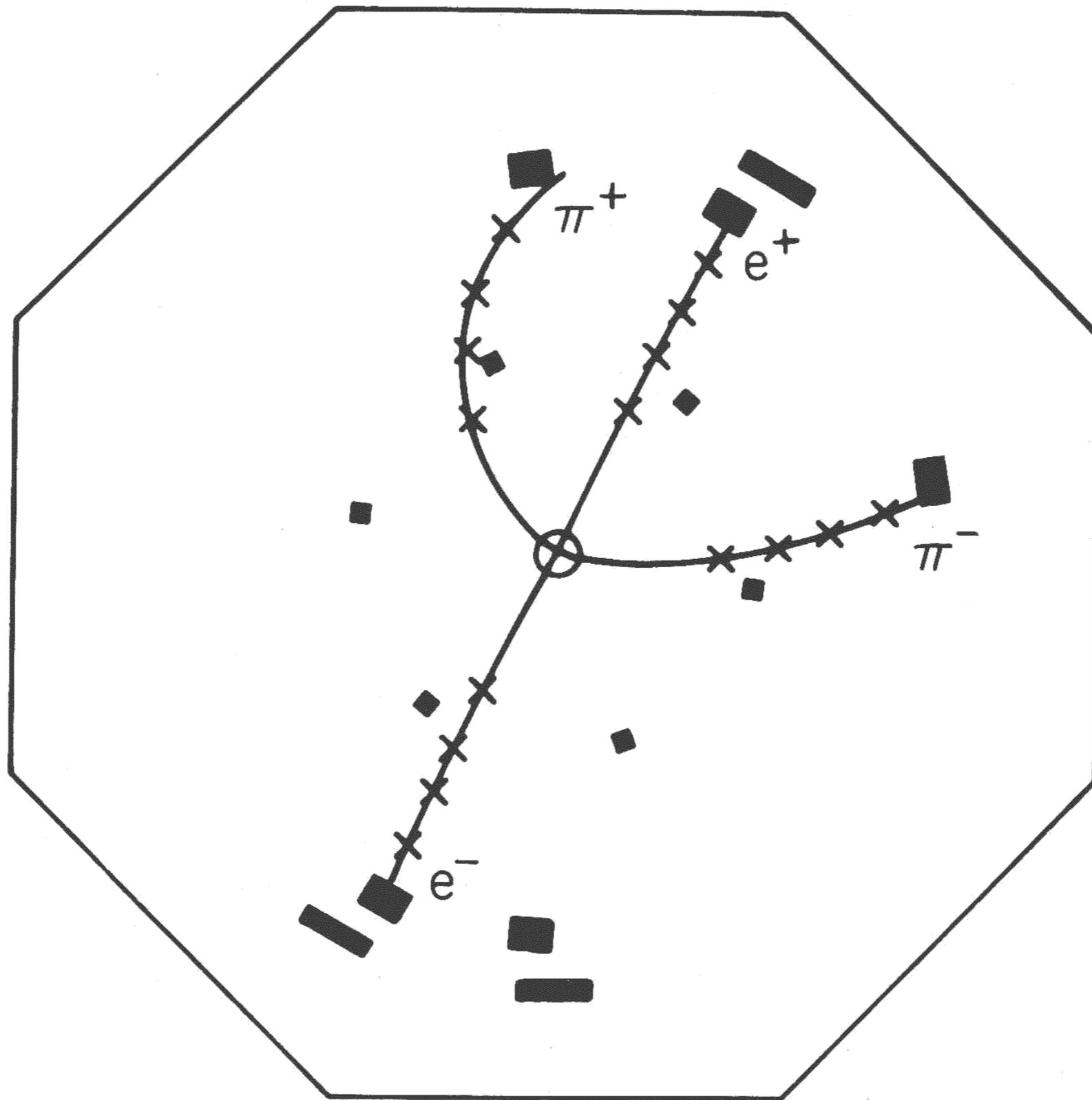
LIVETIME * 4193.40 SEC. LIVETIME FRACTION * .521
 INTEGRATED LUM * .190E 33 T/F * 1537.03
 EXPECTED MU PAIR PRODUCTION IS 5
 E * 2.000 GEV RUN 1522
 EXPECTED MU PAIR PRODUCTION IS 5
 E * 2.000 GEV RUN 1521



Alan Litke's first shift!



$$e^+e^- \rightarrow \psi' \rightarrow \pi^+\pi^- J/\psi$$



Are the New Particles Baryon-Antibaryon Nuclei?

Alfred S. Goldhaber

Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794*

and

Maurice Goldhaber

Physics Department, Brookhaven National Laboratory,† Upton, New York 11973

(Received 25 November 1974)

Baryon-antibaryon bound states and resonances could account for the new particles, as well as narrow states near nucleon-antinucleon threshold, which were reported earlier.

Note added.—The public announcement by the Stanford Linear Accelerator group of a second very sharp resonance at 3.7 GeV lends additional support to this interpretation, and diminishes the appeal of any alternative interpretation that does not provide a natural setting for more than one such particle.

Interpretation of a Narrow Resonance in e^+e^- Annihilation*

Julian Schwinger

University of California at Los Angeles, Los Angeles, California 90024

(Received 25 November 1974)

A previously published unified theory of electromagnetic and weak interactions proposed a mixing between two types of unit-spin mesons, one of which would have precisely the characteristics of the newly discovered neutral resonance at 3.1 GeV. With this interpretation, a substantial fraction of the small hadronic decay rate can be accounted for. It is also remarked that other long-lived particles should exist in order to complete the analogy with ρ^0 , ω , and ϕ .

Possible Interactions of the J Particle*

H. T. Nieh

Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794

and

Tai Tsun Wu

Gordon McKay Laboratory, Harvard University, Cambridge, Massachusetts 02138

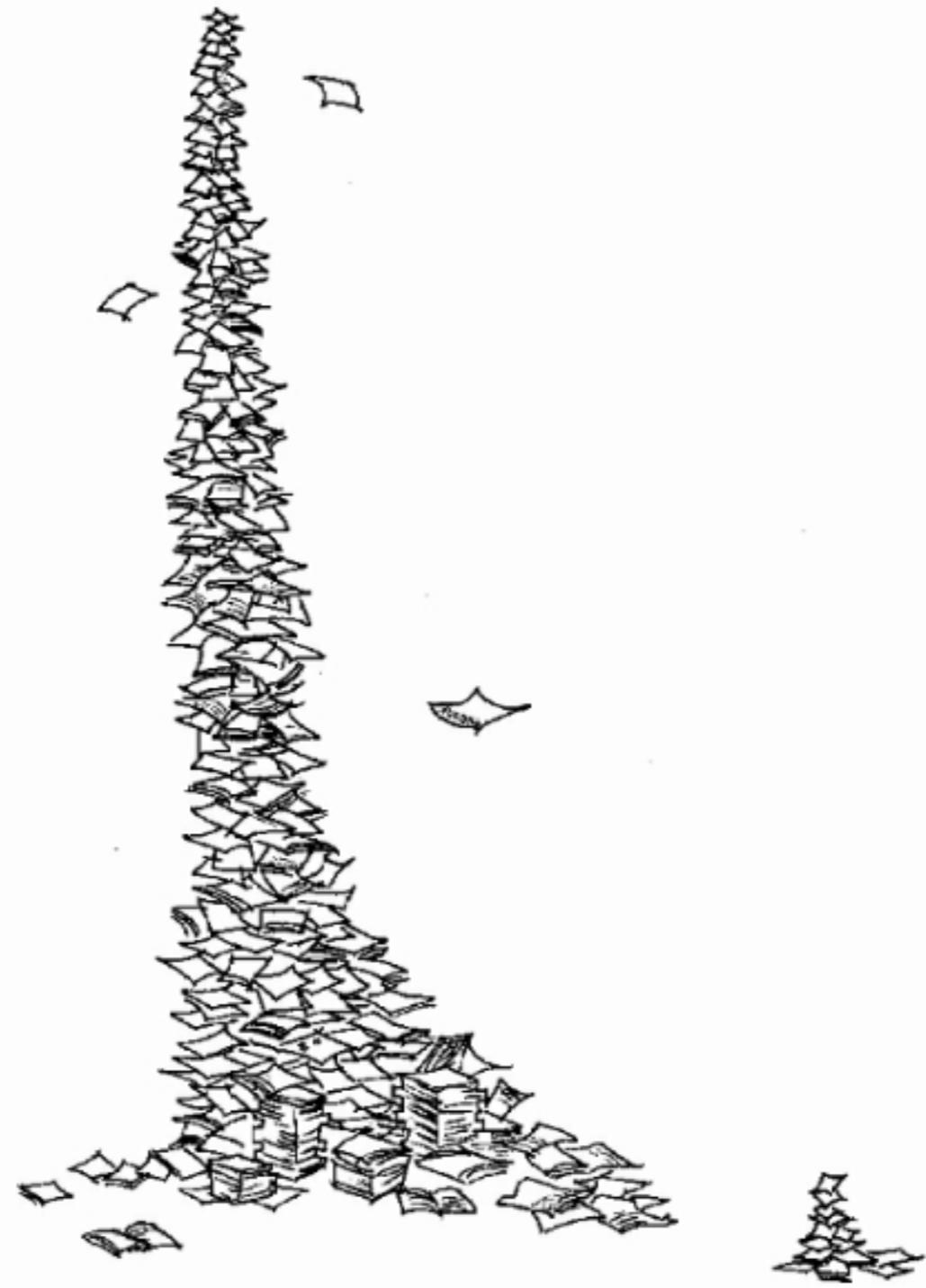
and

Chen Ning Yang

Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794

(Received 25 November 1974)

We discuss some possible interaction schemes for the newly discovered particle J and their experimental implications, as well as the possible existence of two J^0 's like the $K_S - K_L$ case. Of particular interest is the case where the J particle has strong interactions with the hadrons. In this case J can be produced by associated production in hadron-hadron collisions and also singly in relative abundance in ep and μp collisions.



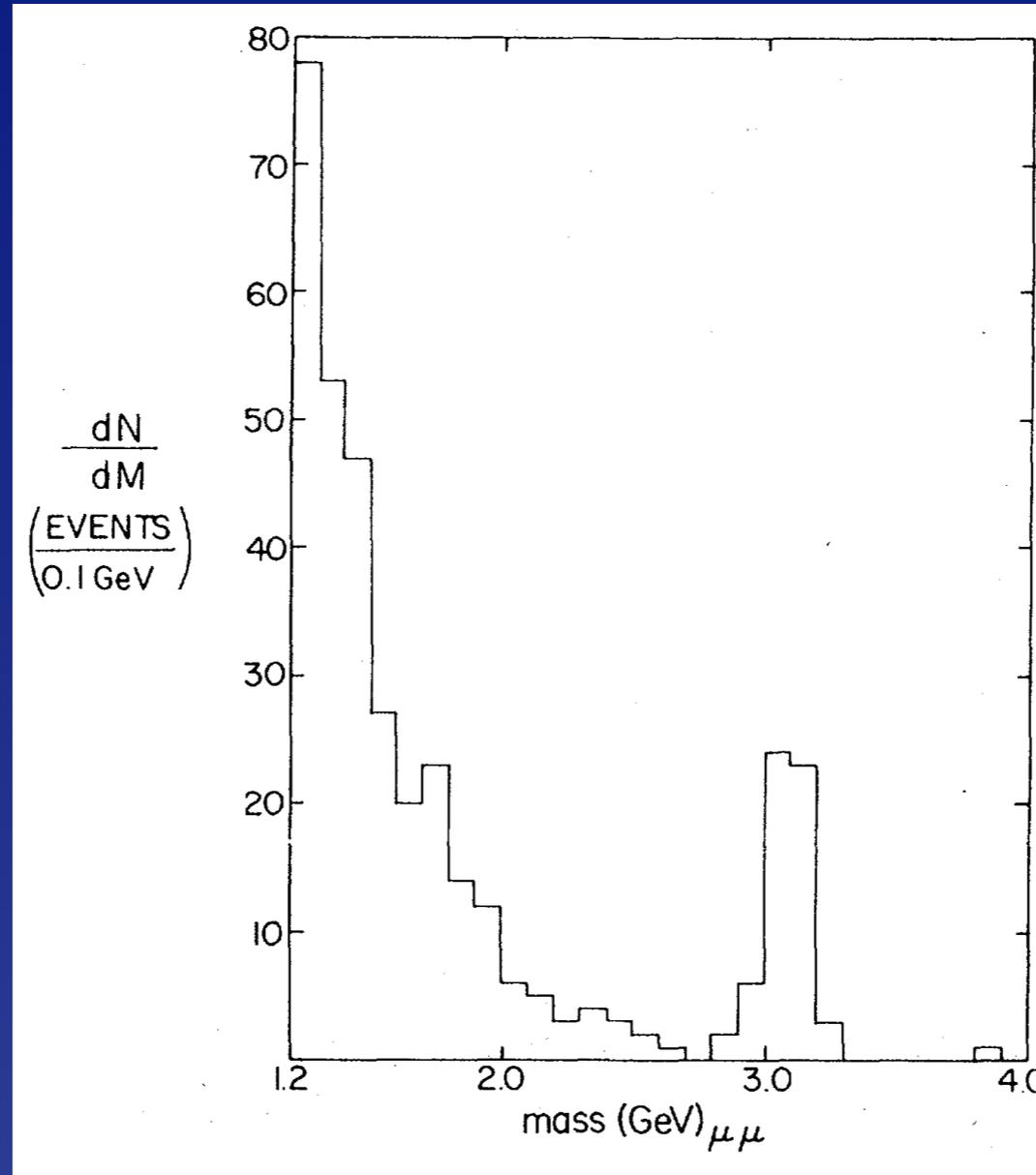
THEORY

EXPERIMENT

J. Jackson

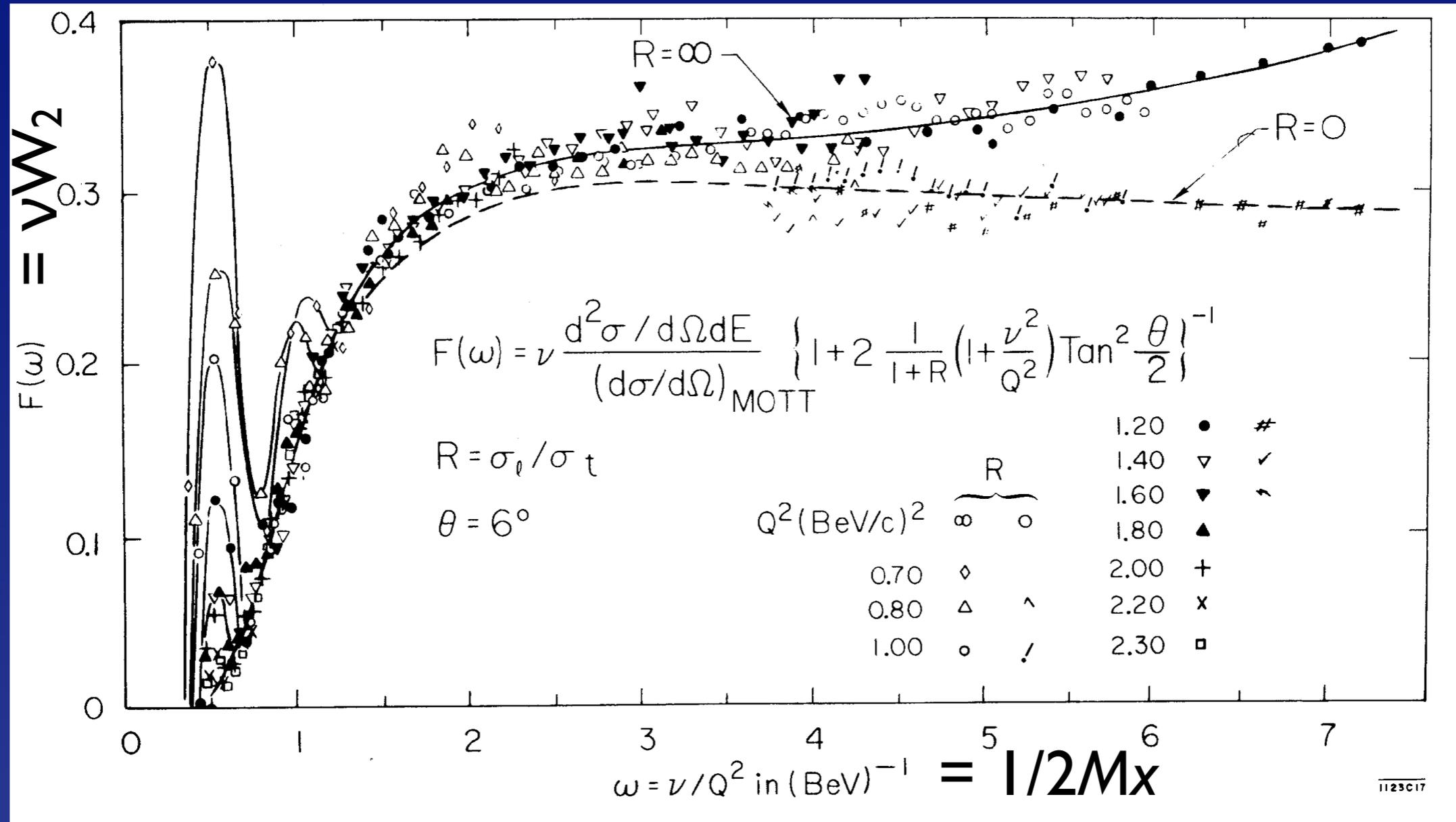
February 1975: It's a hadron!

Fermilab E87 – Broadband Photon Beam



Diffraction γ Be \rightarrow J/ ψ + ...; $\sigma(\text{J}/\psi\text{N}) \approx 1 \text{ mb}$

SLAC-MIT (Bjorken) Scaling Evidence (1968)



Quark model, parton model ...

Gargamelle (1973)

$$\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$$



Neutral currents need GIM mechanism

Search for charm

Mary K. Gaillard* and Benjamin W. Lee

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

Jonathan L. Rosner

University of Minnesota, Minneapolis, Minnesota 55455

A systematic discussion of the phenomenology of charmed particles is presented with an eye to experimental searches for these states. We begin with an attempt to clarify the theoretical framework for charm. We then discuss the $SU(4)$ spectroscopy of the lowest lying baryon and meson states, their masses, decay modes, lifetimes, and various production mechanisms. We also present a brief discussion of searches for short-lived tracks. Our discussion is largely based on intuition gained from the familiar—but not necessarily understood—phenomenology of known hadrons, and predictions must be interpreted only as guidelines for experimenters.

Preprint, August 1974:

$$\phi_c(c\bar{c}) : \quad M(\phi_c) \approx 3 \text{ GeV} \quad \Gamma(\phi_c) \approx 2 \text{ MeV}$$

$$\text{BR}(\phi_c \rightarrow e^+e^-) \approx 1\%$$

Orthocharmonium

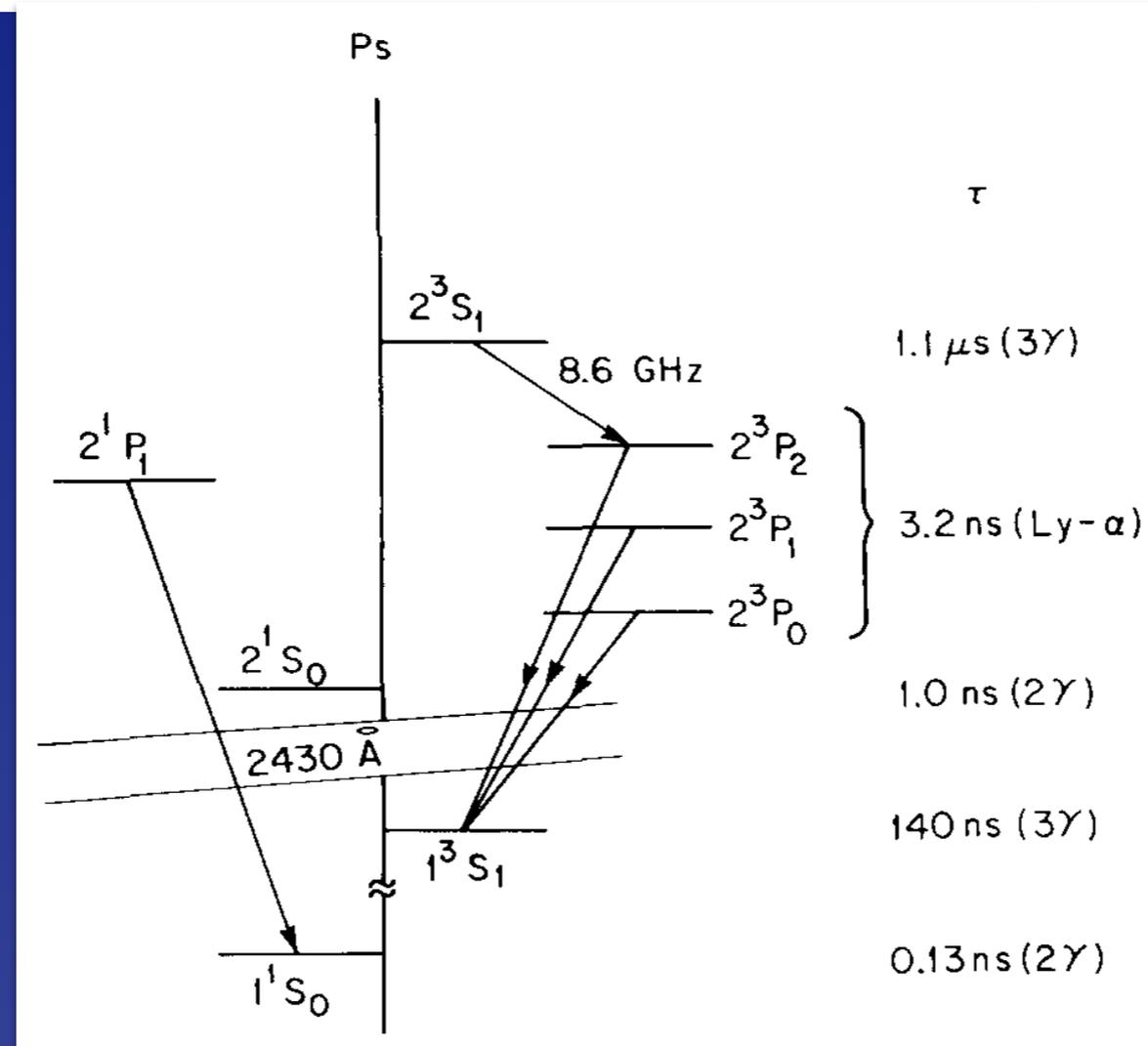
Heavy Quarks and $e^+ e^-$ Annihilation*

Thomas Appelquist† and H. David Politzer‡

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 19 November 1974)

The effects of new, heavy quarks are examined in a colored quark-gluon model. The e^+e^- total cross section scales for energies far above any quark mass. However, it is much greater than the scaling prediction in a domain about the nominal two-heavy-quark threshold, despite $\sigma_{e^+e^-}$ being a weak-coupling problem above 2 GeV. We expect spikes at the low end of this domain and a broad enhancement at the upper end.



Charmonium Spectroscopy

Spectroscopy of the New Mesons*

Thomas Appelquist,† A. De Rújula, and H. David Politzer‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

and

S. L. Glashow§
Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 11 December 1974)

The interpretation of the narrow boson resonances at 3.1 and 3.7 GeV as charmed quark-antiquark bound states implies the existence of other states. Some of these should be copiously produced in the radiative decays of the 3.7-GeV resonance. We estimate the masses and decay rates of these states and emphasize the importance of γ -ray spectroscopy.

The Spectrum of Charmonium

Spectrum of Charmed Quark-Antiquark Bound States*

E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 17 December 1974)

The discovery of narrow resonances at 3.1 and 3.7 GeV and their interpretation as charmed quark-antiquark bound states suggest additional narrow states between 3.0 and 4.3 GeV. A model which incorporates quark confinement is used to determine the quantum numbers and estimate masses and decay widths of these states. Their existence should be revealed by γ -ray transitions among them.

Cornell group (Eichten et al.)

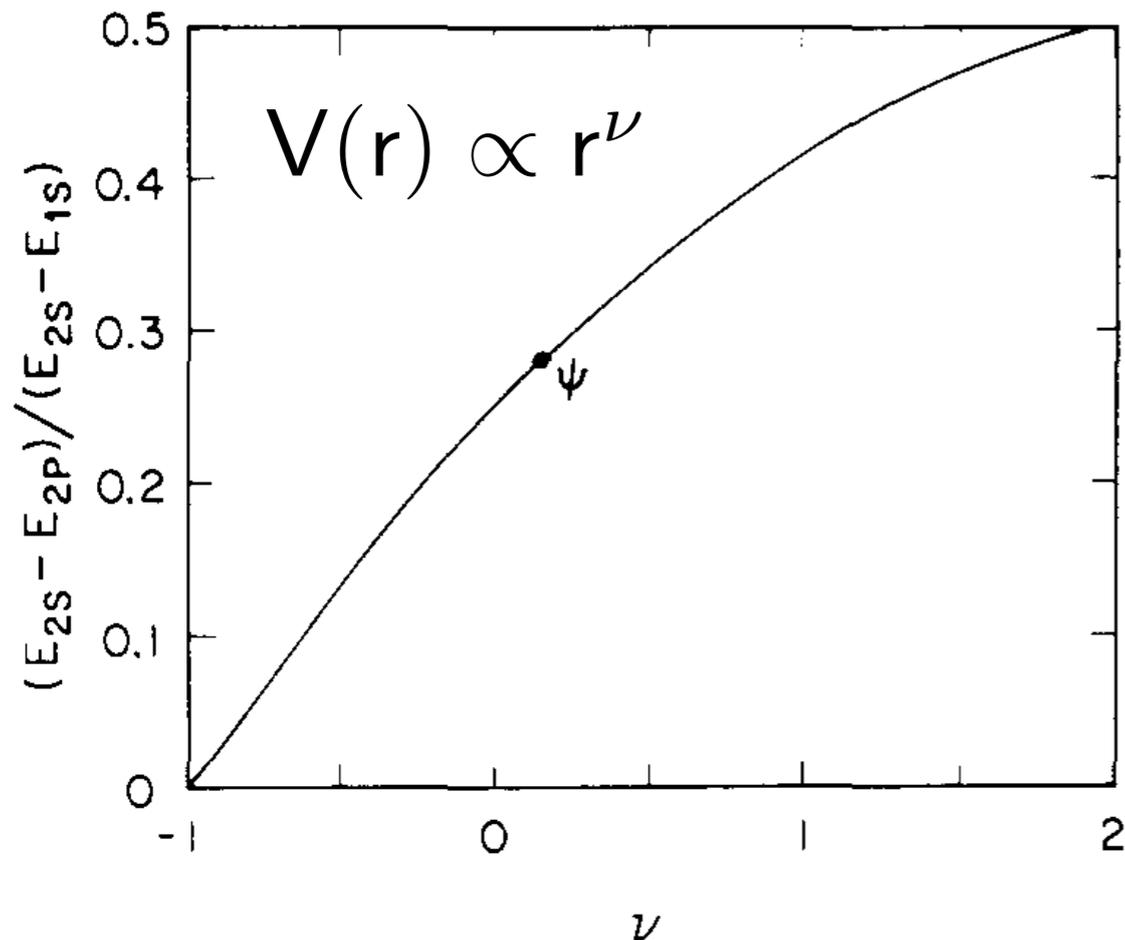


OBSERVATION OF THE TWO PHOTON CASCADE $3.7 \rightarrow 3.1 + \gamma\gamma$ VIA AN INTERMEDIATE STATE P_c

DASP-Collaboration

Received 22 July 1975

The two photon cascade decay of the 3.7 GeV resonance into the 3.1 GeV resonance has been observed in two nearly independent experiments. The clustering of the photon energies around 160 MeV and 420 MeV observed in the channel $3.7 \rightarrow (3.1 \rightarrow \mu^+\mu^-) + \gamma\gamma$ indicates the existence of at least one intermediate state with even charge conjugation at a mass around 3.52 GeV or 3.26 GeV.



$\psi(3684)$ Radiative Decays to High-Mass States*

G. J. Feldman, B. Jean-Marie, B. Sadoulet, F. Vannucci,† G. S. Abrams, A. M. Boyarski, M. Breidenbach, F. Bulos, W. Chinowsky, C. E. Friedberg, G. Goldhaber, G. Hanson, D. L. Hartill,‡ A. D. Johnson, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,§ B. A. Lulu, V. Lüth, H. L. Lynch, C. C. Morehouse, J. M. Paterson, M. L. Perl, F. M. Pierre,|| T. P. Pun, P. Rapidis, B. Richter, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 11 August 1975)

We present experimental evidence for the existence of the decay $\psi(3684) \rightarrow \gamma\chi$, $\chi \rightarrow 4\pi^\pm$, $6\pi^\pm$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-$, and K^+K^- . There is clear evidence for at least two χ states, one at $3.41 \pm 0.01 \text{ GeV}/c^2$ and the other at $3.53 \pm 0.02 \text{ GeV}/c^2$. The $\chi(3410)$ decays into $\pi\pi$ and KK and thus must have even spin and parity.

Laplacian of potential gives order of levels



$$\Gamma(\psi(2S) \rightarrow \gamma\chi_c) \approx 3\Gamma(\psi(2S) \rightarrow ggg)$$

Charmonium: hadronic transitions

$$\text{BR}(\psi(2S) \rightarrow \pi^+ \pi^- J/\psi) \approx 34\%$$

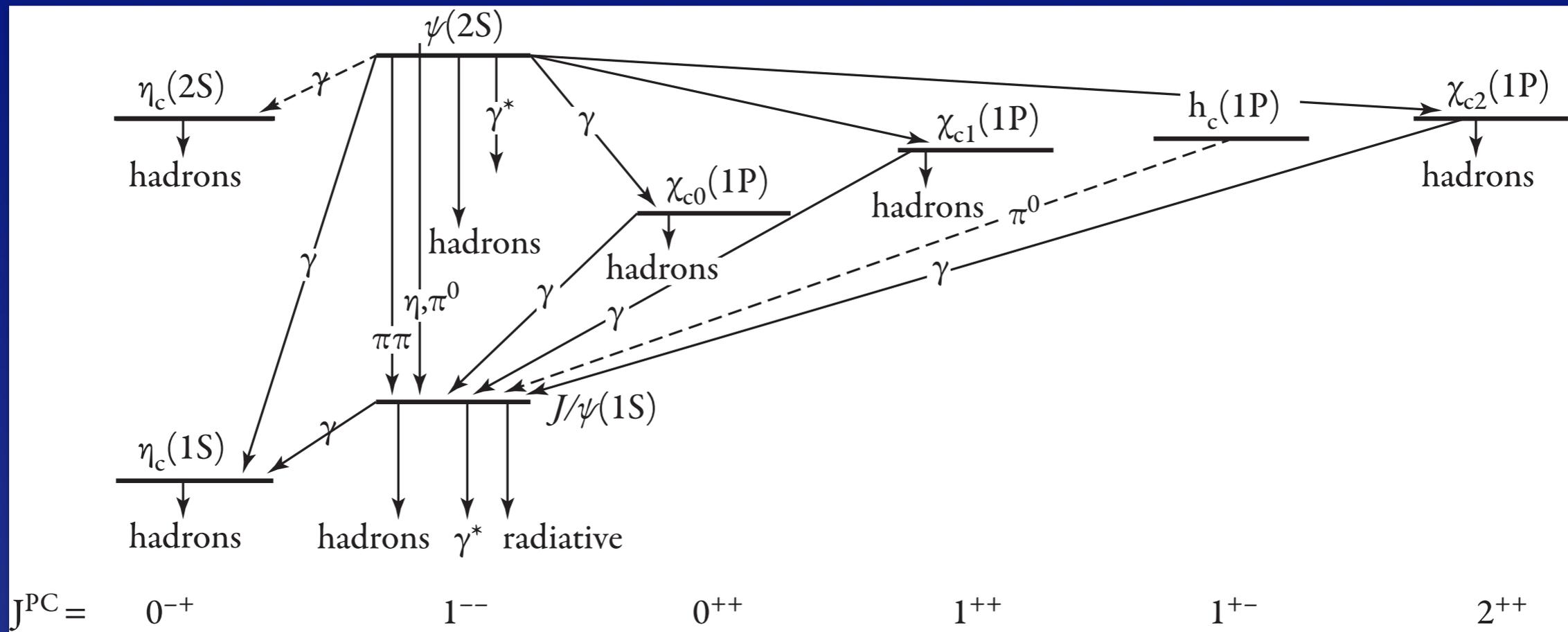
$$\text{BR}(\psi(2S) \rightarrow \pi^0 \pi^0 J/\psi) \approx 18\%$$

Soft-pion theorems

Gottfried's color multipole expansion

Good understanding of 2S-1S;
other Υ transitions, not so simple

Charmonium: the classic states



Nearly coincident thresholds for τ and charm

J. L. Rosner, "The Arrival of Charm"

M. L. Perl, "Reflections on the Discovery of the Tau Lepton"

B.W. Lee & CQ, "An Experimental Fable" — μ, π discovery in e^+e^-

Charmonium Issues

What is it? *Open charm*
Spectrum

Transitions: EM, hadronic

Decays: γ^* , gg, ggg; new forces or products?

Production: direct, cascade, *B*-decays, ...

Initial Charmonium Lessons

Quarks are real mechanical objects

Constituents are spin-1/2

Charm exists; $\psi(3770) \rightarrow D\bar{D}$

Asymptotic freedom gains support

Nonrelativistic quantum mechanics applies

Confining potential implicated

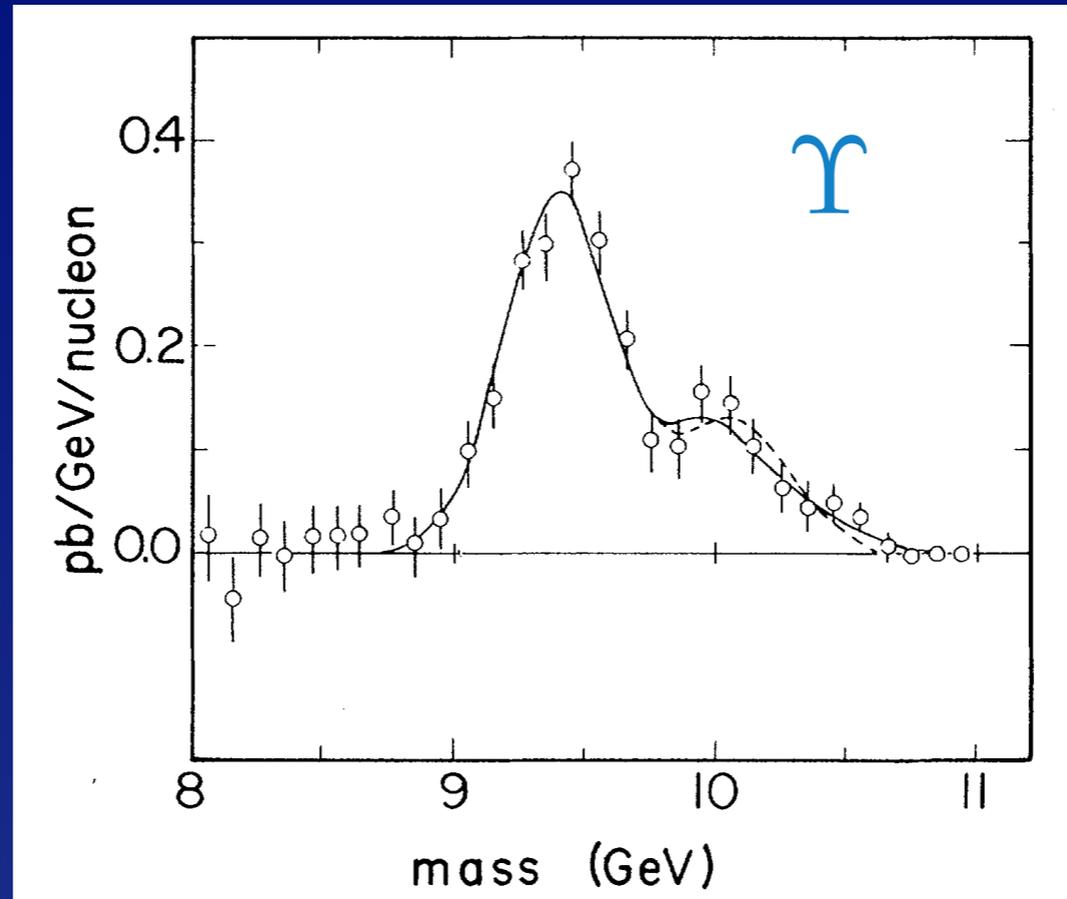
Fermilab E288 Proposal, February 1974

A Study of Di-Lepton Production in Proton Collisions at NAL Lederman et al.

1. Observe and measure the spectrum of virtual photons emitted in p-nucleon collisions via the mass distribution of e^+e^- pairs: $p + p \rightarrow e^+ e^- + \text{anything}$. (1)
Study characteristics, e.g. parity violation, p_{\perp} behavior.
2. Search for structures in the above spectrum, publish these and become famous, e.g. W^0 , B^0 .
3. Qualitatively study the mass spectrum of hadron pairs ($\pi\pi$, πp , etc). This is an interesting background for (1). It uses a crude hadron calorimeter, also required for hadron rejection in (1).
4. Check μe universality by looking, in the same arrangement but with the addition of a pion filter, at $\mu^+\mu^-$ pairs.
5. Extend the Experiment #70 study of single leptons in the double arm arrangement, i.e. W^{\pm} etc. Publish these and become famous.
6. Look at $\pi^0\pi^0$ pairs by double conversion of $\pi^0 \rightarrow \gamma\gamma$ in thin aluminum radiators. This data comes free since one adds 0.1 radiation length to enable an extrapolation to zero target thickness in (1).

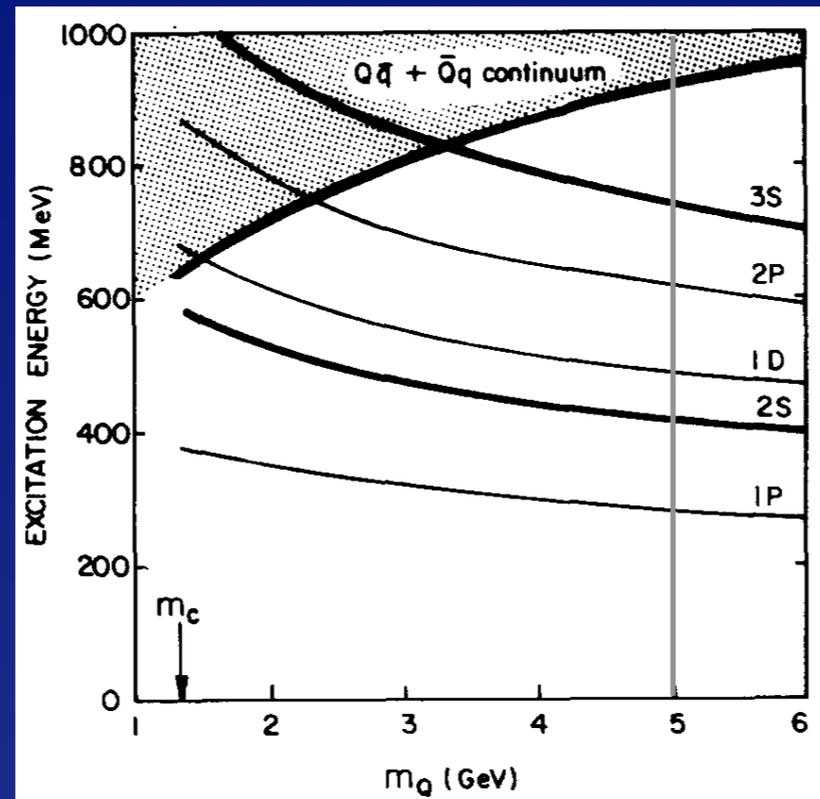
EPS Budapest 1977





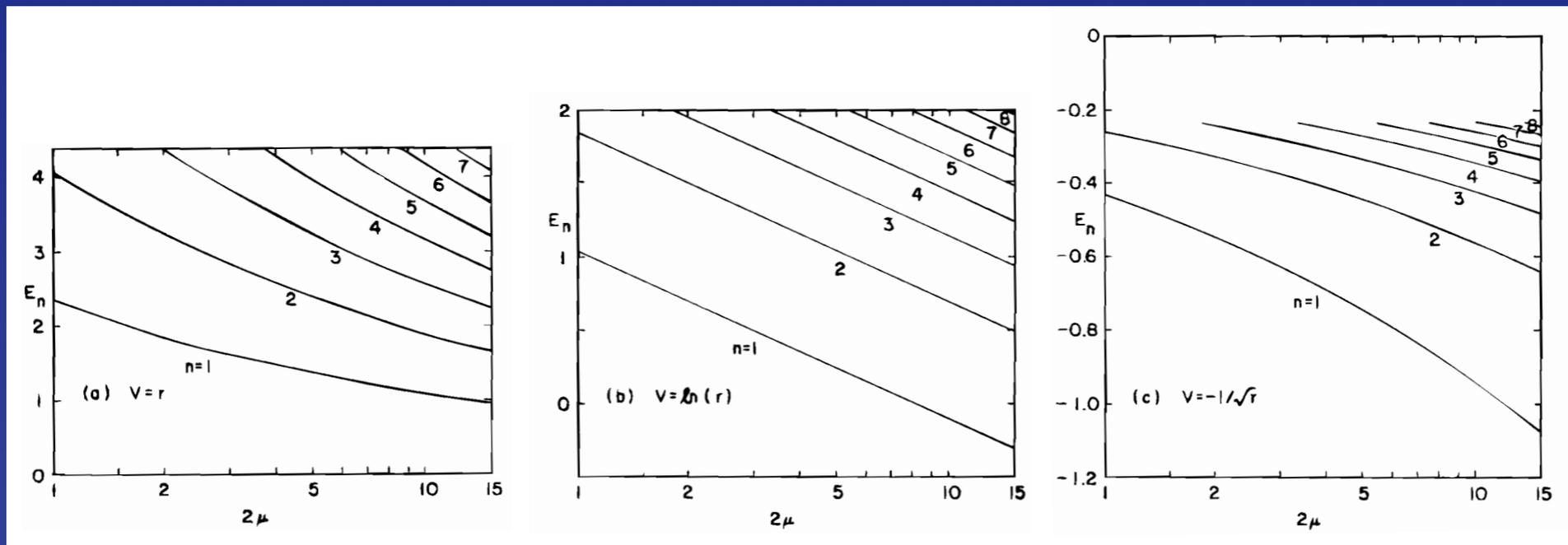
E288	$M(\Upsilon') - M(\Upsilon)$	$M(\Upsilon'') - M(\Upsilon)$
Two-level fit	650 ± 30 MeV	
Three-level fit	610 ± 40 MeV	1000 ± 120 MeV
$M(\psi') - M(\psi)$	≈ 590 MeV	

Eichten & Gottfried: CESR Proposal (November 1976)



$$E(2S) - E(1S) = 420 \text{ MeV}$$

General: # of narrow 3S_1 levels: $M_Q^{1/2}$



Why choose 5 GeV?

Excess events at high inelasticity in

$$\bar{\nu}_\mu N \rightarrow \mu^+ + \dots$$

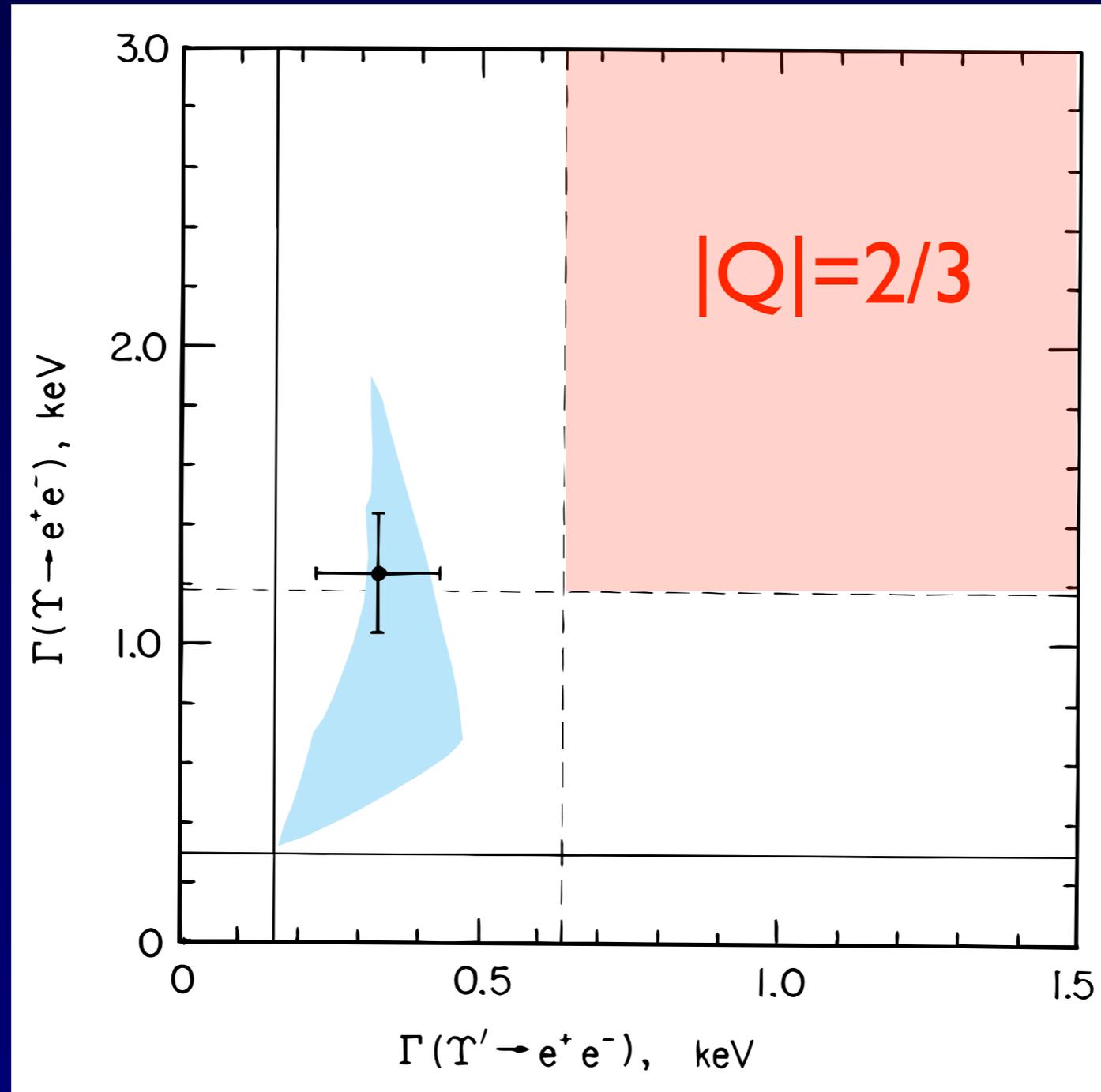
HPWF “high- y anomaly” explained by

$$\begin{pmatrix} u \\ b \end{pmatrix}_R m_b \approx (4 - 5) \text{ GeV} \quad \text{Barnett}$$

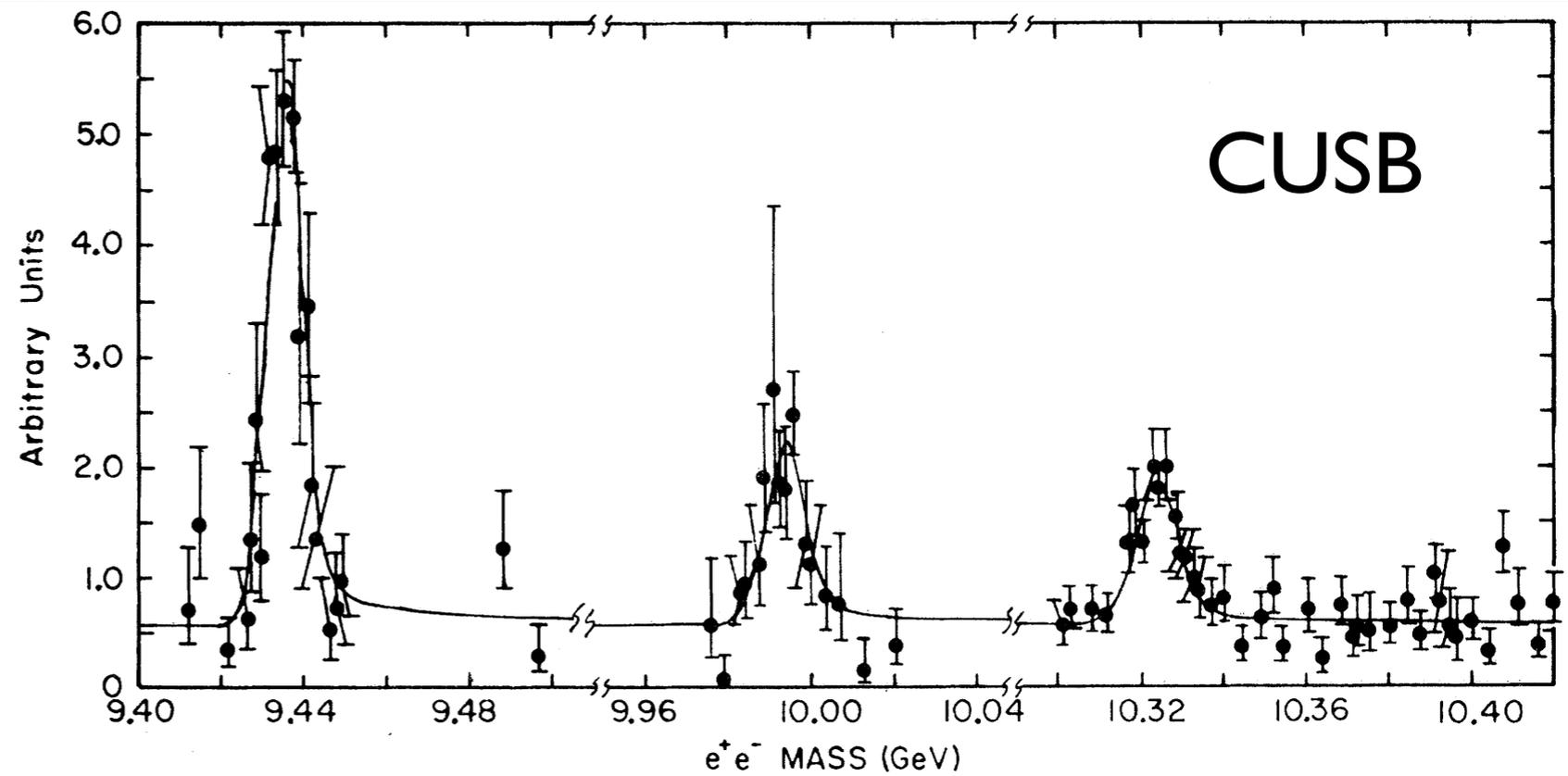
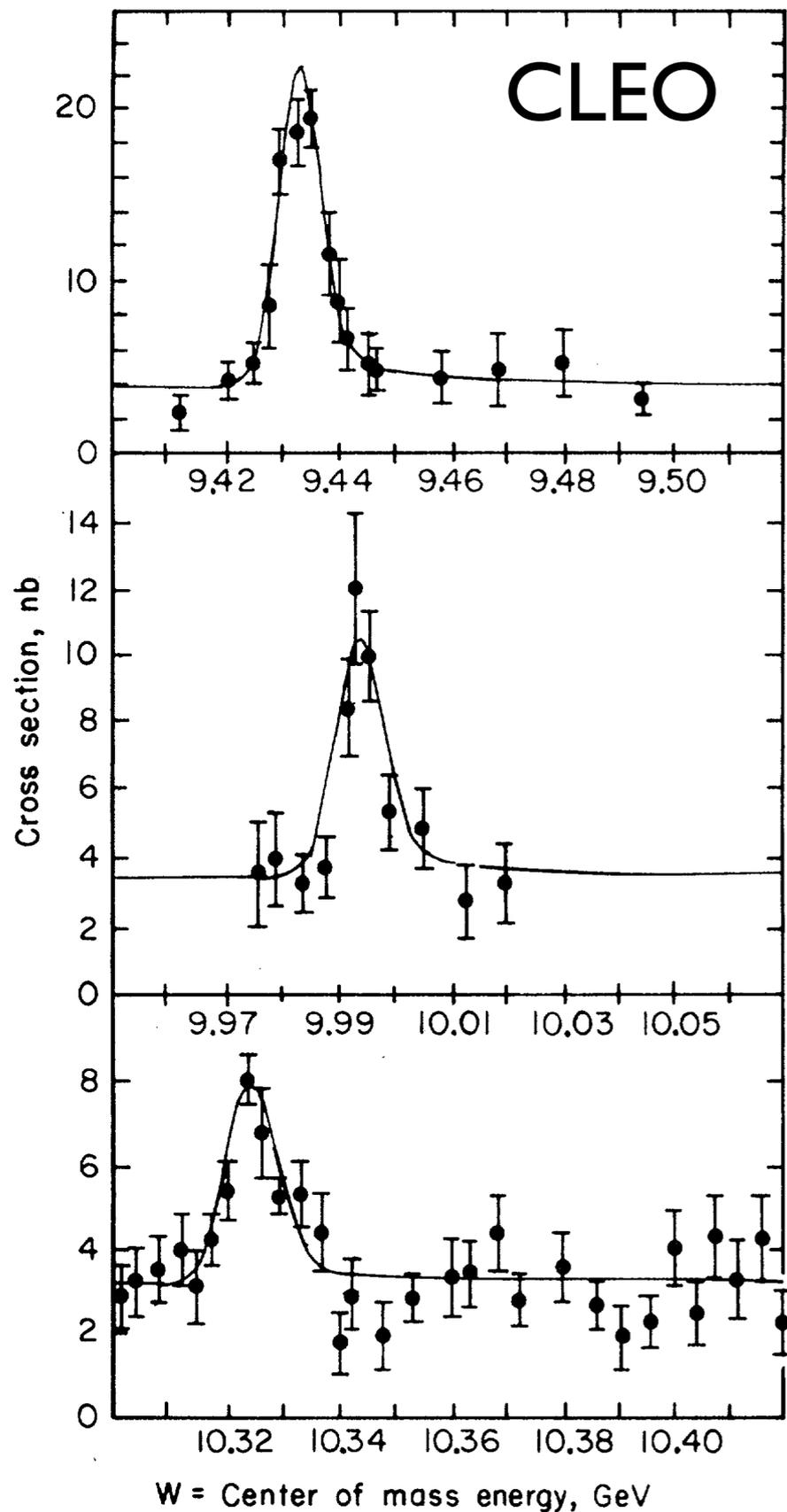
Also at Budapest ...

CDHS Experiment ruled out high- y anomaly

1978: DORIS leptonic widths imply $Q_b = -1/3$

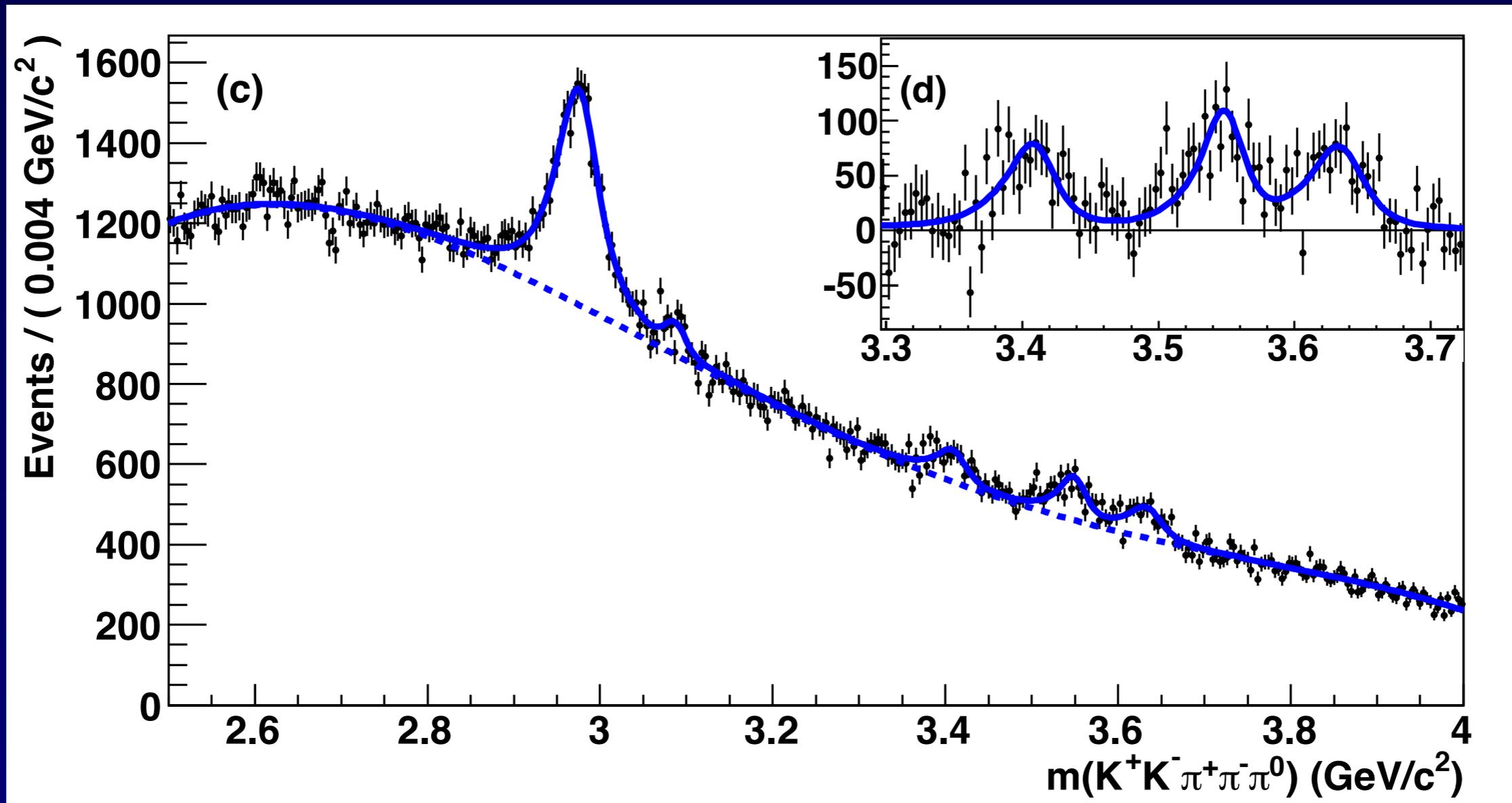


CESR resolves 3 Υ levels 1979-80



$\Upsilon(4S)$ launches B physics 1980

BaBar $\eta_c(1S)$, $\chi_{c0}(1P)$, $\chi_{c2}(1P)$, $\eta_c(2S)$ in $\gamma\gamma$



CDF : $\gamma P \rightarrow J/\psi, \psi', PP \rightarrow \chi_{c0}$

Charmonium formation in $\bar{p}p$ annihilation

48

Fermilab E835 Collaboration / Physics Letters B 566 (2003) 45–50

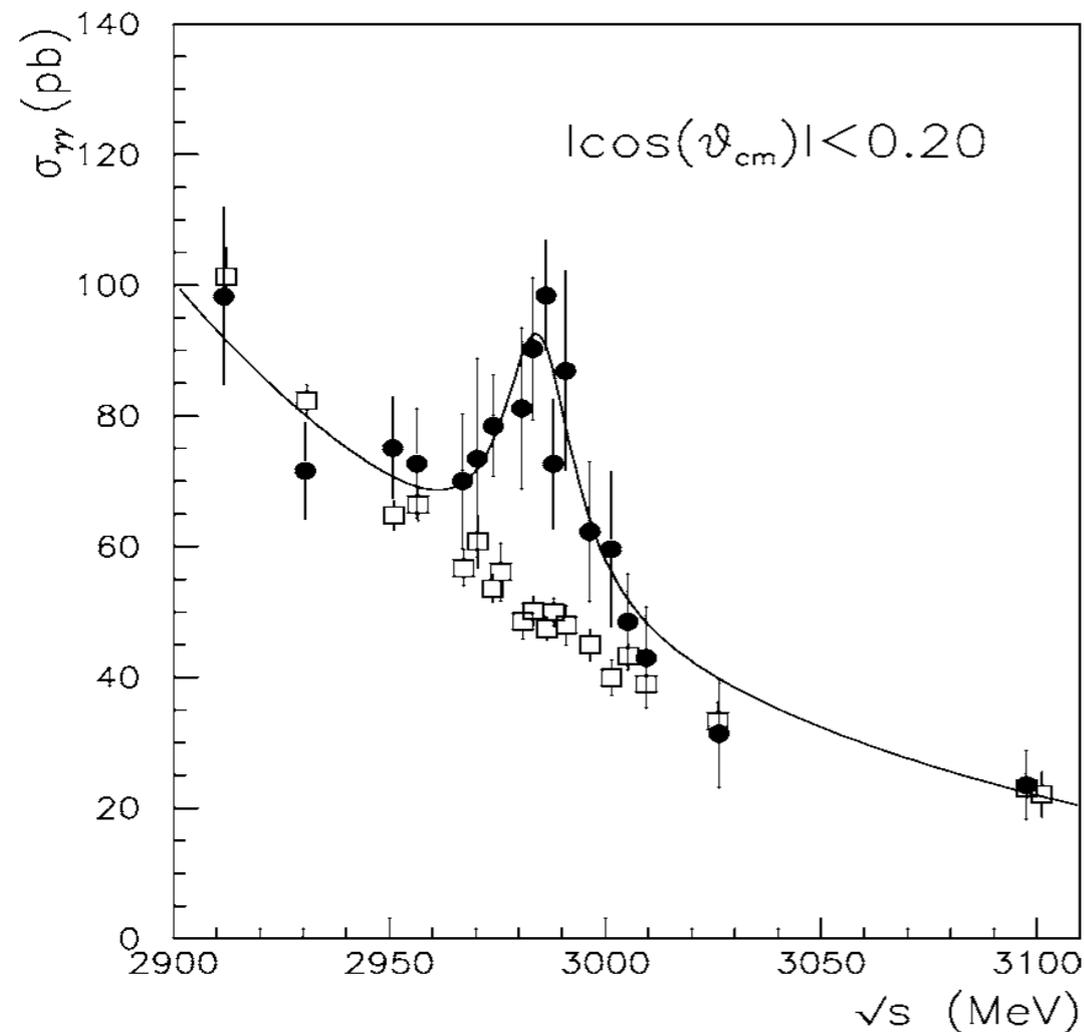


Table 1

Resonance parameters for the η_c . The first error is the statistical error from the fit and the second is the systematic uncertainty. The quantities with asterisks are obtained using $B(\eta_c \rightarrow \bar{p}p)$ from the literature [4]

Parameter	Value
$M(\eta_c) \text{ MeV}/c^2$	$2984.1 \pm 2.1 \pm 1.0$
$\Gamma(\eta_c) \text{ MeV}$	$20.4^{+7.7}_{-6.7} \pm 2.0$
$B_{in} B_{out} \times 10^8$	$22.4^{+3.8}_{-3.7} \pm 2.0$
$B_{in} \Gamma(\eta_c \rightarrow \gamma\gamma) \times 10^3 \text{ keV}$	$4.6^{+1.3}_{-1.1} \pm 0.4$
* $\Gamma_{\gamma\gamma}(\eta_c) \text{ keV}$	$3.8^{+1.1+1.9}_{-1.0-1.0}$
* $B(\eta_c \rightarrow \gamma\gamma) \times 10^4$	$1.87 \pm 0.32^{+0.95}_{-0.50}$

$$\delta s^{1/2} \approx 300 \text{ keV}$$

Initial Upsilon Lessons

Requires *one* new quark species

Interquark interaction is flavor-independent

Potential shape measured

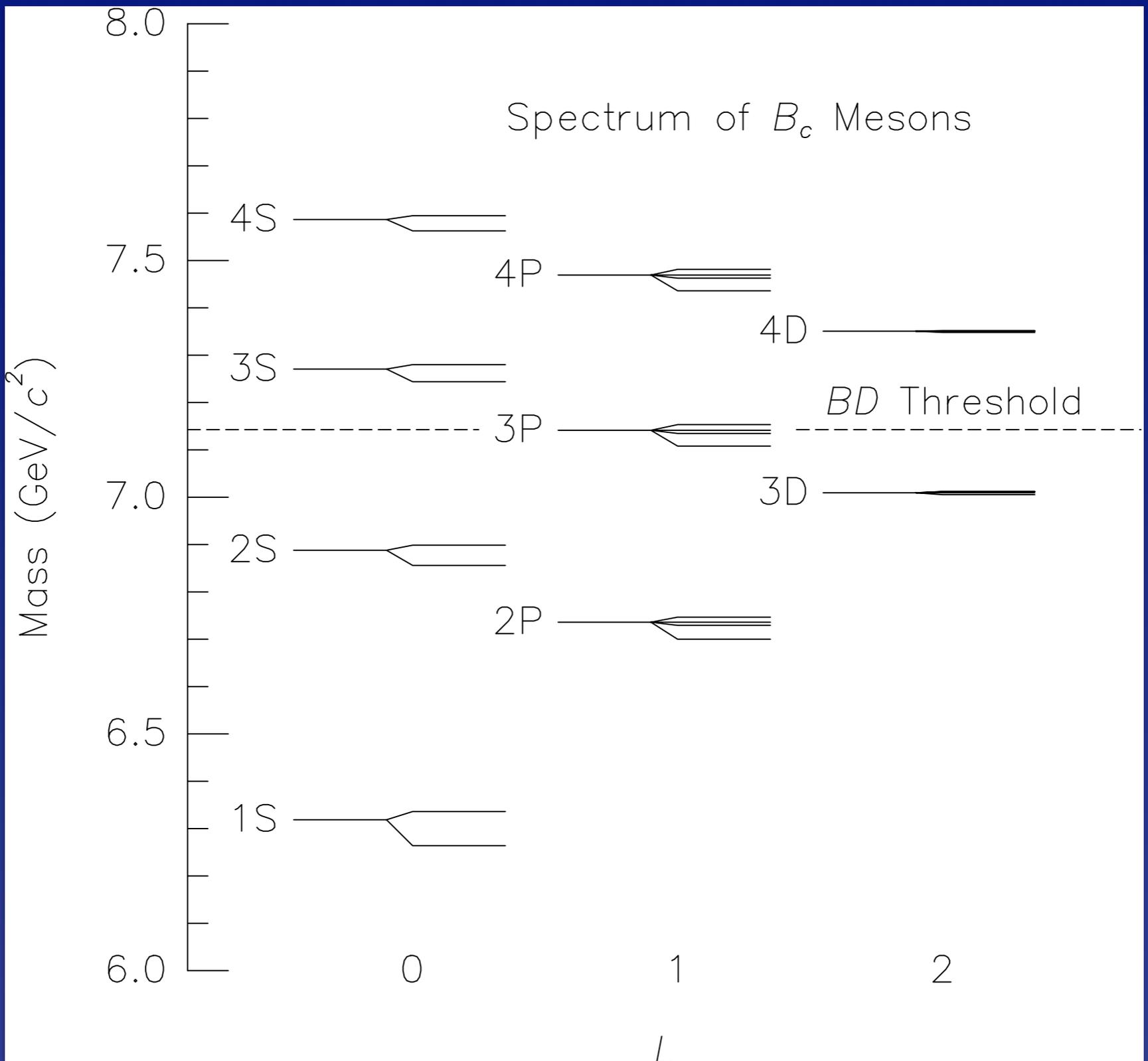
$\Upsilon(4S)$ is a fountain of B mesons

Υ decays allow new-particle searches

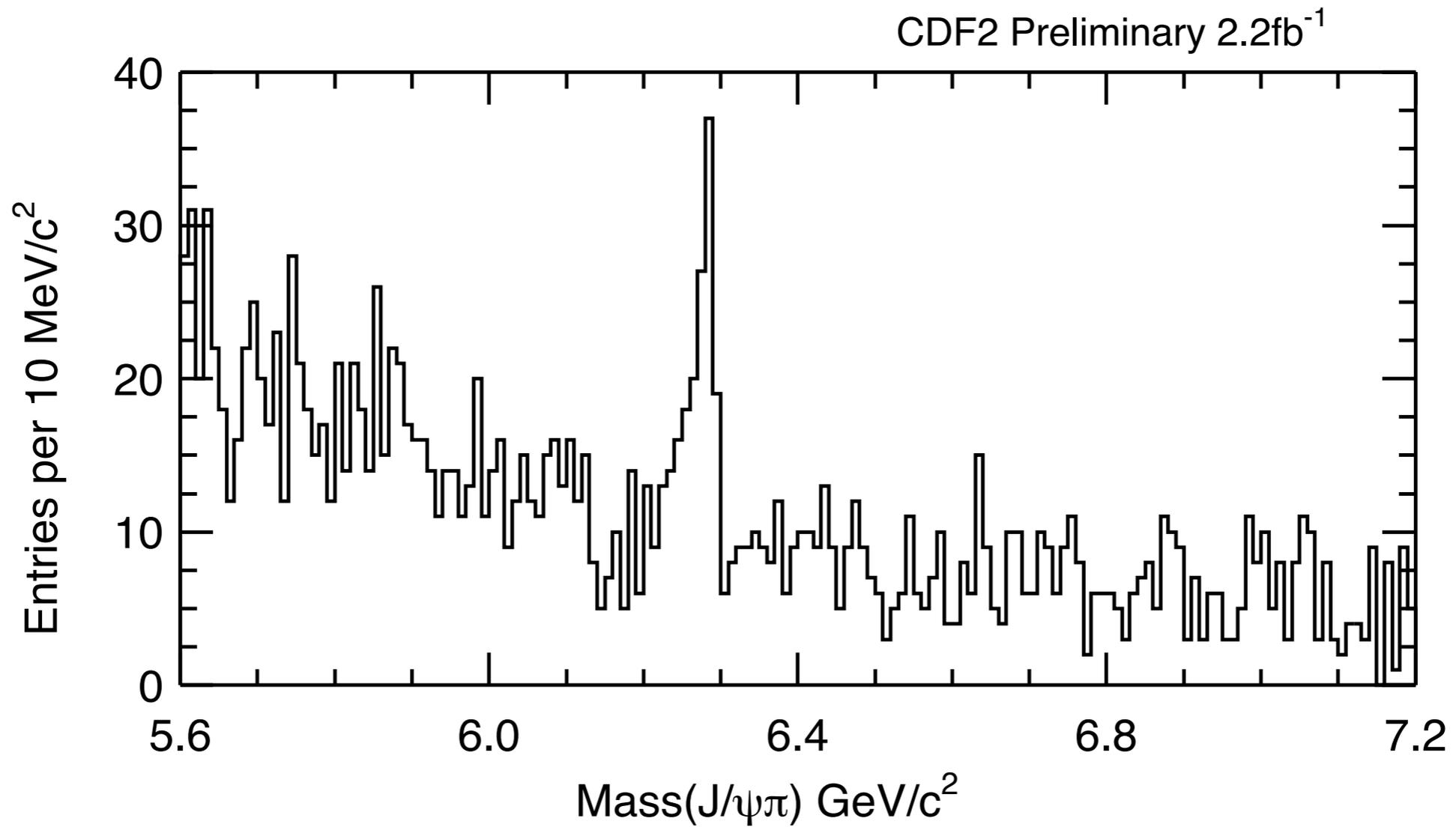
$\Upsilon(5S)$ a source of B_s mesons

...

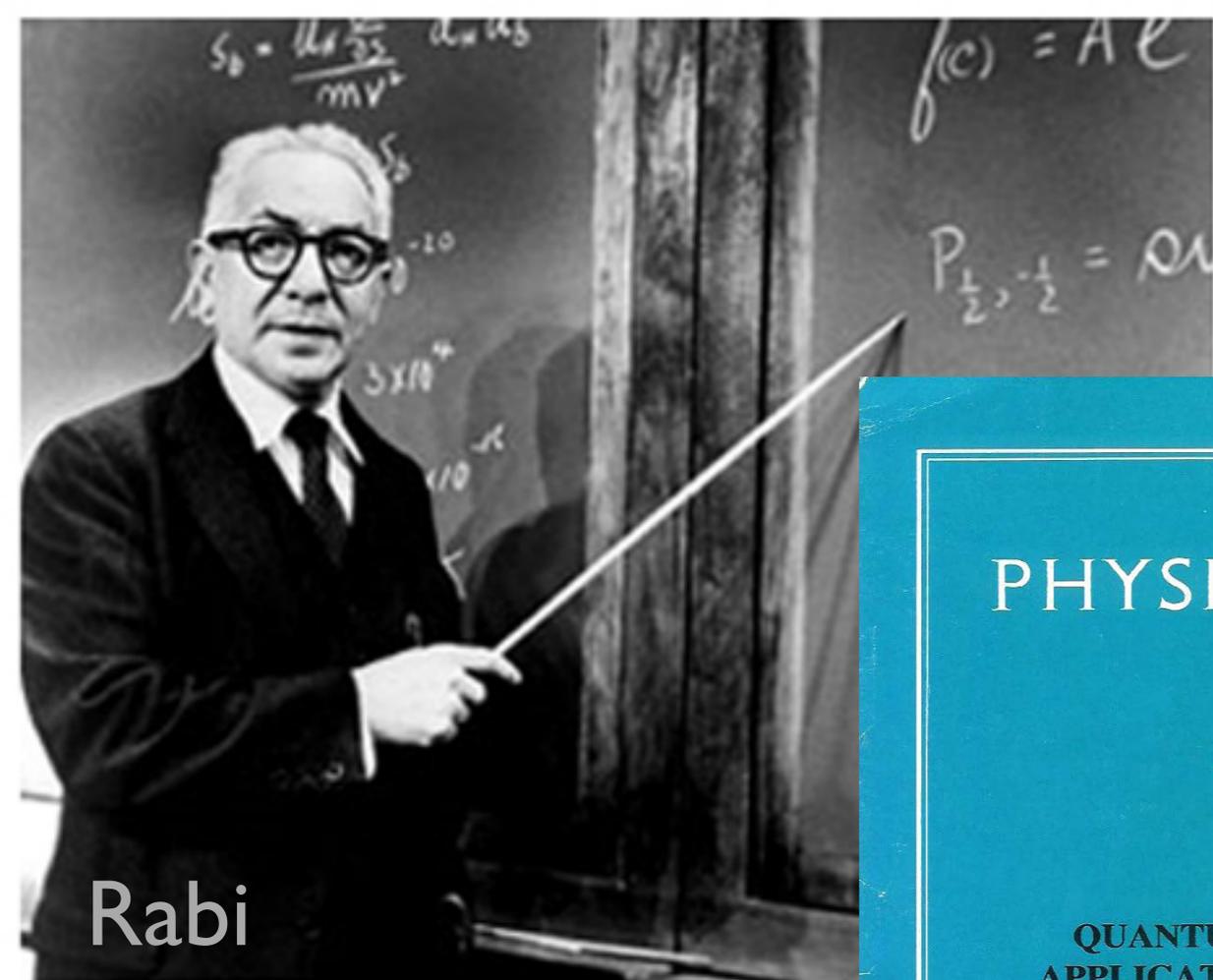
Anticipating B_c (1994)



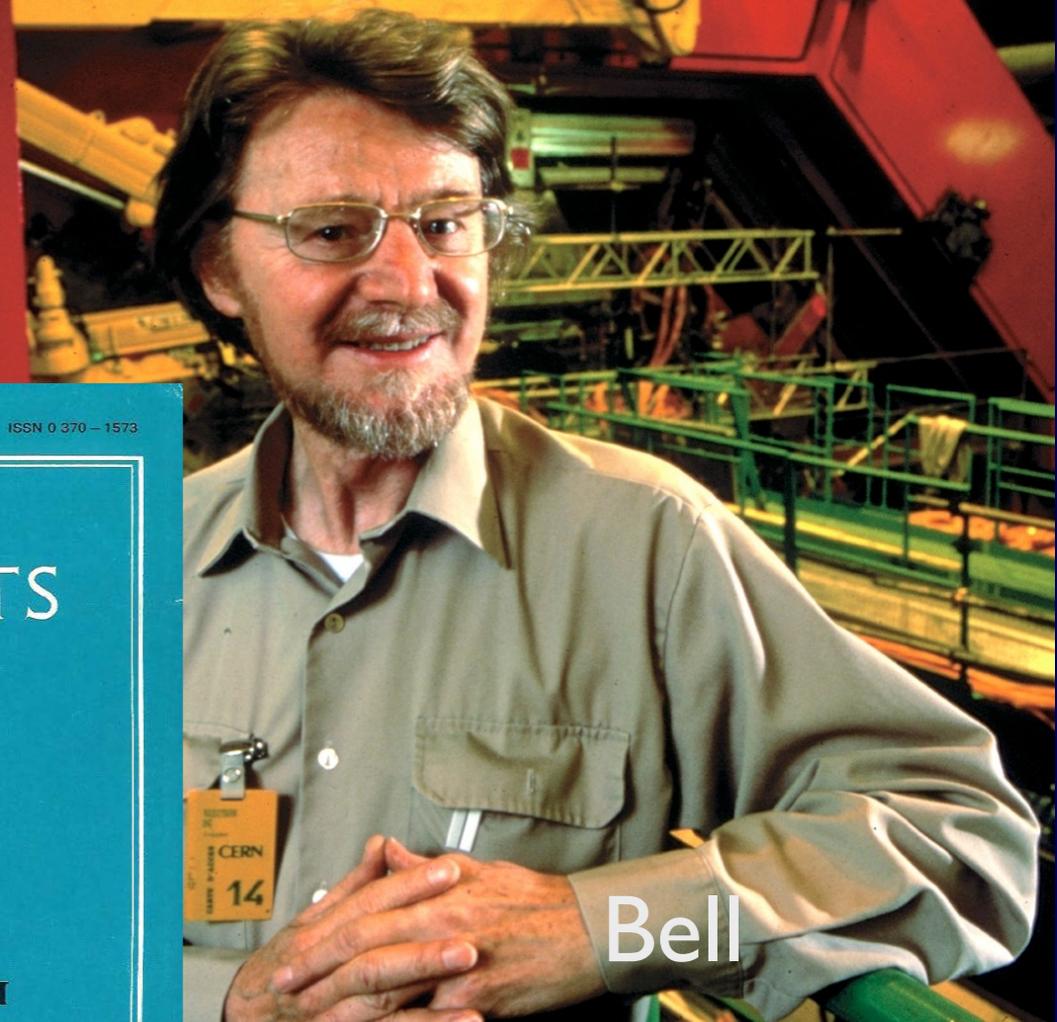
$B_c(6276)$



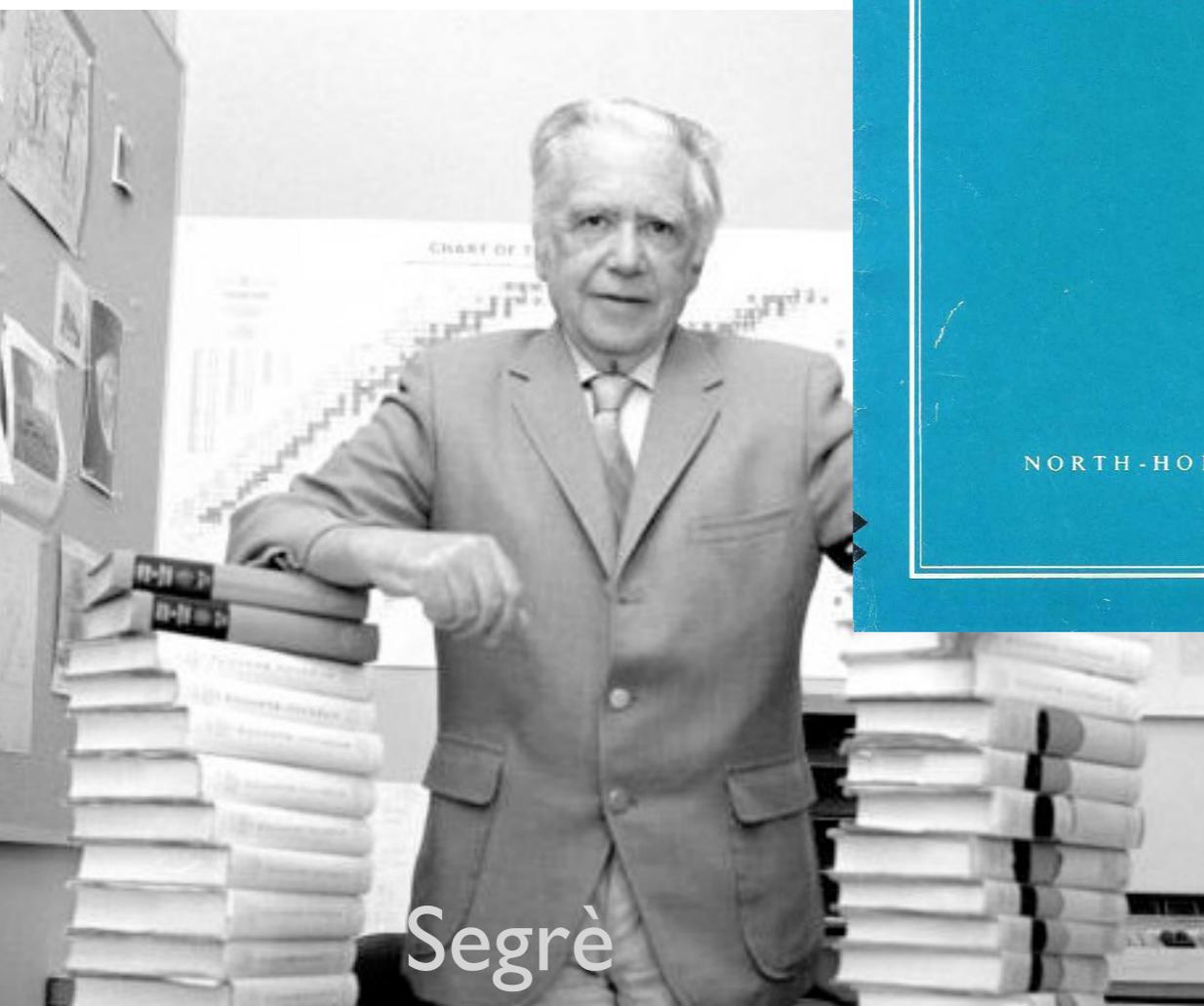
Quarkonium transmutation



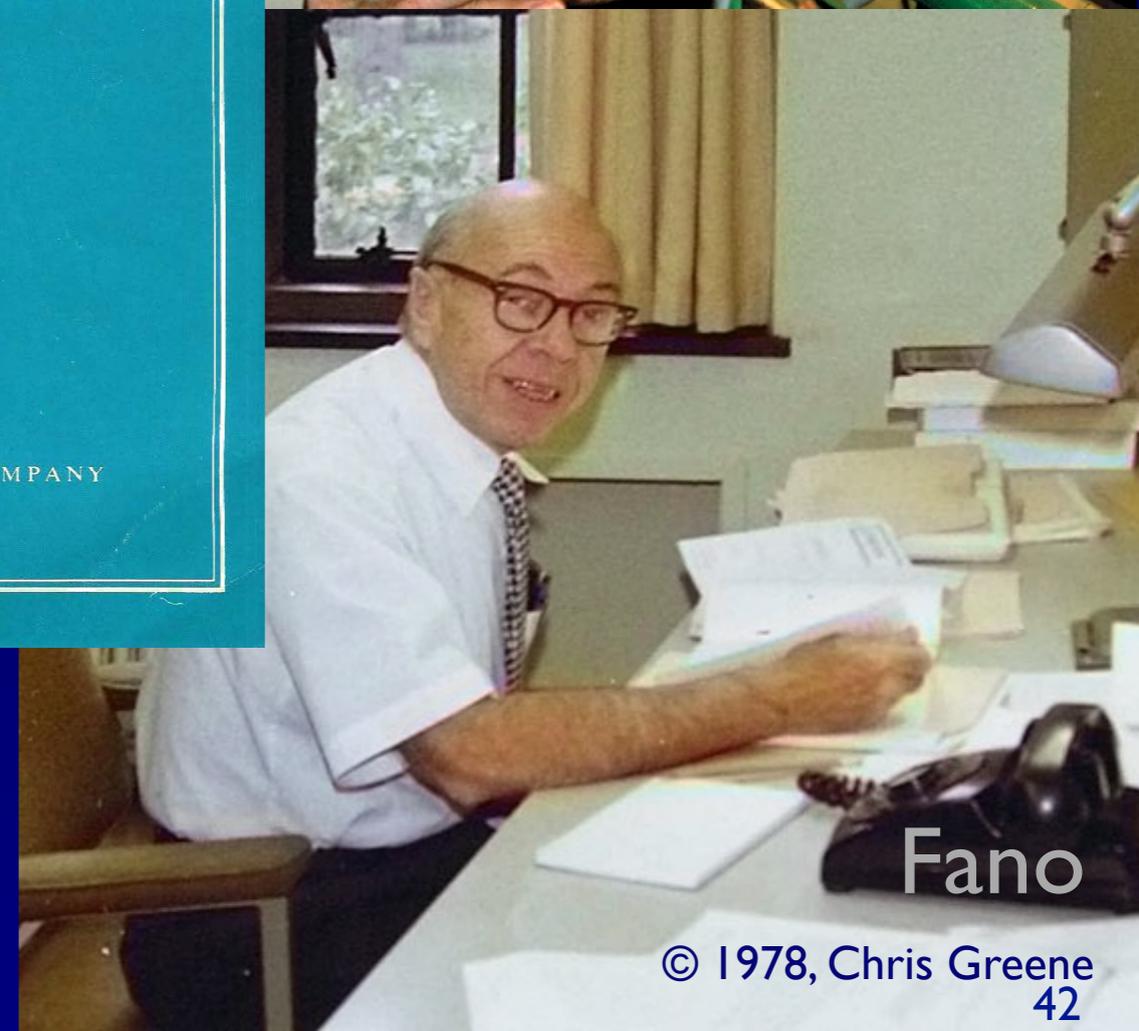
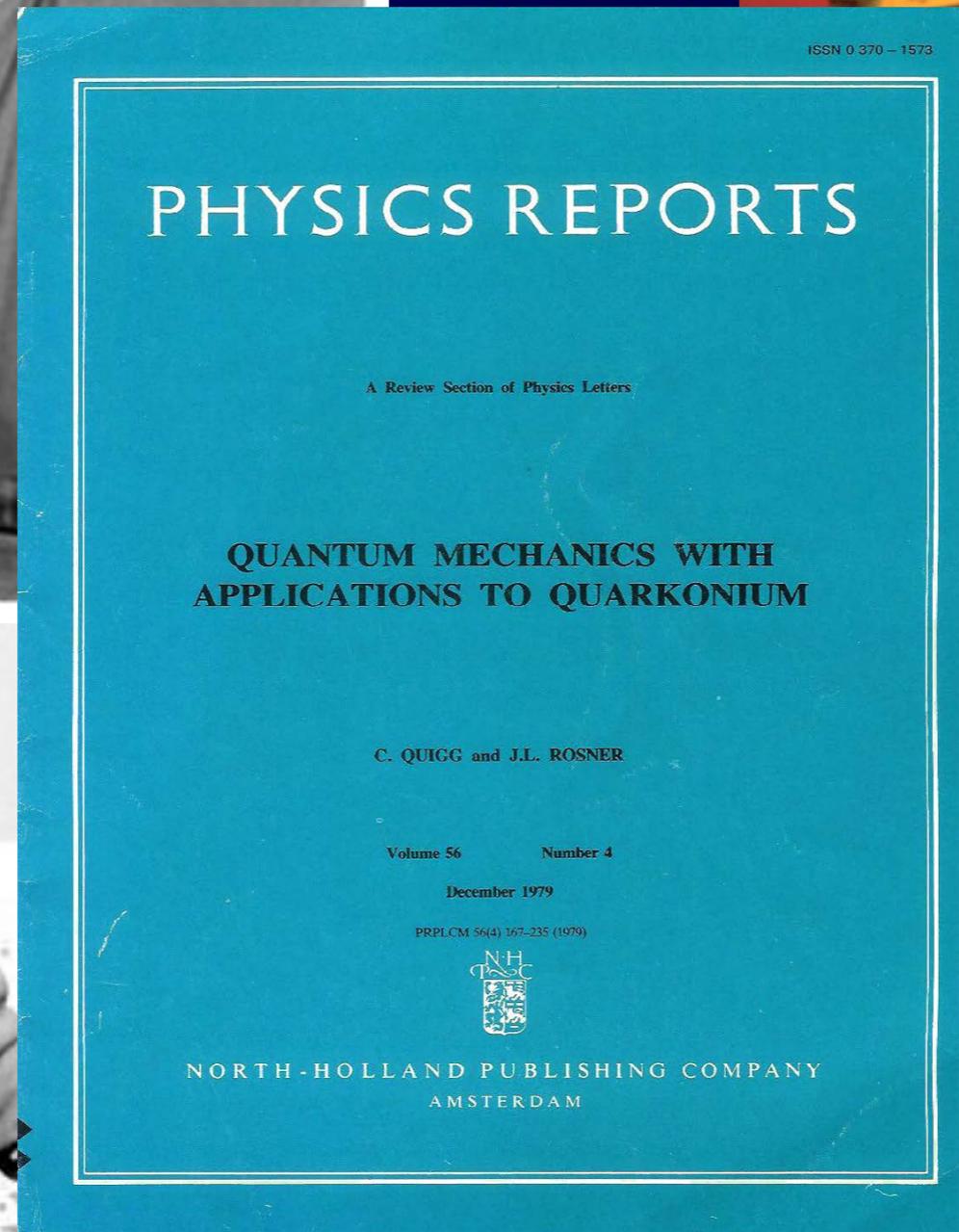
Rabi



Bell

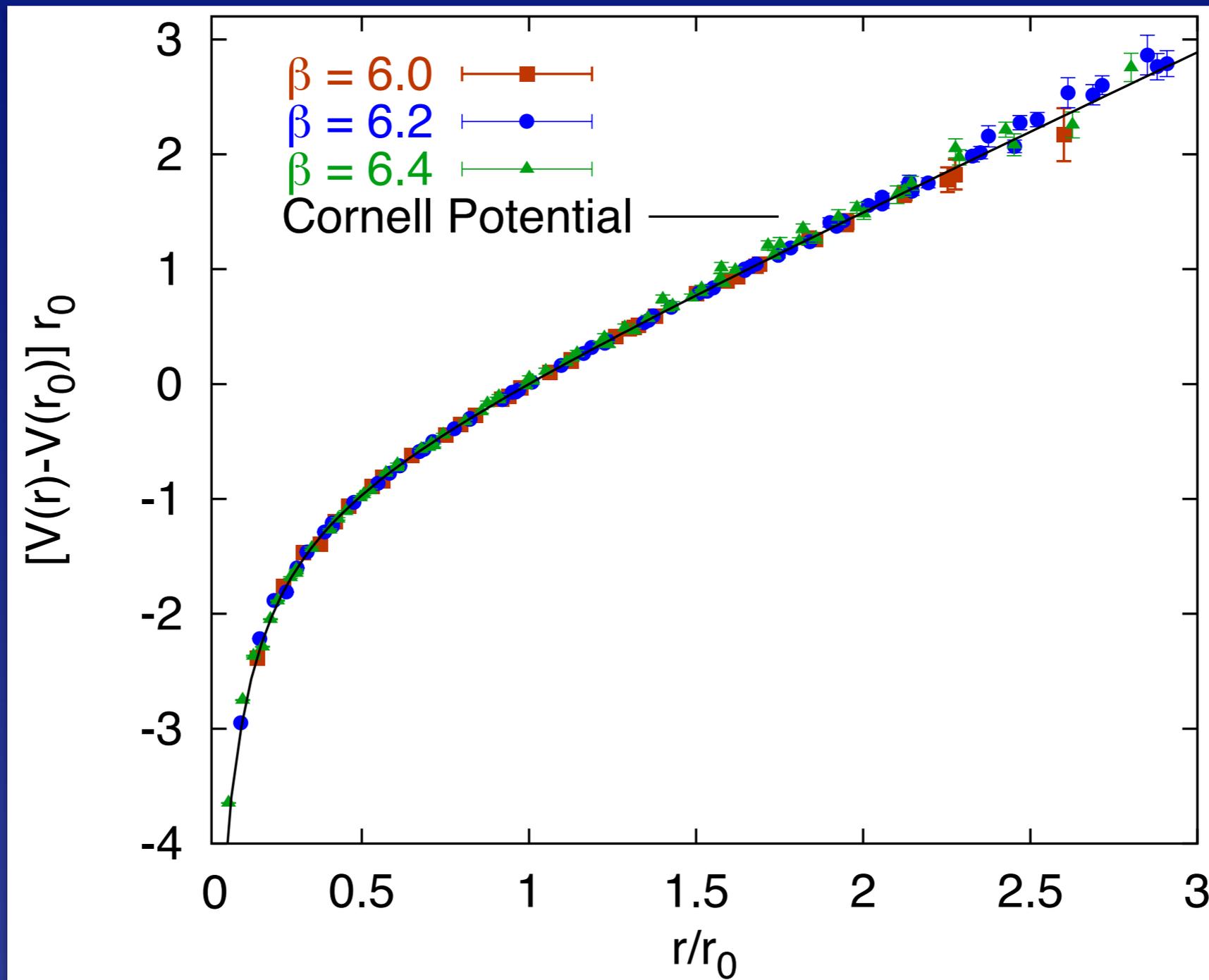


Segrè



Fano

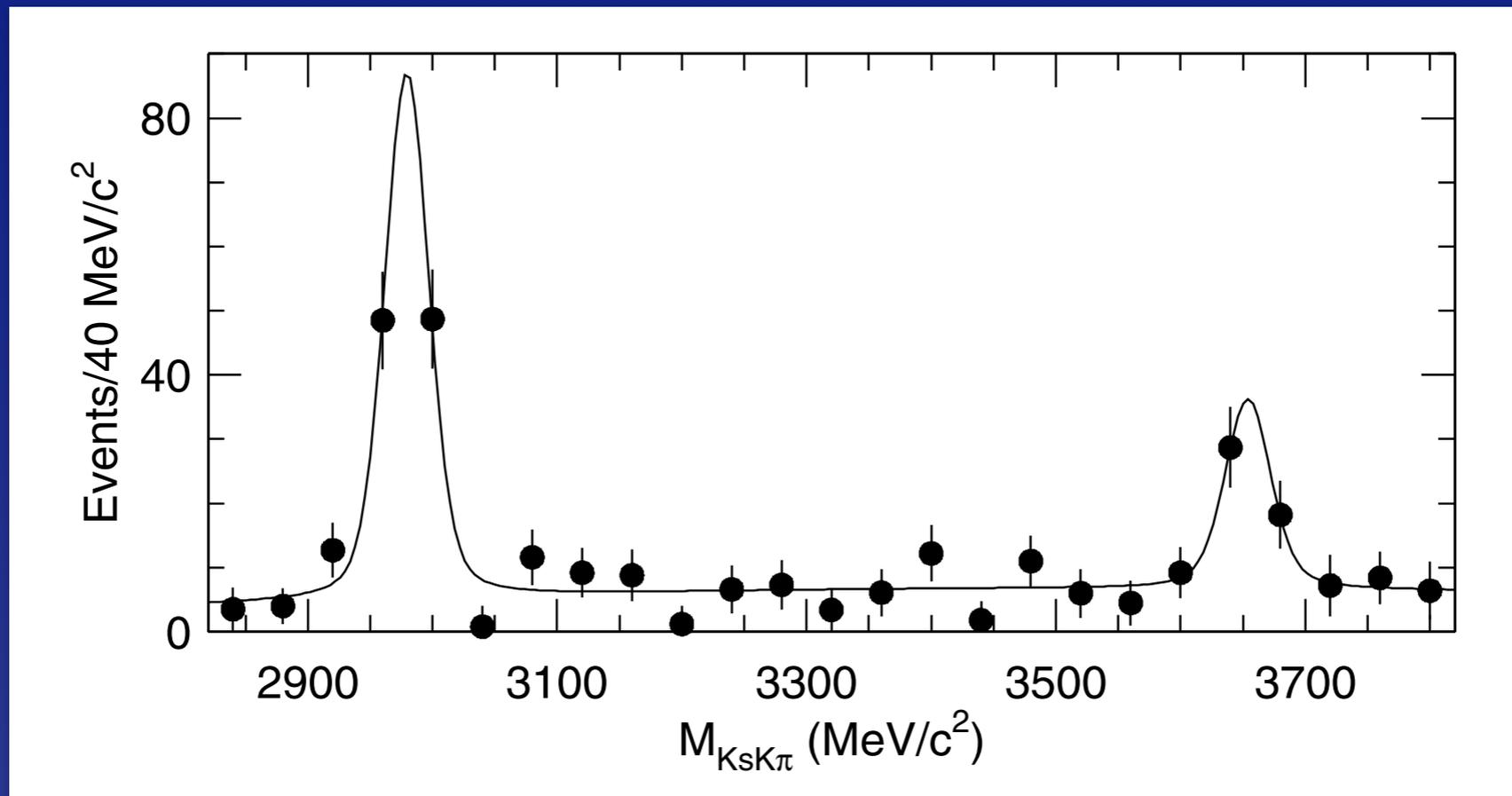
Lattice QCD: $V(r)$ between static color sources



Early example, no dynamical quarks

$\Upsilon(4S)$ as a tool for charmonium spectrum

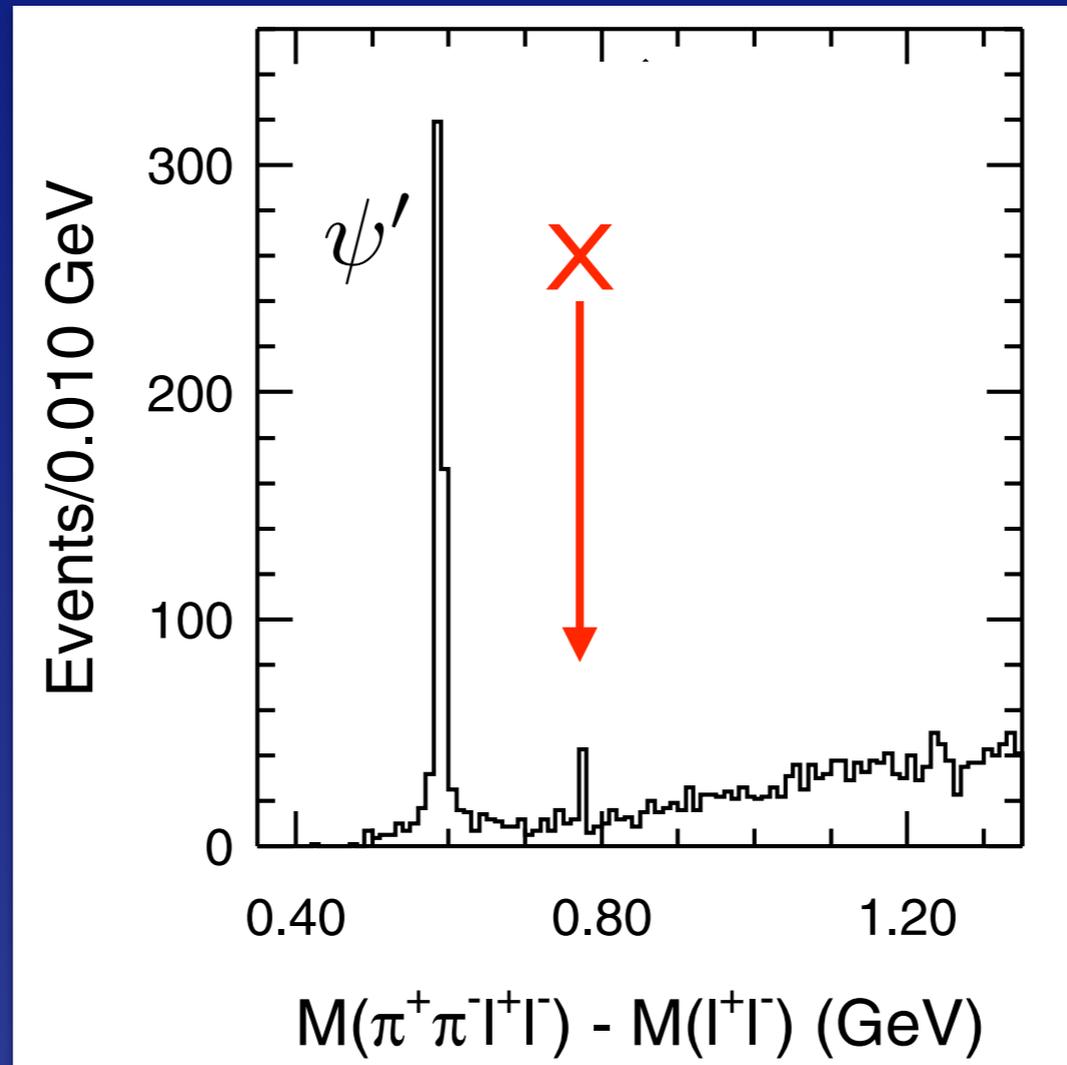
Belle discovers η'_c in $B \rightarrow K K_S K^\mp \pi^\pm$ (2002)



\rightsquigarrow Look for other missing levels, e.g., $\eta_{c2}(^1D_2)$, $\psi_2(^3D_2)$, $\psi_3(^3D_3)$

$\Upsilon(4S)$ as a tool for charmonium spectrum

Belle: $X(3872)$ in $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ (2003)



$J^{PC} = 1^{++}$; not simple charmonium or anything else?

Quarkonium-associated (candidate) states

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \rightarrow K + (J/\psi \pi^+ \pi^-)$ $p\bar{p} \rightarrow (J/\psi \pi^+ \pi^-) + \dots$ $B \rightarrow K + (J/\psi \pi^+ \pi^- \pi^0)$ $B \rightarrow K + (D^0 \bar{D}^0 \pi^0)$ $B \rightarrow K + (J/\psi \gamma)$ $B \rightarrow K + (\psi' \gamma)$ $pp \rightarrow (J/\psi \pi^+ \pi^-) + \dots$	Belle [82, 89], BaBar [85], LHCb [90] CDF [83, 91, 92, 125], D0 [84] Belle [94], BaBar [59] Belle [95], BaBar [96] BaBar [126], Belle [127], LHCb [128] BaBar [126], Belle [127], LHCb [128] LHCb [86], CMS [87]
$X(3915)$	3917.4 ± 2.7	28_{-9}^{+10}	0^{++}	$B \rightarrow K + (J/\psi \omega)$ $e^+ e^- \rightarrow e^+ e^- + (J/\psi \omega)$	Belle [58], BaBar [59] Belle [60], BaBar [61]
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+ e^- \rightarrow e^+ e^- + (D\bar{D})$	Belle [64], BaBar [65]
$X(3940)$	3942_{-8}^{+9}	37_{-17}^{+27}	$0(?)^{-(?) +}$	$e^+ e^- \rightarrow J/\psi + (D^* \bar{D})$ $e^+ e^- \rightarrow J/\psi + (\dots)$	Belle [27] Belle [26]
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+ e^- \rightarrow \gamma + (D\bar{D})$	BaBar [129], Belle [130]
$Y(4008)$	4008_{-49}^{+121}	226 ± 97	1^{--}	$e^+ e^- \rightarrow \gamma + (J/\psi \pi^+ \pi^-)$	Belle [32]
$Y(4140)$	4144 ± 3	17 ± 9	$?^{?+}$	$B \rightarrow K + (J/\psi \phi)$	CDF [74, 75], CMS [77]
$X(4160)$	4156_{-25}^{+29}	139_{-65}^{+113}	$0(?)^{-(?) +}$	$e^+ e^- \rightarrow J/\psi + (D^* \bar{D})$	Belle [27]
$Y(4260)$	4263_{-9}^{+8}	95 ± 14	1^{--}	$e^+ e^- \rightarrow \gamma + (J/\psi \pi^+ \pi^-)$ $e^+ e^- \rightarrow (J/\psi \pi^+ \pi^-)$ $e^+ e^- \rightarrow (J/\psi \pi^0 \pi^0)$	BaBar [30, 131], CLEO [132], Belle [32] CLEO [133] CLEO [133]
$Y(4274)$	4292 ± 6	34 ± 16	$?^{?+}$	$B \rightarrow K + (J/\psi \phi)$	CDF [75], CMS [77]
$X(4350)$	$4350.6_{-5.1}^{+4.6}$	$13.3_{-10.0}^{+18.4}$	$0/2^{++}$	$e^+ e^- \rightarrow e^+ e^- (J/\psi \phi)$	Belle [81]
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+ e^- \rightarrow \gamma + (\psi' \pi^+ \pi^-)$	BaBar [31], Belle [33]
$X(4630)$	4634_{-11}^{+9}	92_{-32}^{+41}	1^{--}	$e^+ e^- \rightarrow \gamma (\Lambda_c^+ \Lambda_c^-)$	Belle [134]
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+ e^- \rightarrow \gamma + (\psi' \pi^+ \pi^-)$	Belle [33]
$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \rightarrow \pi^- + (J/\psi \pi^+)$ $Y(4260) \rightarrow \pi^- + (D\bar{D}^*)^+$	BESIII [39], Belle [40] BESIII [56]
$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?) -}$	$Y(4260) \rightarrow \pi^- + (h_c \pi^+)$ $Y(4260) \rightarrow \pi^- + (D^* \bar{D}^*)^+$	BESIII [41] BESIII [42]
$Z_1^+(4050)$	4051_{-43}^{+24}	82_{-55}^{+51}	$?^{?+}$	$B \rightarrow K + (\chi_{c1} \pi^+)$	Belle [43], BaBar [53]
$Z^+(4200)$	4196_{-32}^{+35}	370_{-149}^{+99}	1^{+-}	$B \rightarrow K + (J/\psi \pi^+)$	Belle [51]
$Z_2^+(4250)$	4248_{-45}^{+185}	177_{-72}^{+321}	$?^{?+}$	$B \rightarrow K + (\chi_{c1} \pi^+)$	Belle [43], BaBar [53]
$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \rightarrow K + (\psi' \pi^+)$ $B \rightarrow K + (J\psi \pi^+)$	Belle [44, 46, 47], LHCb [48] Belle [51]
$Y_b(10890)$	10888.4 ± 3.0	$30.7_{-7.7}^{+8.9}$	1^{--}	$e^+ e^- \rightarrow (\Upsilon(nS) \pi^+ \pi^-)$	Belle [117]
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$“\Upsilon(5S)” \rightarrow \pi^- + (\Upsilon(nS) \pi^+), n = 1, 2, 3$ $“\Upsilon(5S)” \rightarrow \pi^- + (h_b(nP) \pi^+), n = 1, 2$ $“\Upsilon(5S)” \rightarrow \pi^- + (B\bar{B}^*)^+, n = 1, 2$	Belle [119, 122] Belle [119] Belle [123]
$Z_b^0(10610)$	10609 ± 6		1^{+-}	$“\Upsilon(5S)” \rightarrow \pi^0 + (\Upsilon(nS) \pi^0), n = 1, 2, 3$	Belle [121]
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$“\Upsilon(5S)” \rightarrow \pi^- + (\Upsilon(nS) \pi^+), n = 1, 2, 3$ $“\Upsilon(5S)” \rightarrow \pi^- + (h_b(nP) \pi^+), n = 1, 2$ $“\Upsilon(5S)” \rightarrow \pi^- + (B^* \bar{B}^*)^+, n = 1, 2$	Belle [119] Belle [119] Belle [123]

Quarkonium-associated states above flavor threshold

Mostly narrow, seen in hadronic transitions or decays

What are they?

Quarkonium (+ coupled-channels, thresholds)

Threshold effects

New body plans:

quarkonium hybrids ($q\bar{q}g$)

two-quark–two-antiquark states, including

dimeson “molecules”

tetraquarks

diquarkonium

hadroquarkonium

and superpositions!

