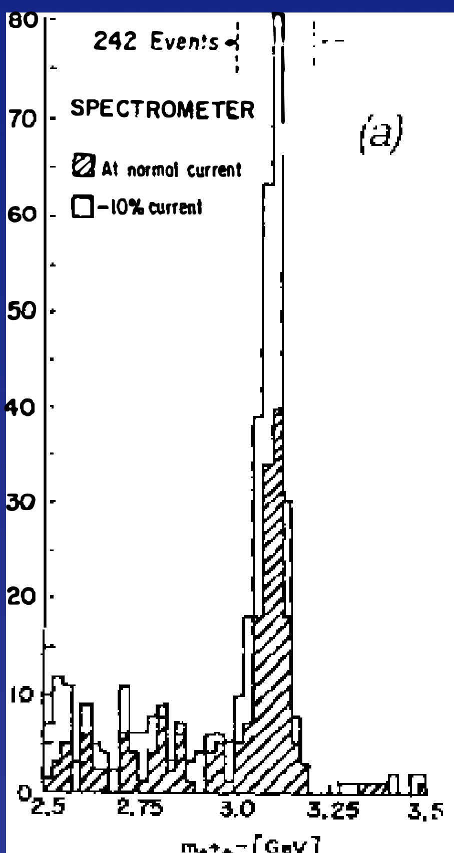
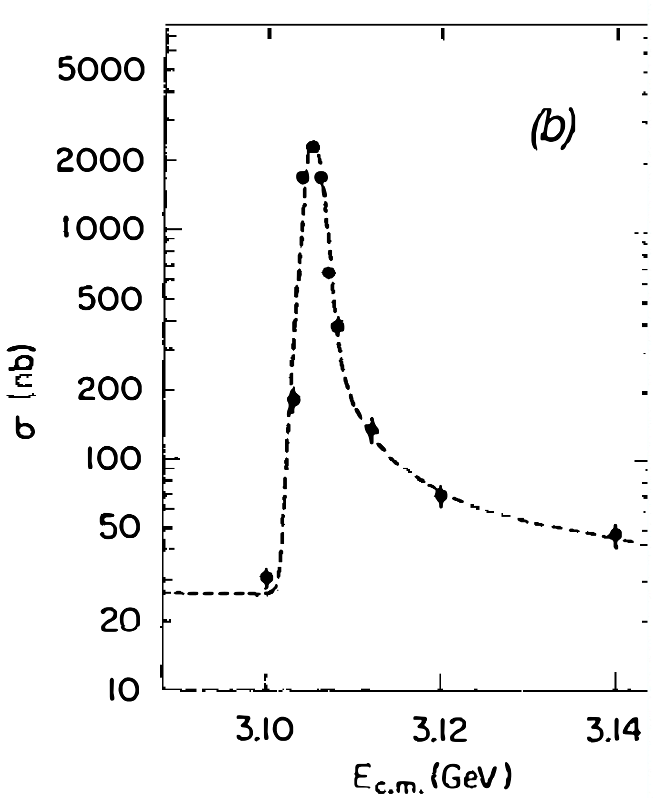
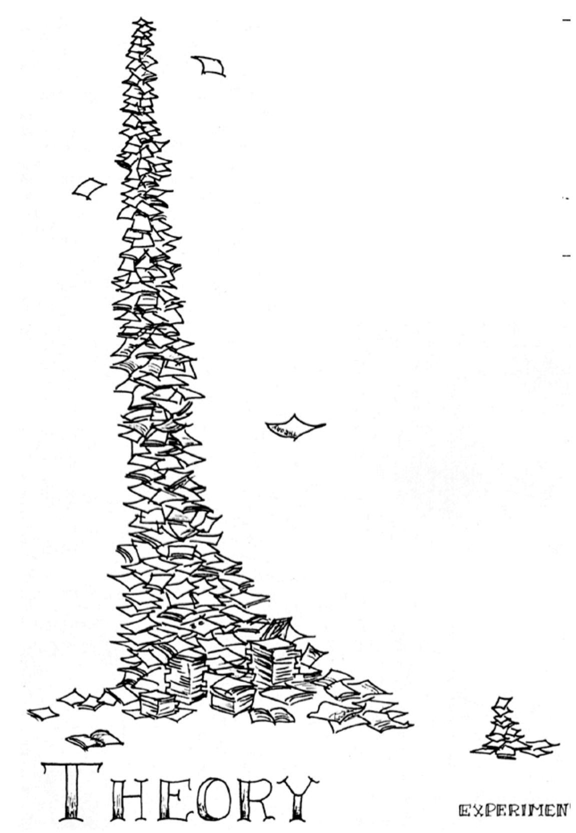
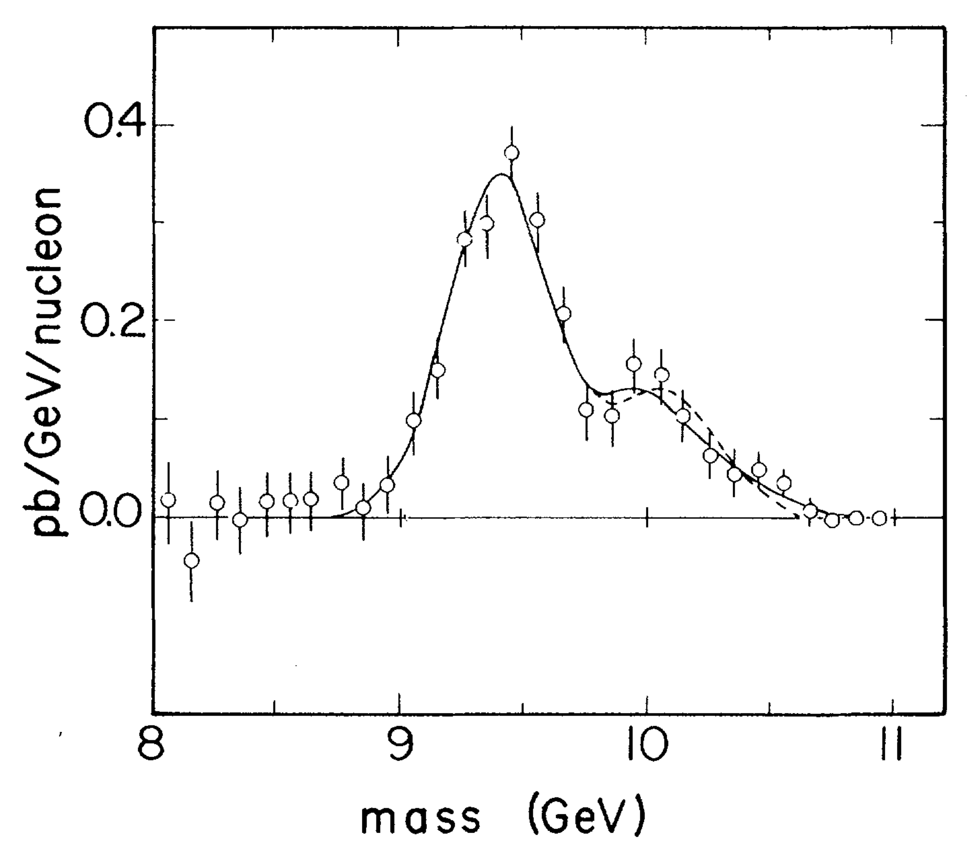
Celebrating Quarkonium: The First Forty Years

Chris Quigg
Fermilab & CERN









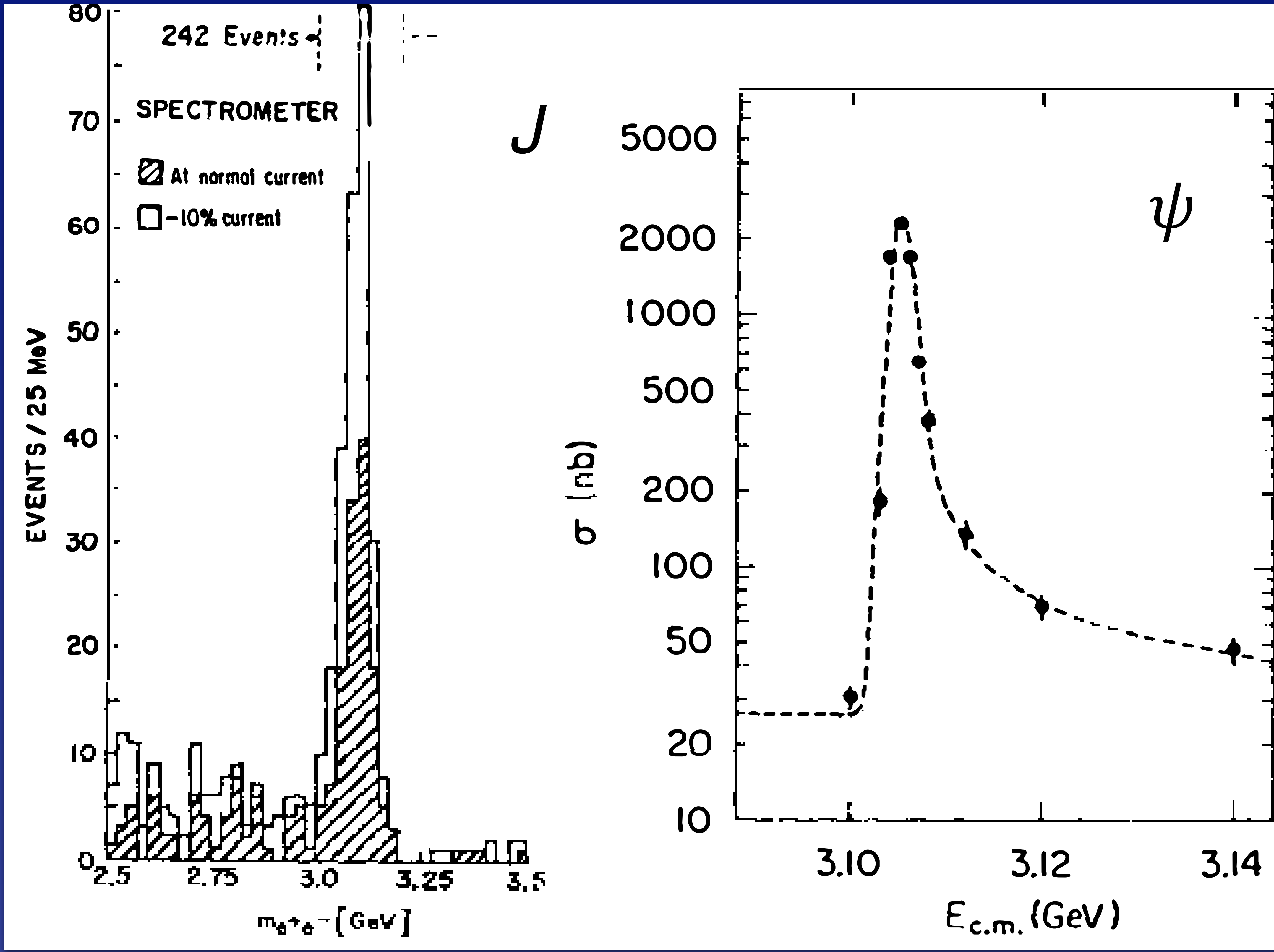
CERN PH Seminar · 11 November 2014

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.

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."

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.

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

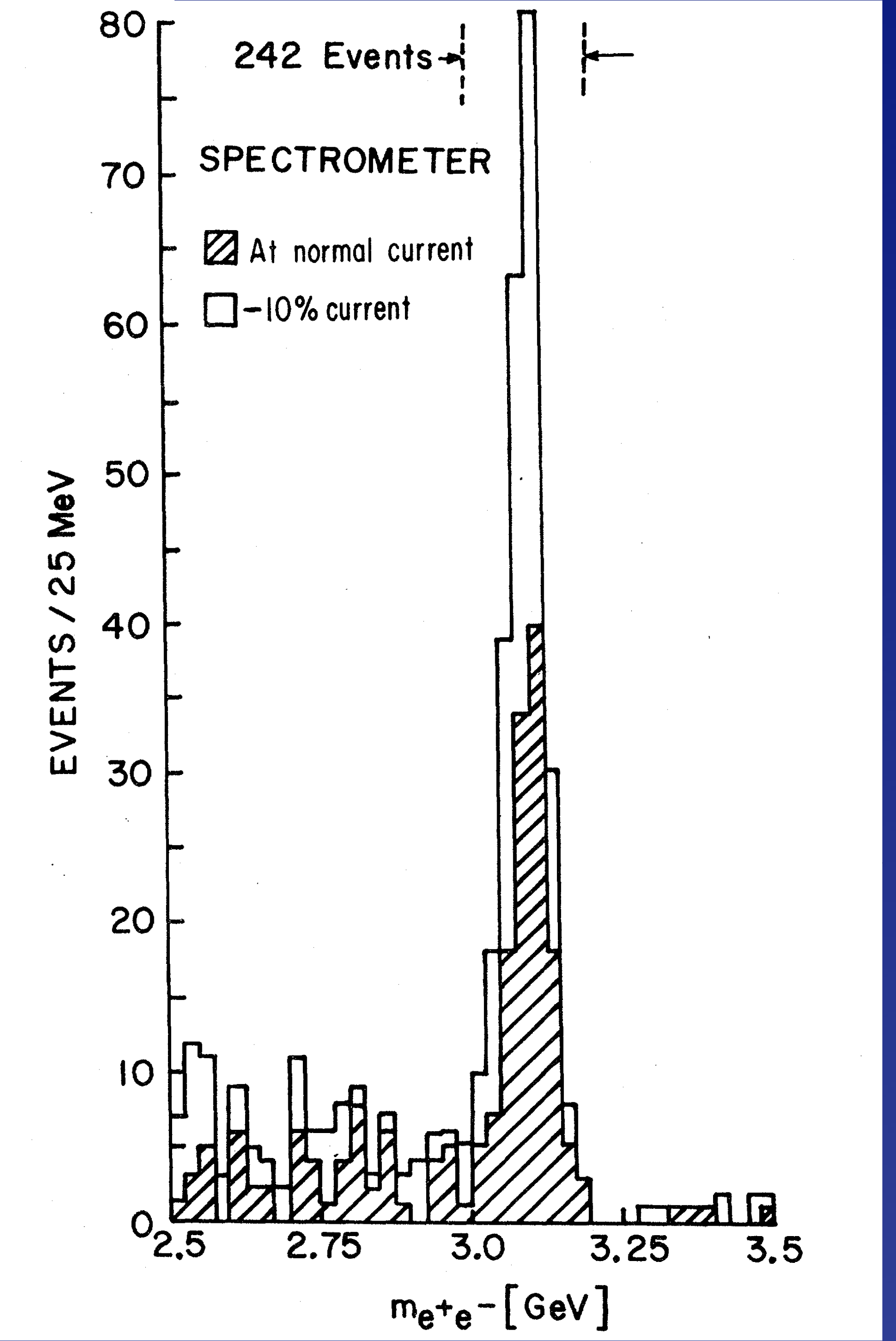
Experimental Observation of a Heavy Particle J†

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 $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.



VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

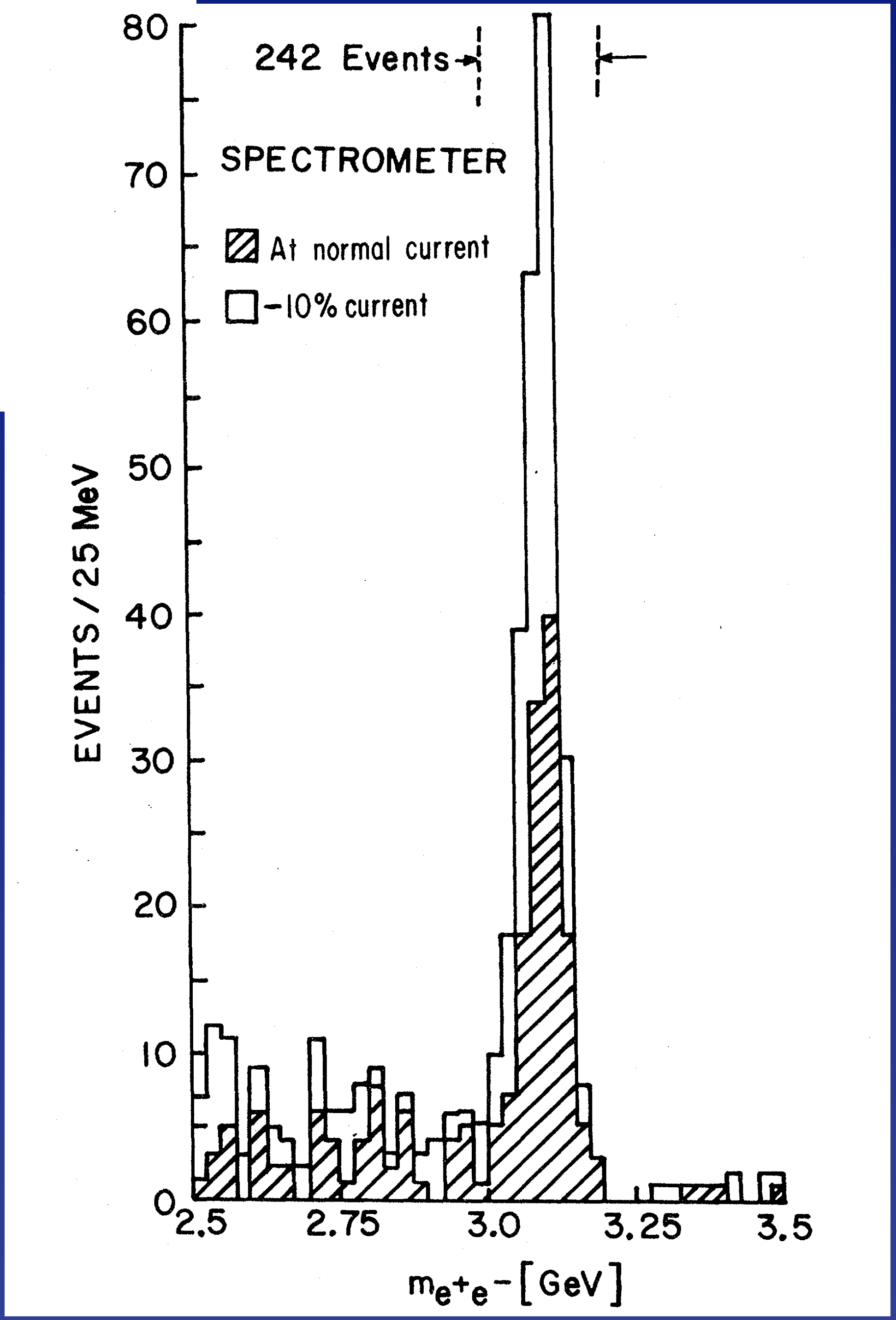
Experimental Observation of a Heavy Particle J†

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 $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ 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?


80
242 Events
SPECTROMETER
70
60
50
40
30
EVENTS / 25 MeV

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

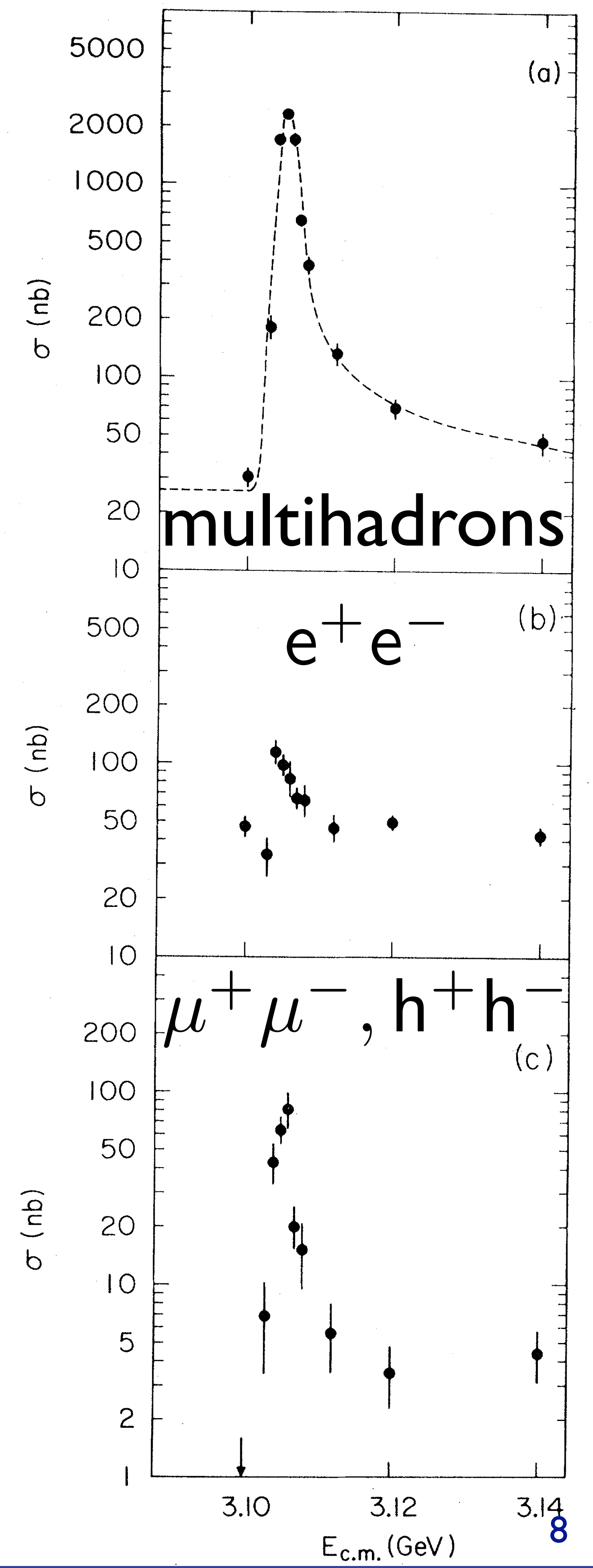
and

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 $e^+e^- \to$ 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.



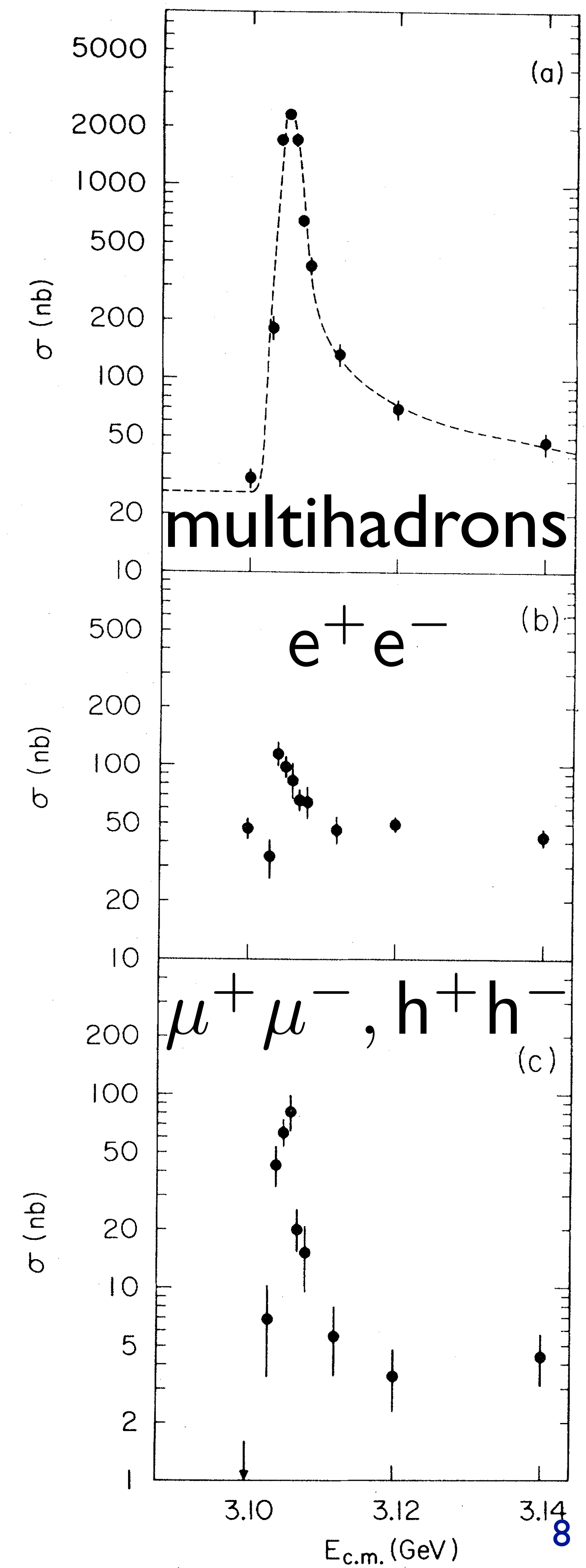
Discovery of a Narrow Resonance in e^+e^- Annihilation*

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 $e^+e^- \rightarrow$ 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

Preliminary Result of Frascati (ADONE) on the Nature of a New 3.1-GeV Particle Produced in e^+e^- Annihilation*

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. Celvetti, F. Costantini, P. Lariccia, P. Parascandalo, 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.

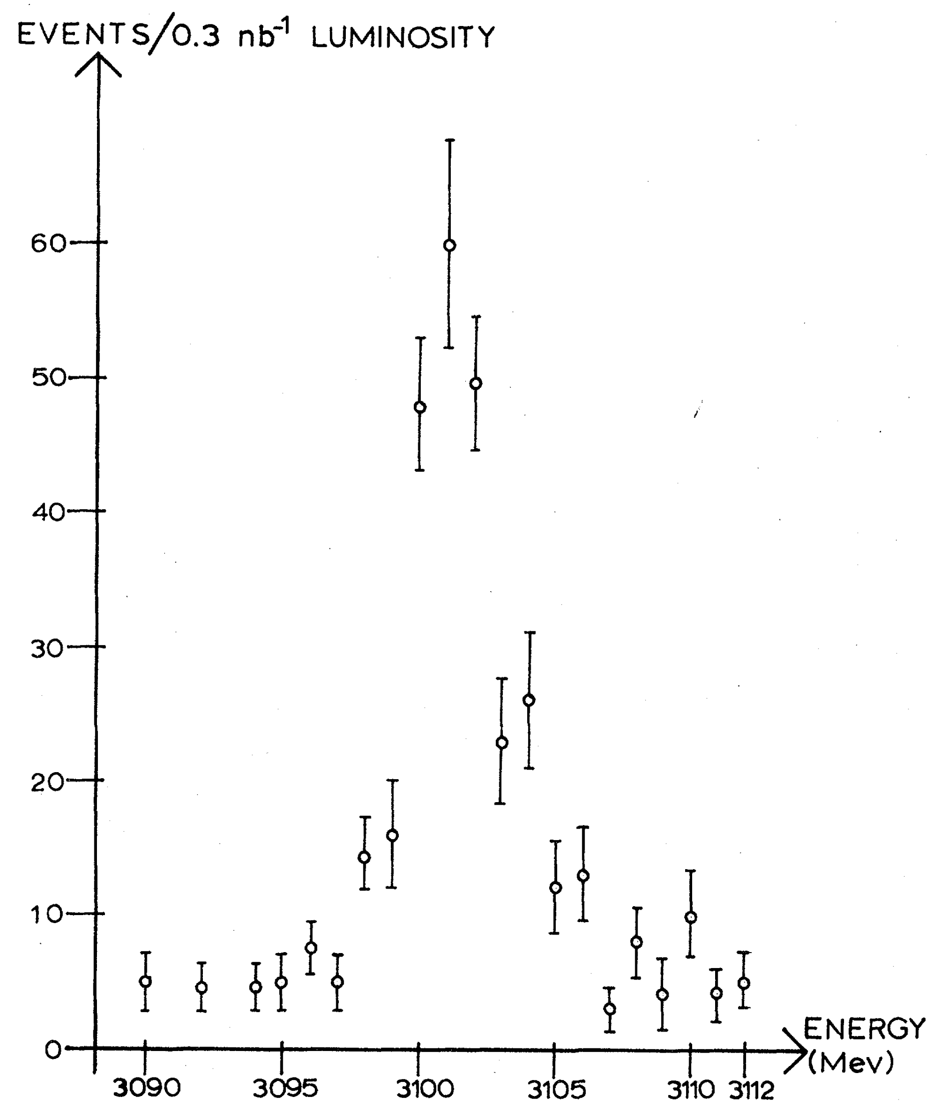


FIG. 1. Result from the Gamma-Gamma Group, total of 446 events. The number of events per 0.3 nb^{-1} luminosity is plotted versus the total c.m. energy of the machine.

Volume 53B, number 4 PHYSICS LETTERS 23 December 1974

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

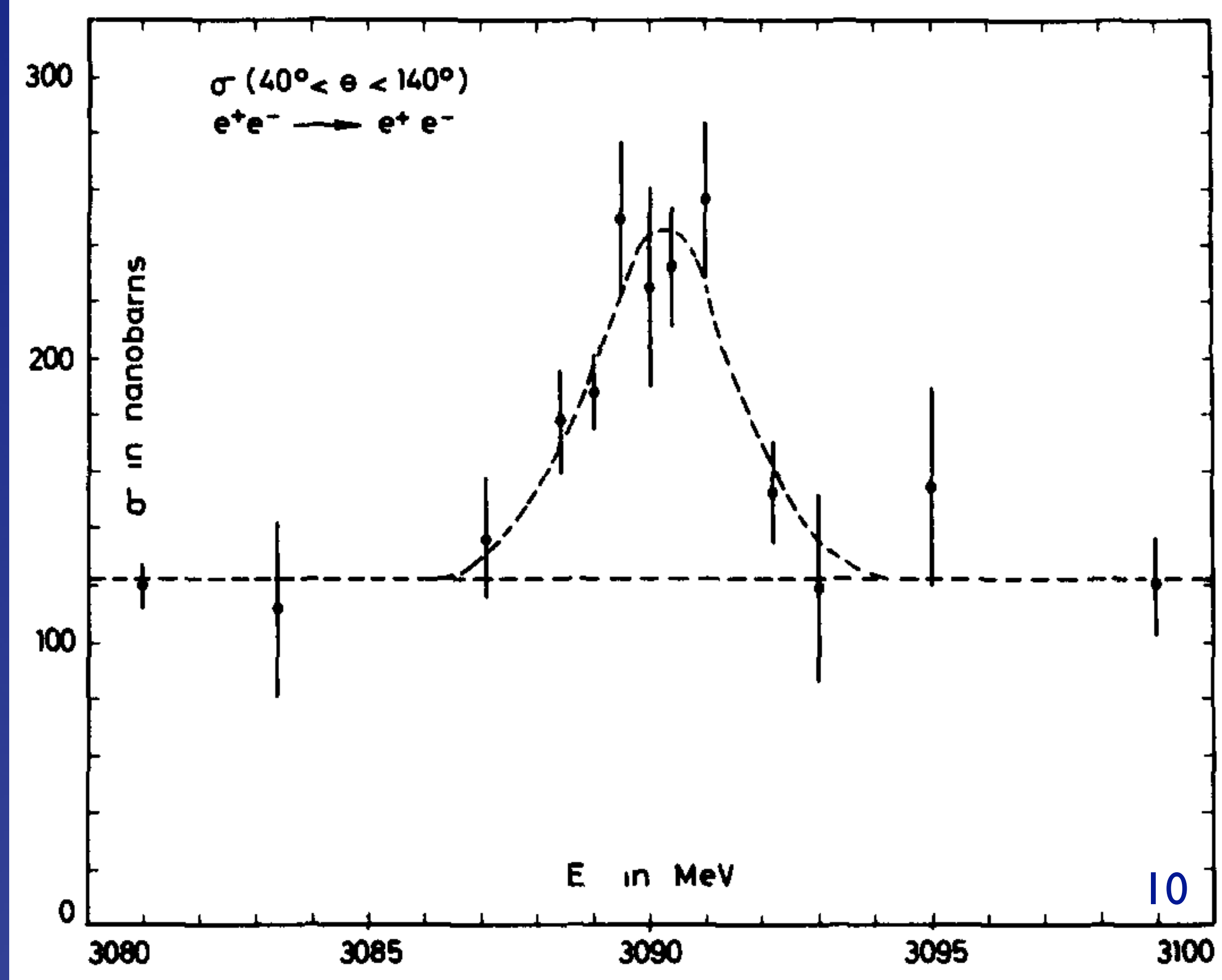
K. BERKELMAN*, D. CORDS, R. FELST, E. GADERMANN, G. GRINDHAMMER, H. HULTSCHIG, P. JOOS, W. KOCH, U. KÖTZ, H. KREHBIEL, D. KREINICK, J. LUDWIG, K.-H. MESS, K.C. MOFFEITT, D. NOTZ**, G. POELZ, K. SAUERBERG, P. SCHMÜSER, G. VOGEL, B.H. WIIK, G. WOLF
Deutsches Elektronen-Synchrotron DESY and II. Institut 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 $\Gamma_{ee}^2/\Gamma_{tot}$ = 0.23 ± 0.05 keV for the resonance.



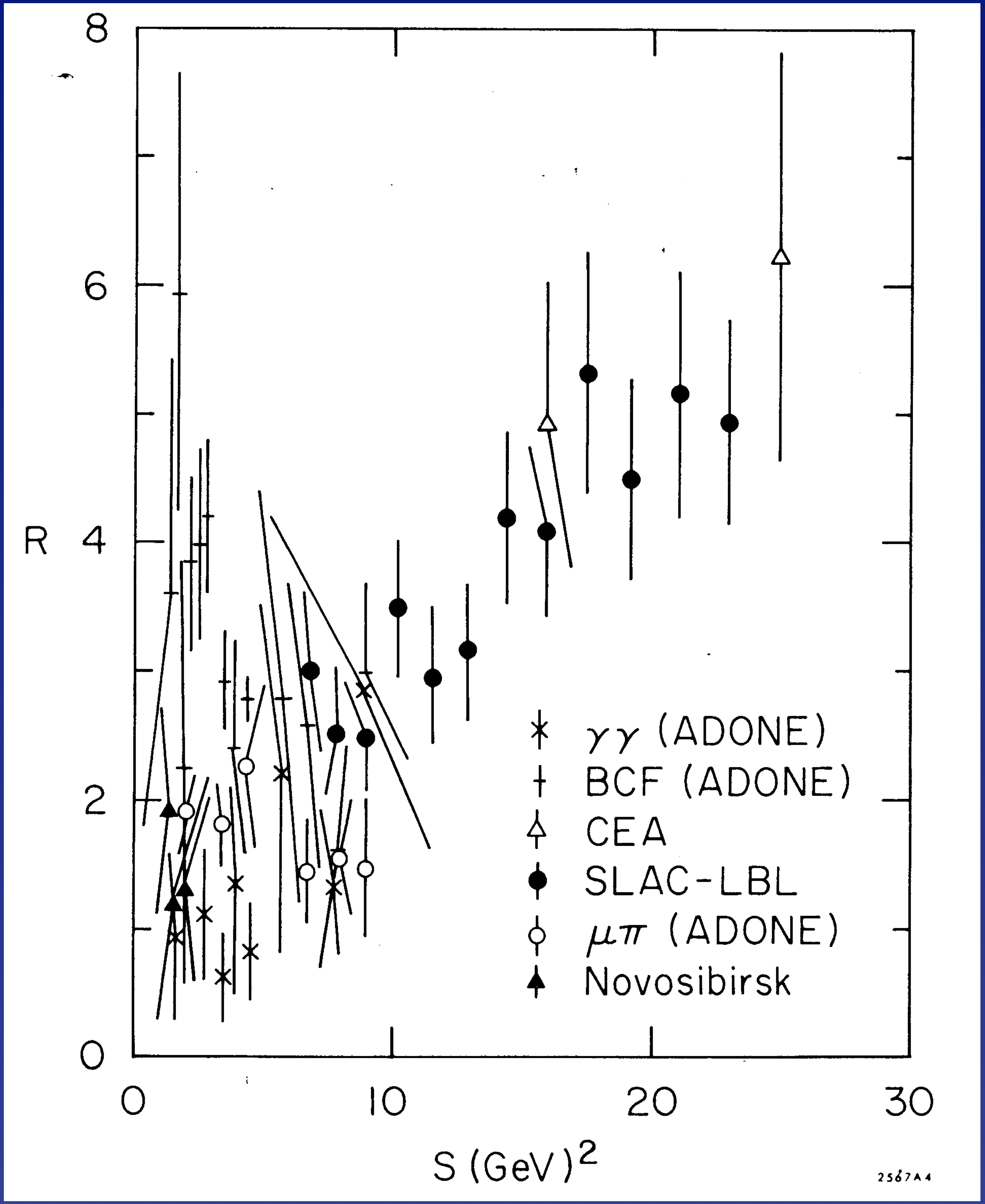
ICHEP, London: Summer 1974

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 $(GeV/c)^2$ 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

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



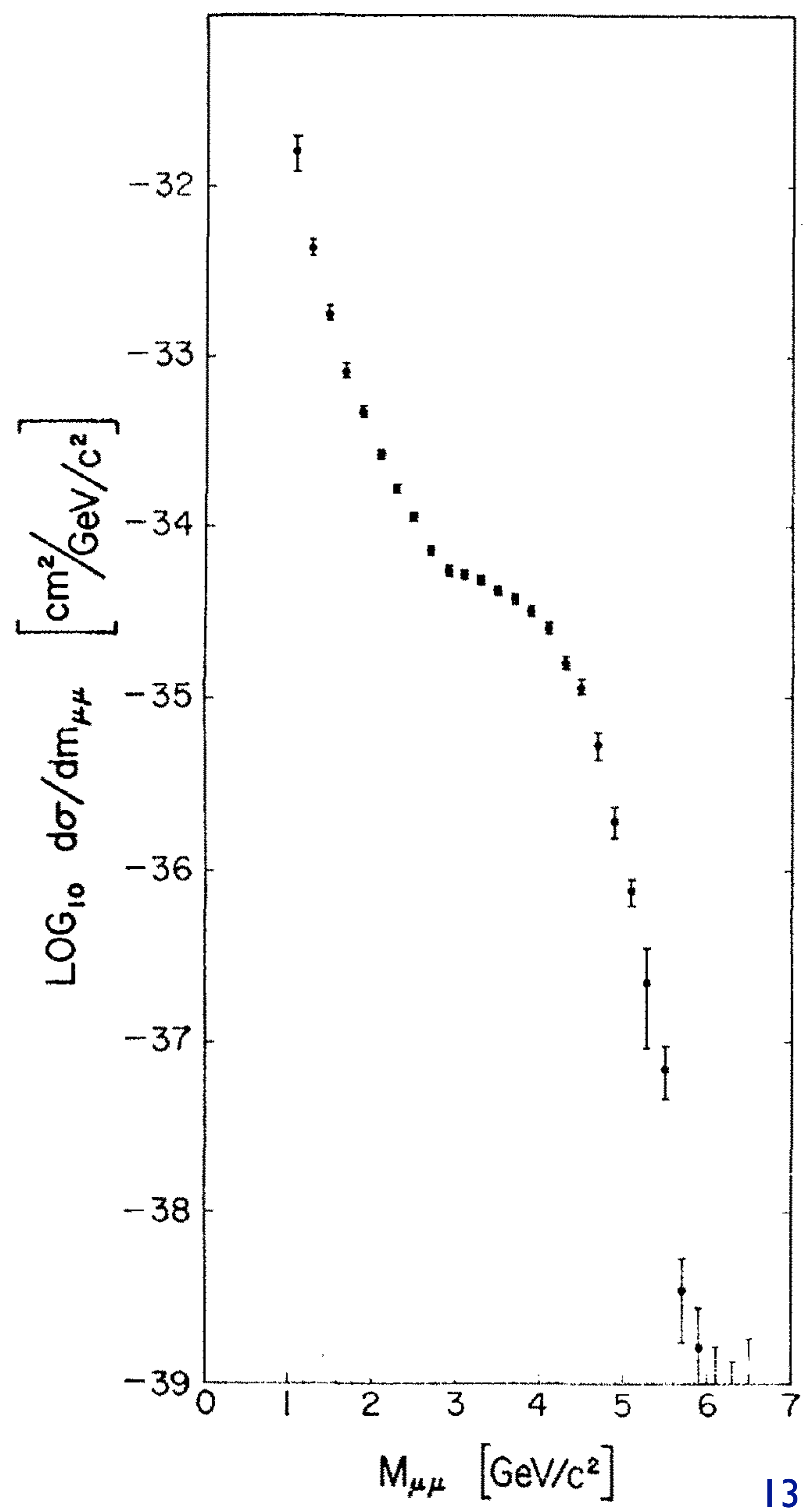
Observation of Massive Muon Pairs in Hadron Collisions*

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 $1 < m_{\mu\mu} < 6.7$ 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 $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}^5$ cm^2 (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.



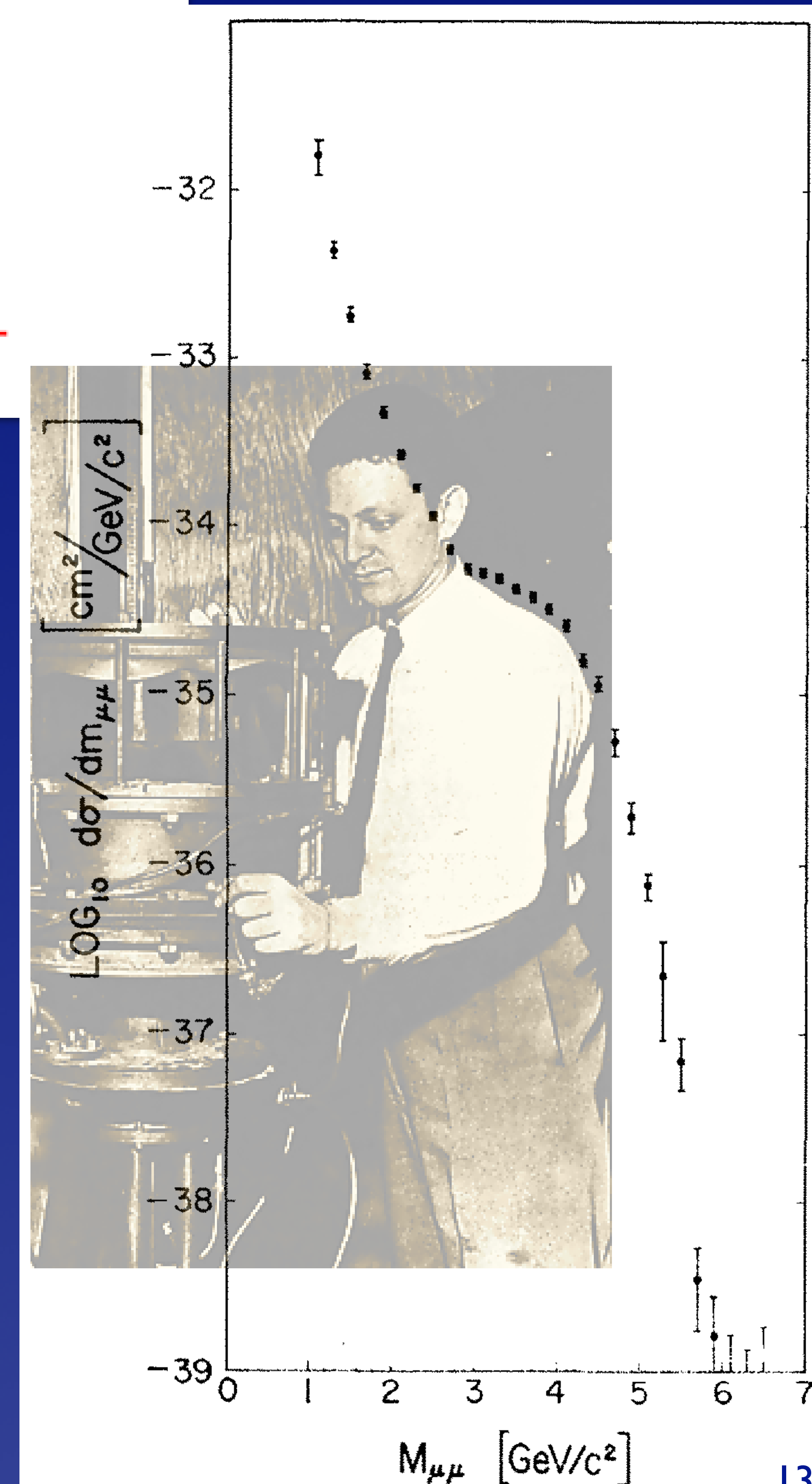
Observation of Massive Muon Pairs in Hadron Collisions*

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 $1 < m_{\mu\mu} < 6.7$ 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 $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}^5$ cm^2 (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.



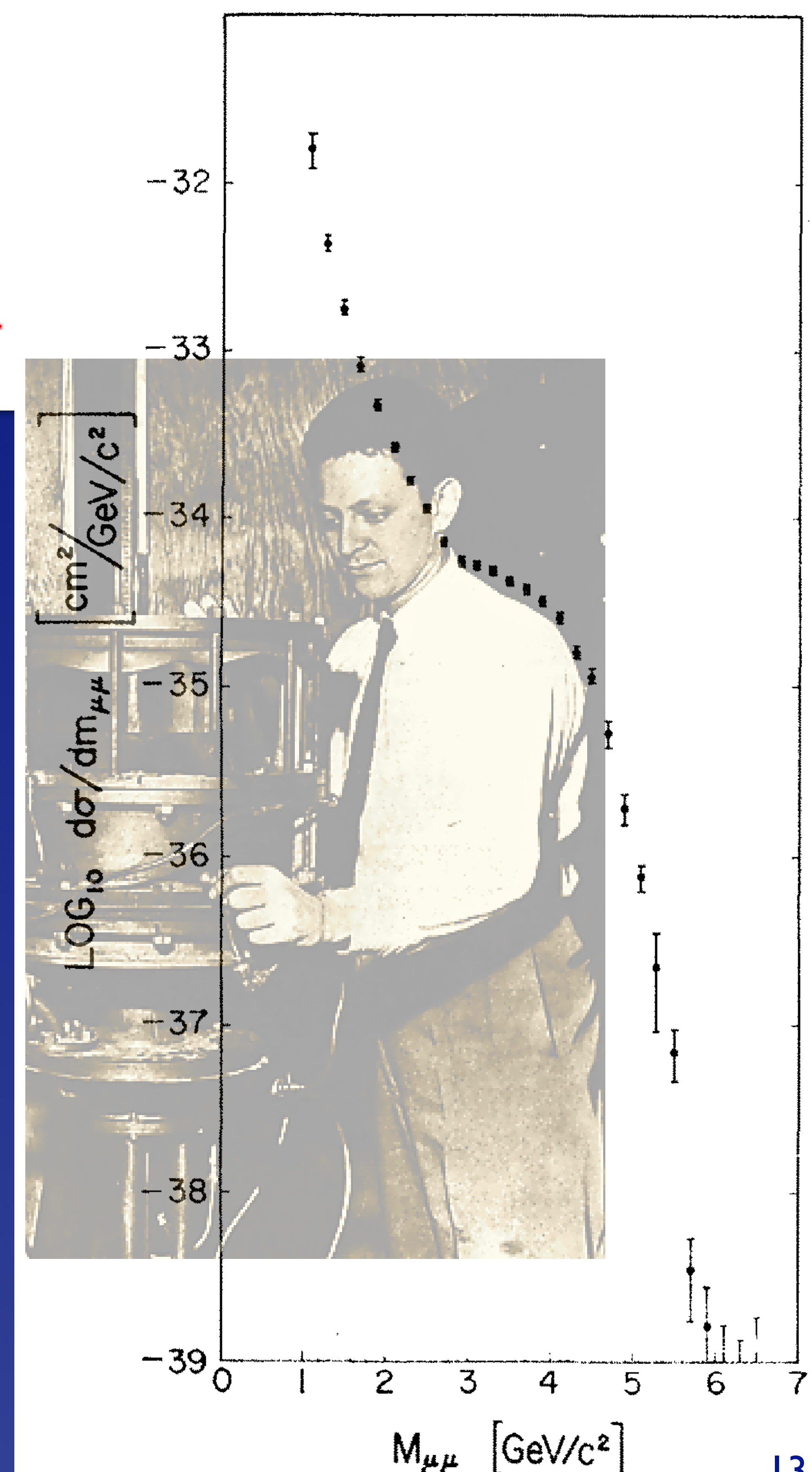
Observation of Massive Muon Pairs in Hadron Collisions*

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 $1 < m_{\mu\mu} < 6.7$ 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 $d\sigma/dm_{\mu\mu} \approx 10^{-32}/m_{\mu\mu}{}^5$ cm^2 (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

New and Surprising Type Of Atomic Particle Found

By WALTER SULLIVAN

Experiments conducted independently on the East and West Coasts have disclosed a new type of atomic particle.

Its properties are so unexpected that there are differing views as to how it might fit into current theories on the elementary nature of matter.

The experiments were done at the Stanford Linear Accelerator in Palo Alto, Calif., by a team under Dr. Burton Richter and at the Brookhaven National Laboratory in Upton, L.I., by a group under Dr. Samuel C. C. Ting of the Massachusetts Institute of Technology.

In a statement yesterday, the two men said:

"The suddenness of the discovery coupled with the totally unexpected properties of the particle are what make it so exciting. It is not like the particles we know and must have some new kinds of structure.

"The theorists are working frantically to fit it into the framework of our present knowledge of the elementary particle. We experimenters hope to keep them busy for some time to come."

Some scientists believe that the new particle will prove to be the long-sought manifestation of the so-called weak force—one of the four basic forces in nature. The others are gravity, electromagnetism and the strong force that binds together the atomic nucleus.

It is also suspected that the particle may be related to a recently developed theory equating two of those forces — electromagnetism and the weak force— as manifestations of the same phenomenon. However, the properties of the newly discovered particle are not those predicted for either

Continued on Page 29, Column 1

The New York Times
Published: November 17, 1974

New and Surprising Type Of Atomic Particle Found

By WALTER SULLIVAN

Experiments conducted independently on the East and West Coasts have disclosed a new type of atomic particle.

Its properties are so unexpected that there are differing views as to how it might fit into current theories on the elementary nature of matter.

The experiments were done at the Stanford Linear Accelerator in Palo Alto, Calif., by a team under Dr. Burton Richter and at the Brookhaven National Laboratory in Upton, L.I., by a group under Dr. Samuel C. C. Ting of the Massachusetts Institute of Technology.

In a statement yesterday, the two men said:

"The suddenness of the discovery coupled with the totally unexpected properties of the particle are what make it so exciting. It is not like the particles we know and must have some new kinds of structure.

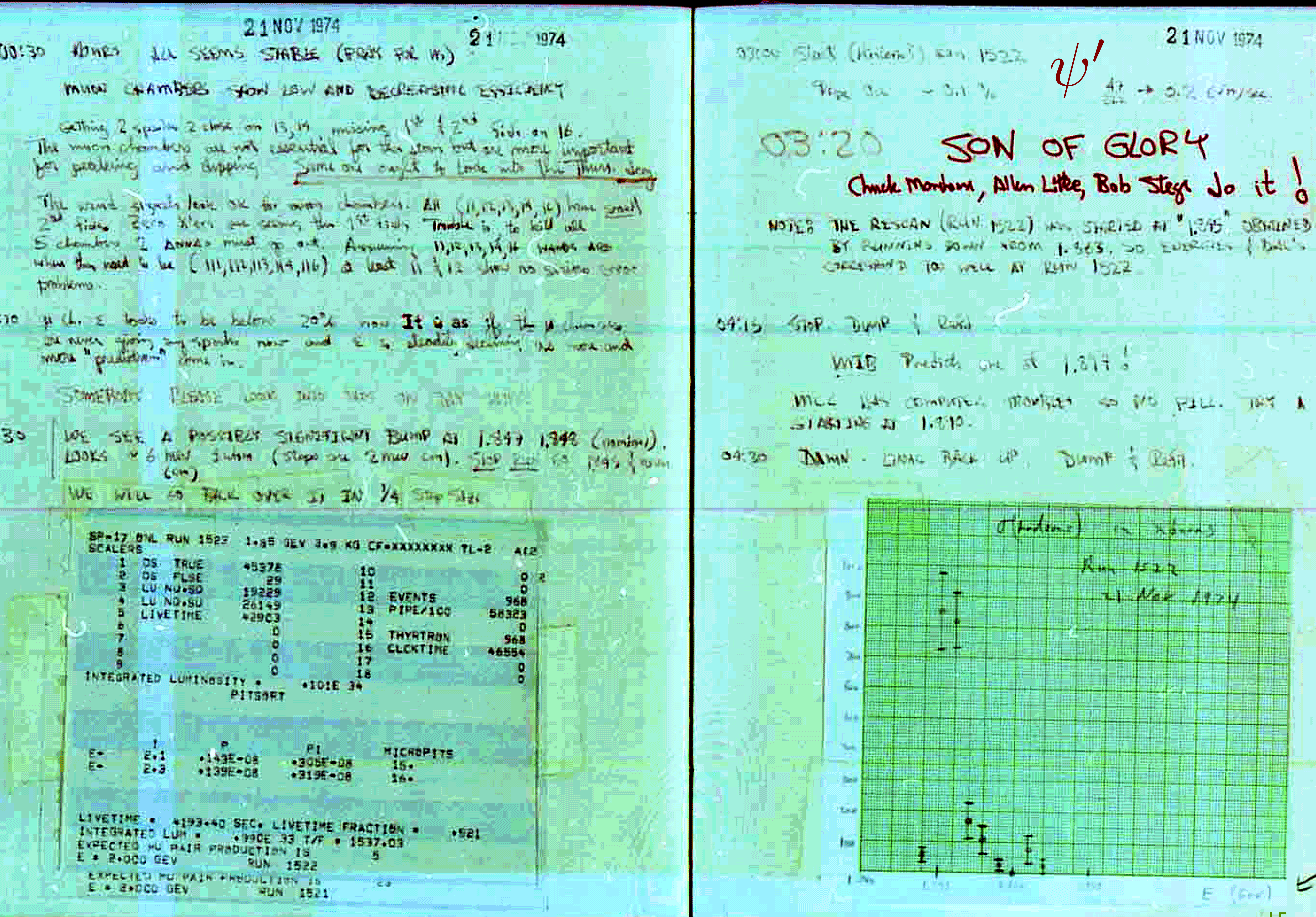
"The theorists are working frantically to fit it into the framework of our present knowledge of the elementary particle. We experimenters hope to keep them busy for some time to come."

Some scientists believe that the new particle will prove to be the long-sought manifestation of the so-called weak force—one of the four basic forces in nature. The others are gravity, electromagnetism and the strong force that binds together the atomic nucleus.

It is also suspected that the particle may be related to a recently developed theory equating two of those forces — electromagnetism and the weak force— as manifestations of the same phenomenon. However, the properties of the newly discovered particle are not those predicted for either

Continued on Page 29, Column 1

The New York Times
Published: November 17, 1974



ψ'

21 NOV 1974

00:30 Power — All seems stable

Muon chambers show low and decreasing efficiency

Getting 2 sparks 2 close on 13, 14 missing 1st & 2nd side on 16. The muon chambers are not essential for the scan but are most important for ... Someone ought to look into this thing.

μ ch. ε looks to be below 20% now. It is as if the μ chambers are never giving any sparks now and ε is steadily ...

Somebody please look into this ...

30 We see a possibly significant bump at 1.847 1.848 (cm). Looks ≈ 6 MeV ... (steps are 2 MeV cm). ...

We will go back over it in 1/4 step size

```
SP-17 BNL RUN 1522  1.85 GEV 3.9 KG CF=XXXXXXXX TL=2   A12
SCALERS
    1  DS  TRUE     45378        10                      0 2
    2  DS  FLSE        29        11                      0
    3  LU NU.SO     19229        12  EVENTS            968
    4  LU ND.SU     26149        13  PIPE/100        58323
    5  LIVETIME     42903        14                      0
    6                   0        15  THYRTRON          968
    7                   0        16  CLCKTIME        46554
    8                   0        17                      0
    9                   0        18                      0
INTEGRATED LUMINOSITY =      .101E 34
                    PITSORT

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

LIVETIME =  4193.40 SEC. LIVETIME FRACTION =      .921
INTEGRATED LUM =      .990E 33 T/F = 1537.03
EXPECTED MU PAIR PRODUCTION IS          5
E = 2.000 GEV          RUN  1522
EXPECTED MU PAIR PRODUCTION IS
E = 2.000 GEV          RUN  1521
```

21 NOV 1974

03:00 Start ... Run 1522

03:20 SON OF GLORY

Chuck Morehouse, Allen Litke, Bob Stege do it!

Notes: The rescan (Run 1522) was started at "1.845" obtained by running down from 1.863, so energies ... correspond too well at Run 1522.

04:15 Stop. Dump & Run

WTB Predicts one at 1.847!

... starting at 1.840.

04:30 Damn ... back up. Dump & Run.

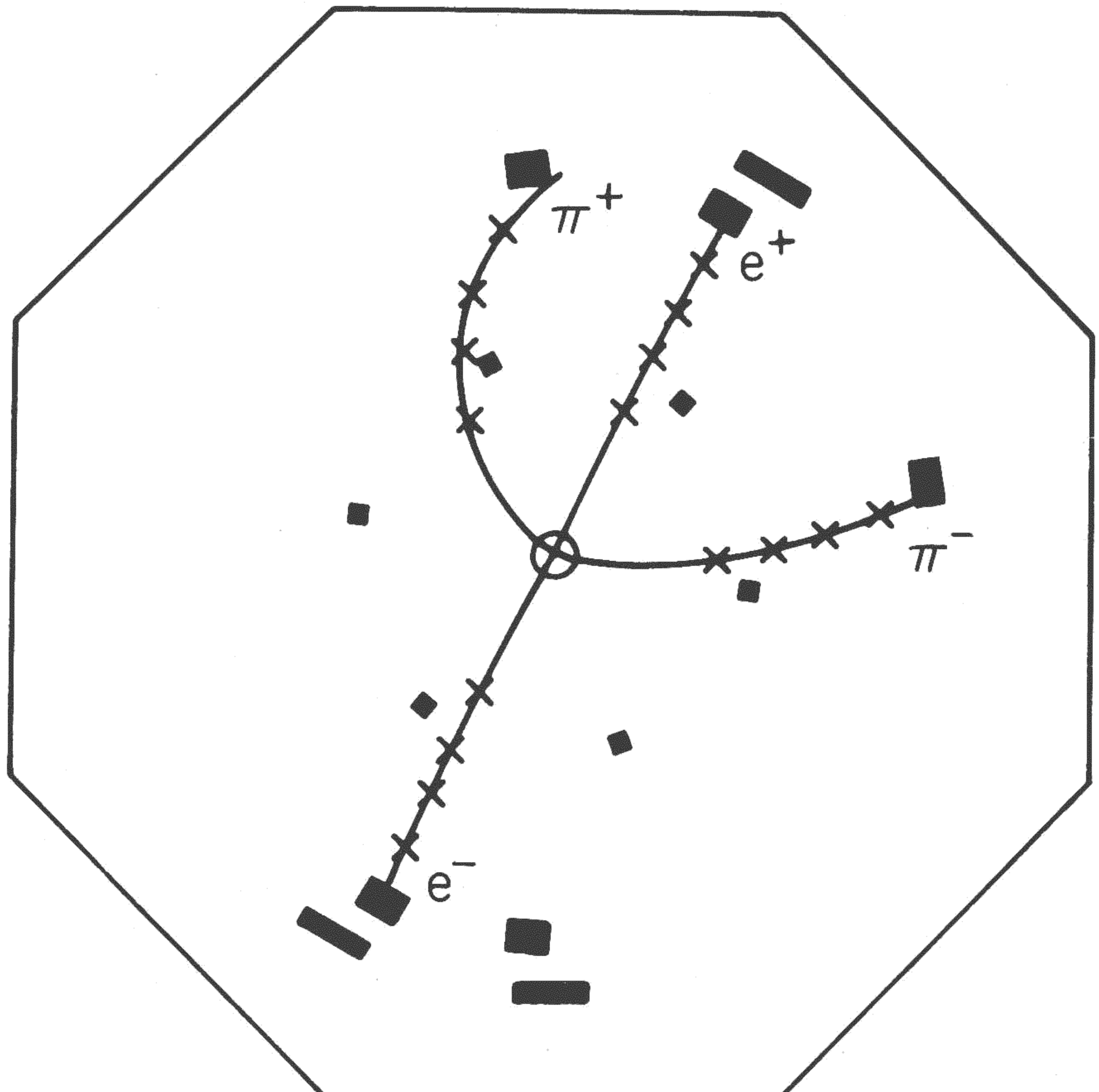
σ(hadrons)

Run 1522

21 Nov 1974

E (GeV)

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



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.

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.

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.

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.

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.

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

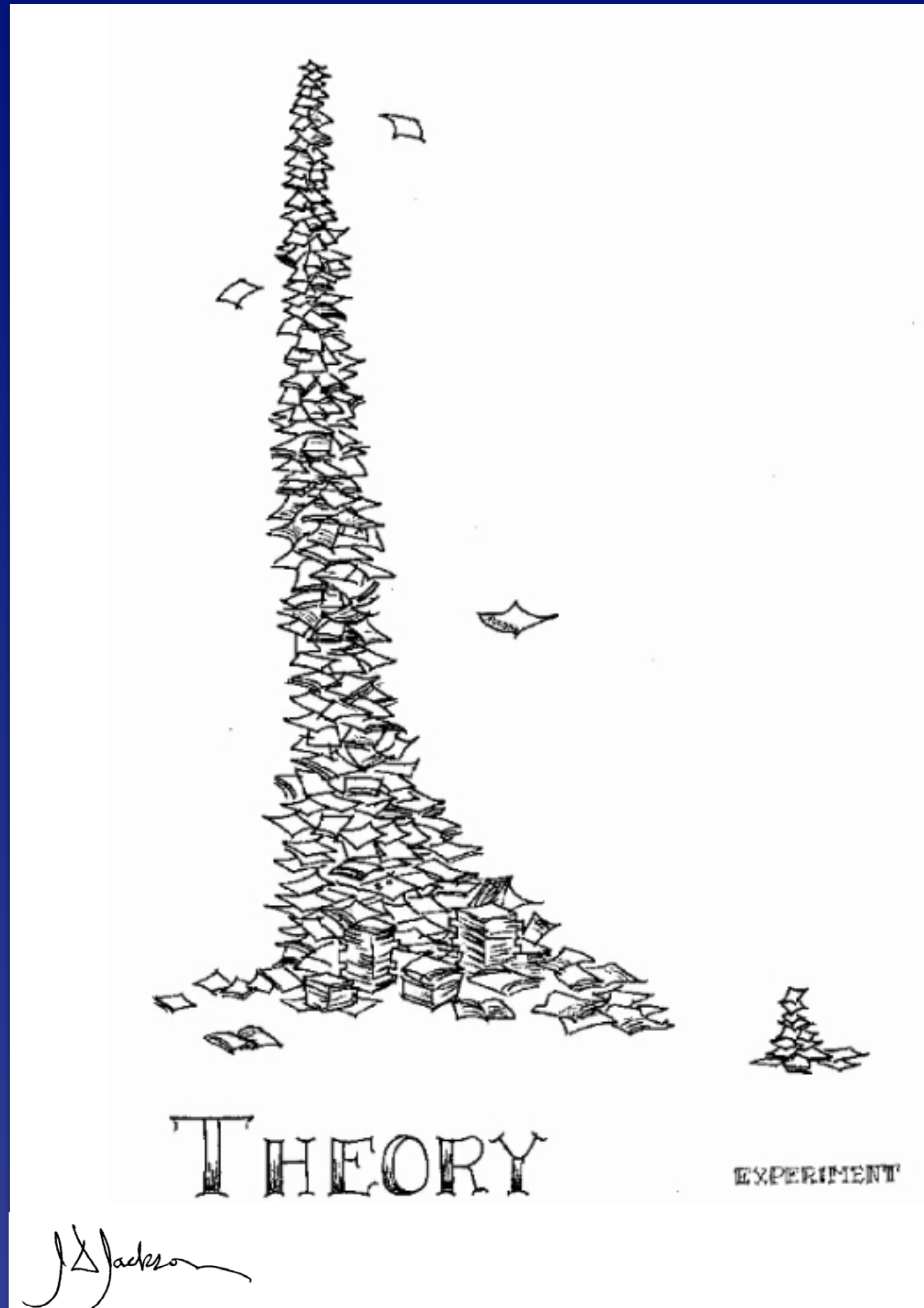
and

Tai Tsun Wu
Gordon McKay Laboratory, Harvard University, Cambridge, Massachusetts 02138

and

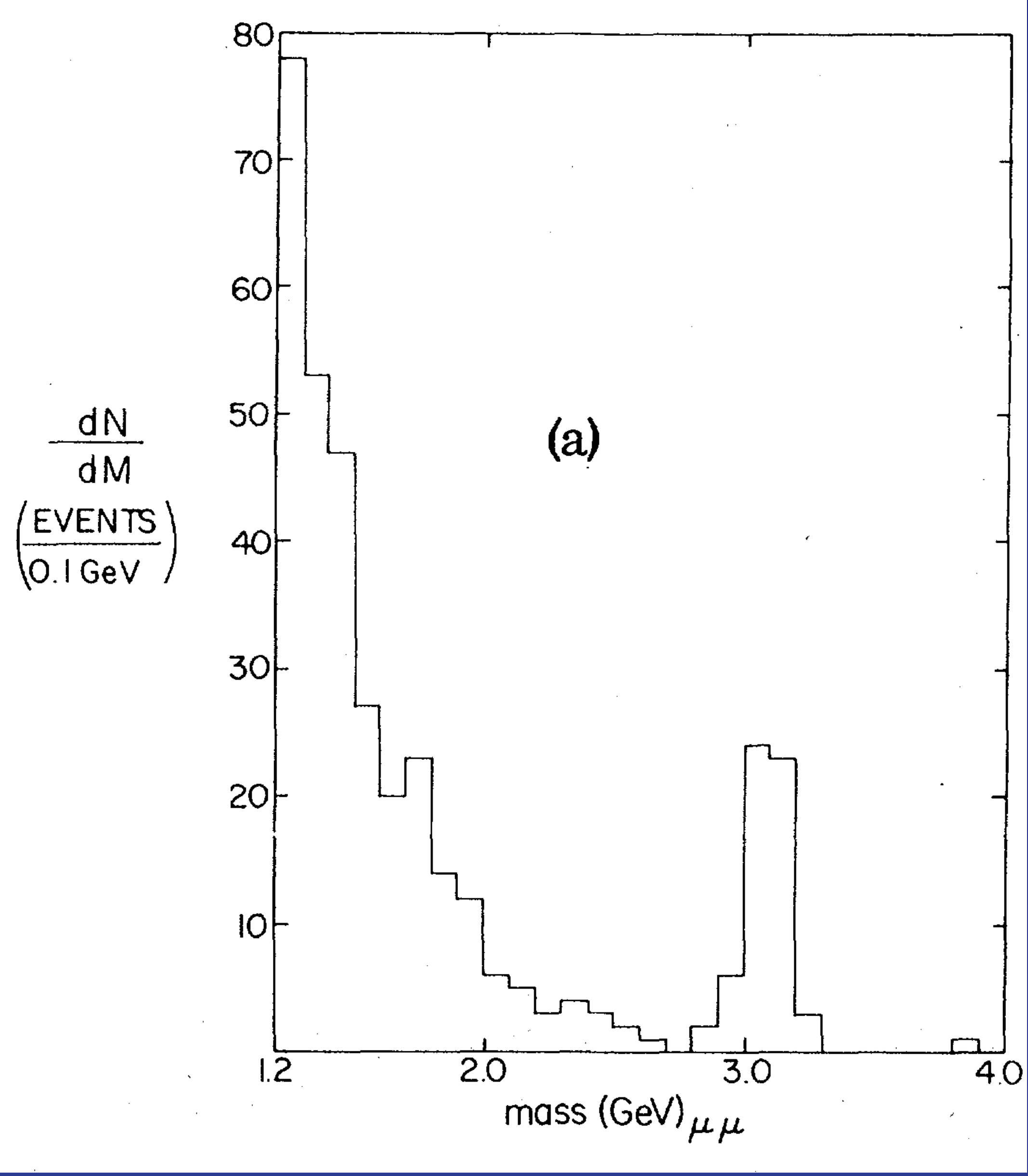
Chen Ning Yang
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794
(Received 25 November 1974)

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

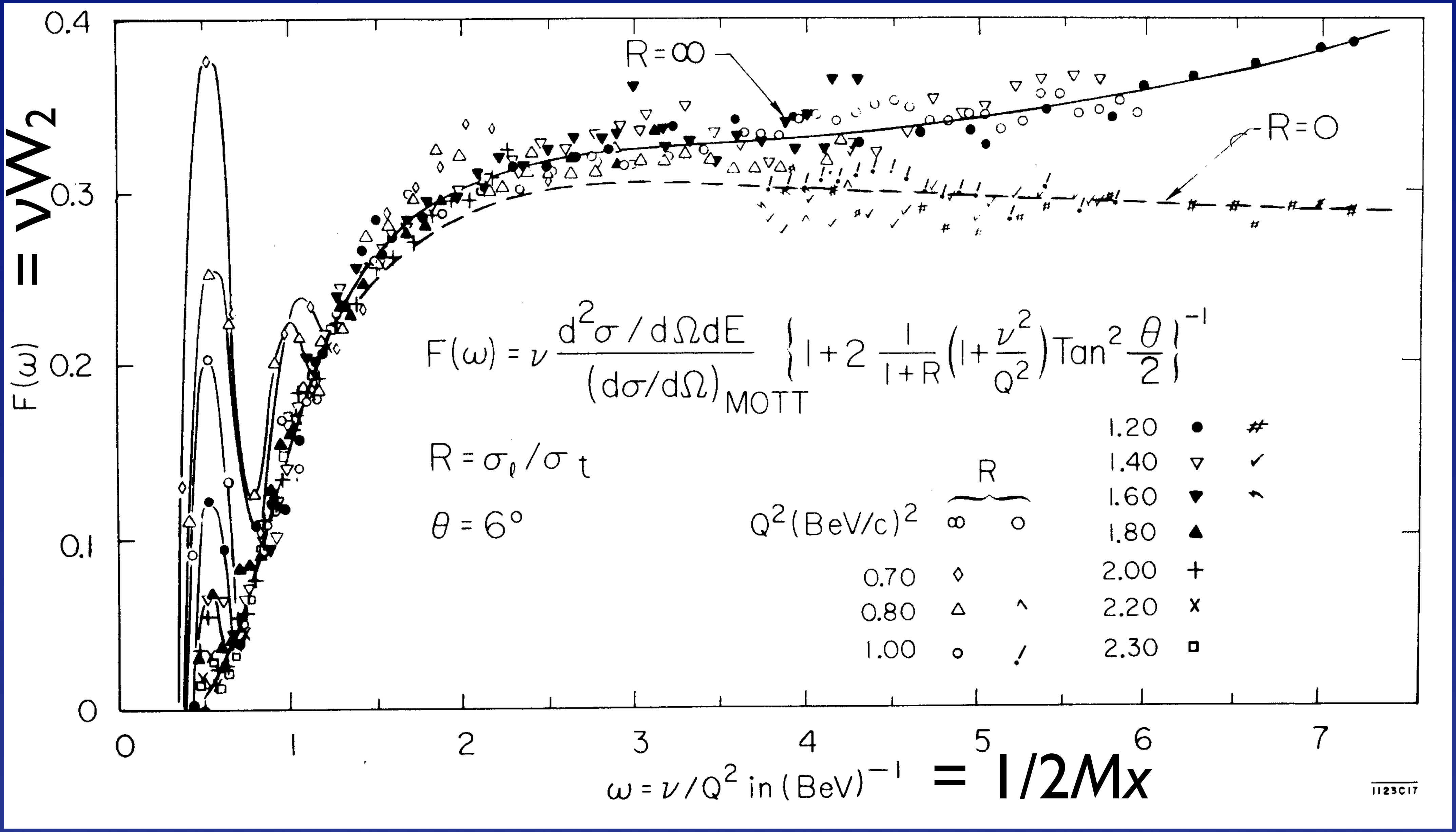
February 1975: It's a hadron!

Fermilab E87 – Broadband Photon Beam



Diffractive γ Be $\rightarrow$ J/ψ + ...; σ(J/ψN) $\approx$ 1 mb

SLAC–MIT (Bjorken) Scaling Evidence (1968)



Quark model, parton model …

Gargamelle (1973)

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

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

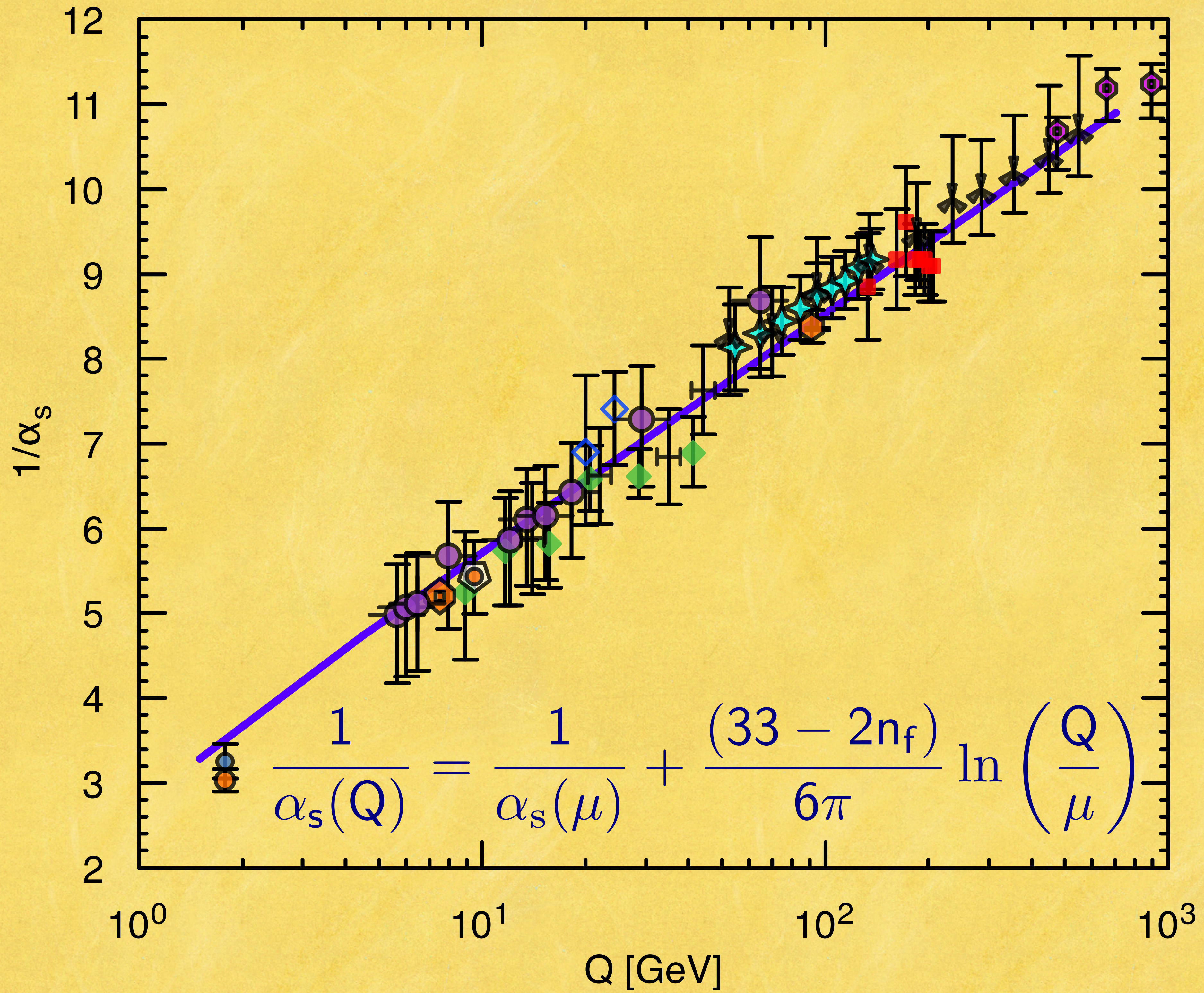
A systematic discussion of the phenomenology of charmed particles is presented with an eye to experimental searches for these states. We begin with an attempt to clarify the theoretical framework for charm. We then discuss the $SU(4)$ spectroscopy of the lowest lying baryon and meson states, their masses, 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:

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

$$BR(\phi_c \to e^+e^-) \approx 1\%$$

Evolution of the strong coupling "constant"



$$\frac{1}{\alpha_s(Q)} = \frac{1}{\alpha_s(\mu)} + \frac{(33-2n_f)}{6\pi}\ln\left(\frac{Q}{\mu}\right)$$

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)

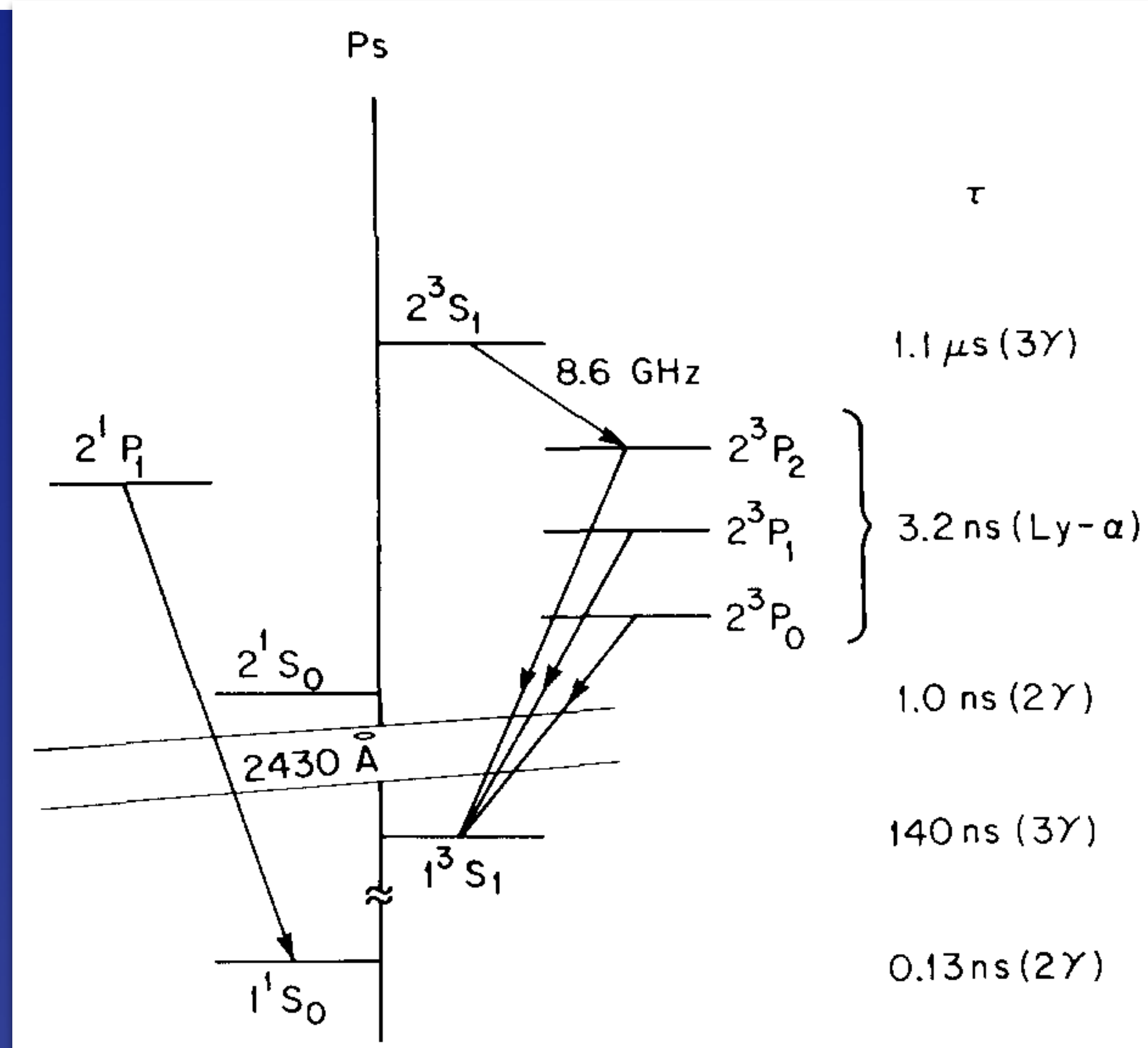
The effects of new, heavy quarks are examined in a colored quark-gluon model. The e^+e^- total cross section scales for energies far above any quark mass. However, it is much greater than the scaling prediction in a domain about the nominal two-heavy-quark threshold, despite $\sigma_{e^+e^-}$ being a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

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.



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.

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.

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.

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.

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)

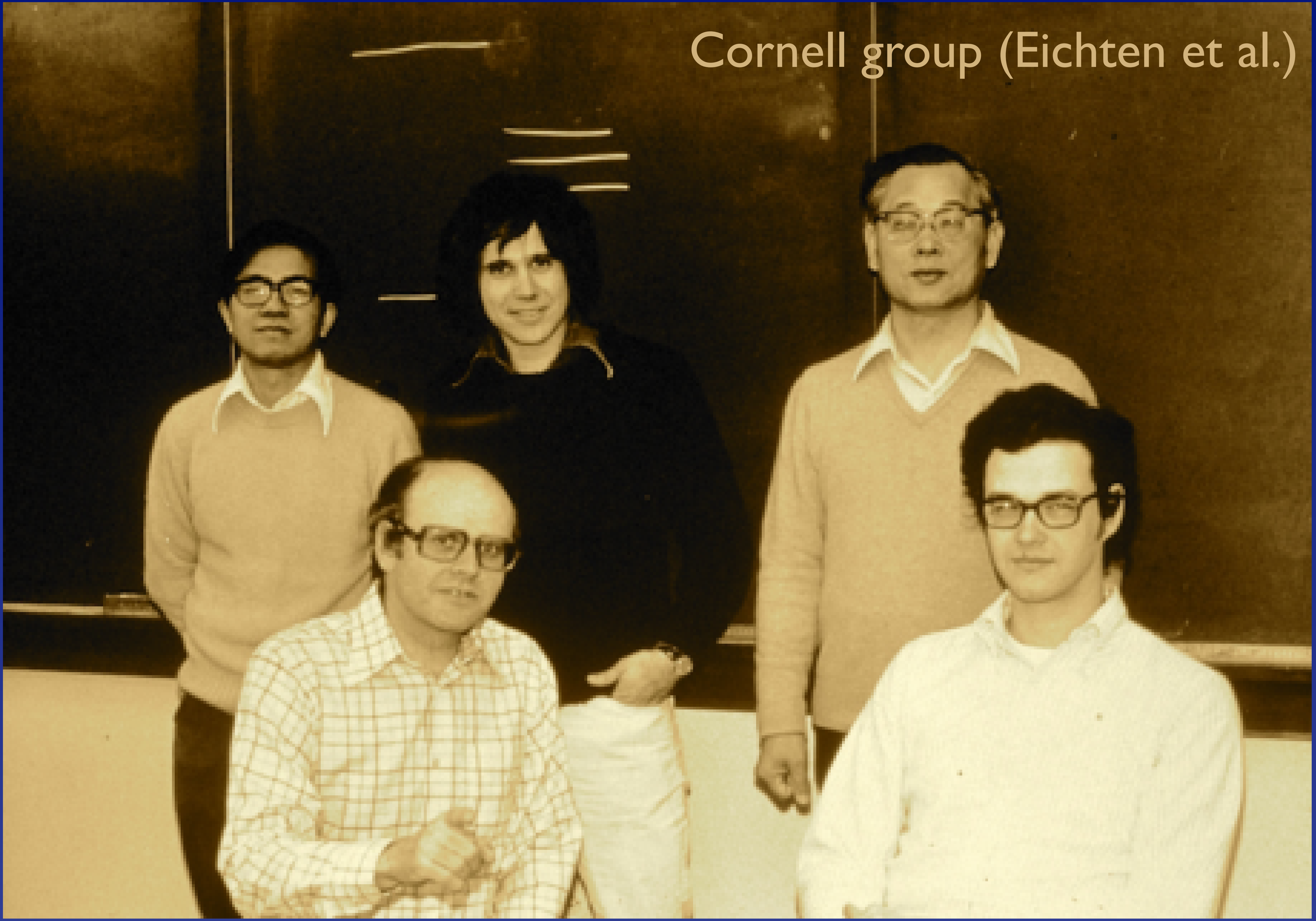
The interpretation of the narrow boson resonances at 3.1 and 3.7 GeV as charmed quark-antiquark bound states implies the existence of other states. Some of these should be copiously produced in the radiative decays of the 3.7-GeV resonance. We estimate the masses and decay rates of these states and emphasize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


Cornell group (Eichten et al.)

Volume 57B, number 4 PHYSICS LETTERS 21 July 1975

OBSERVATION OF THE TWO PHOTON CASCADE $3.7 \to 3.1 + \gamma\gamma$ 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 $3.7 \to (3.1 \to \mu^+\mu^-) + \gamma\gamma$ indicates the existence of at least one intermediate state with even charge conjugation at a mass around 3.52 GeV or 3.26 GeV.

PHYSICAL REVIEW LETTERS

VOLUME 35 29 SEPTEMBER 1975 NUMBER 13

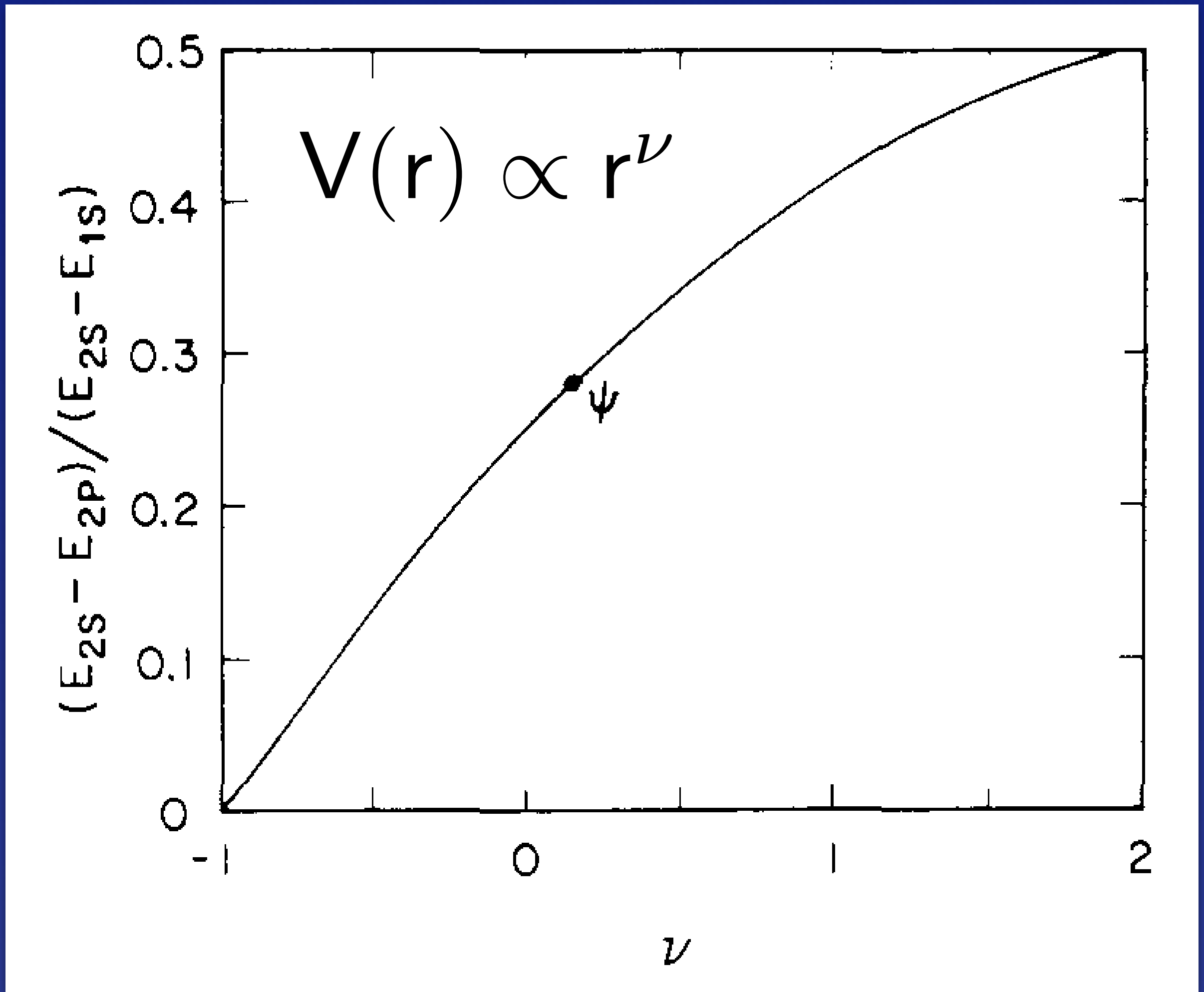
$\psi(3684)$ Radiative Decays to High-Mass States*

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



Curvature of potential gives order of levels

Volume 57B, number 4 PHYSICS LETTERS 21 July 1975

OBSERVATION OF THE TWO PHOTON CASCADE 3.7 → 3.1 + γγ 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 $3.7 \to (3.1 \to \mu^+\mu^-) + \gamma\gamma$ indicates the existence of at least one intermediate state with even charge conjugation at a mass around 3.52 GeV or 3.26 GeV.

PHYSICAL REVIEW LETTERS

VOLUME 35 29 SEPTEMBER 1975 NUMBER 13

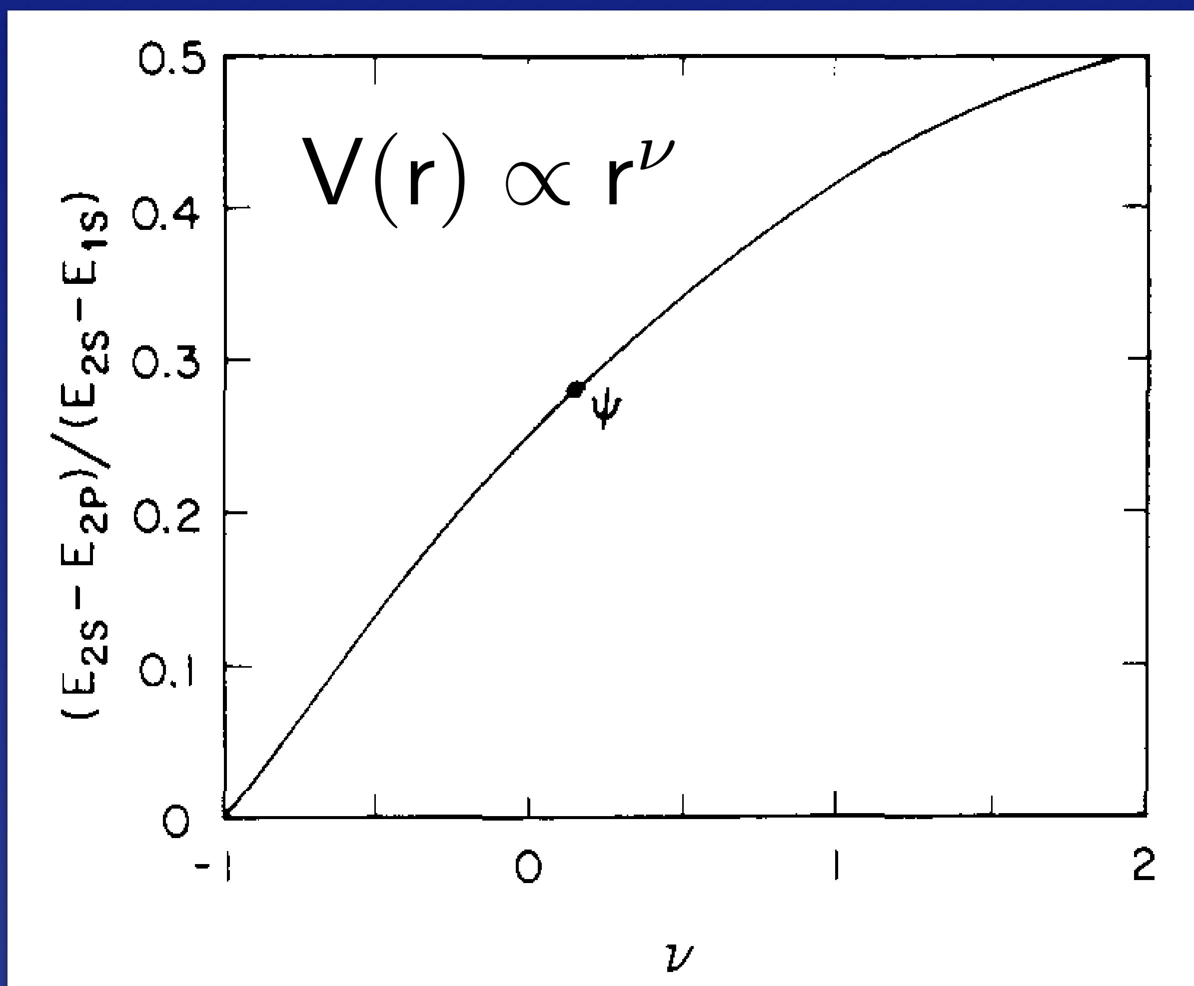
ψ(3684) Radiative Decays to High-Mass States*

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



Curvature of potential gives order of levels

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

Charmonium: hadronic transitions

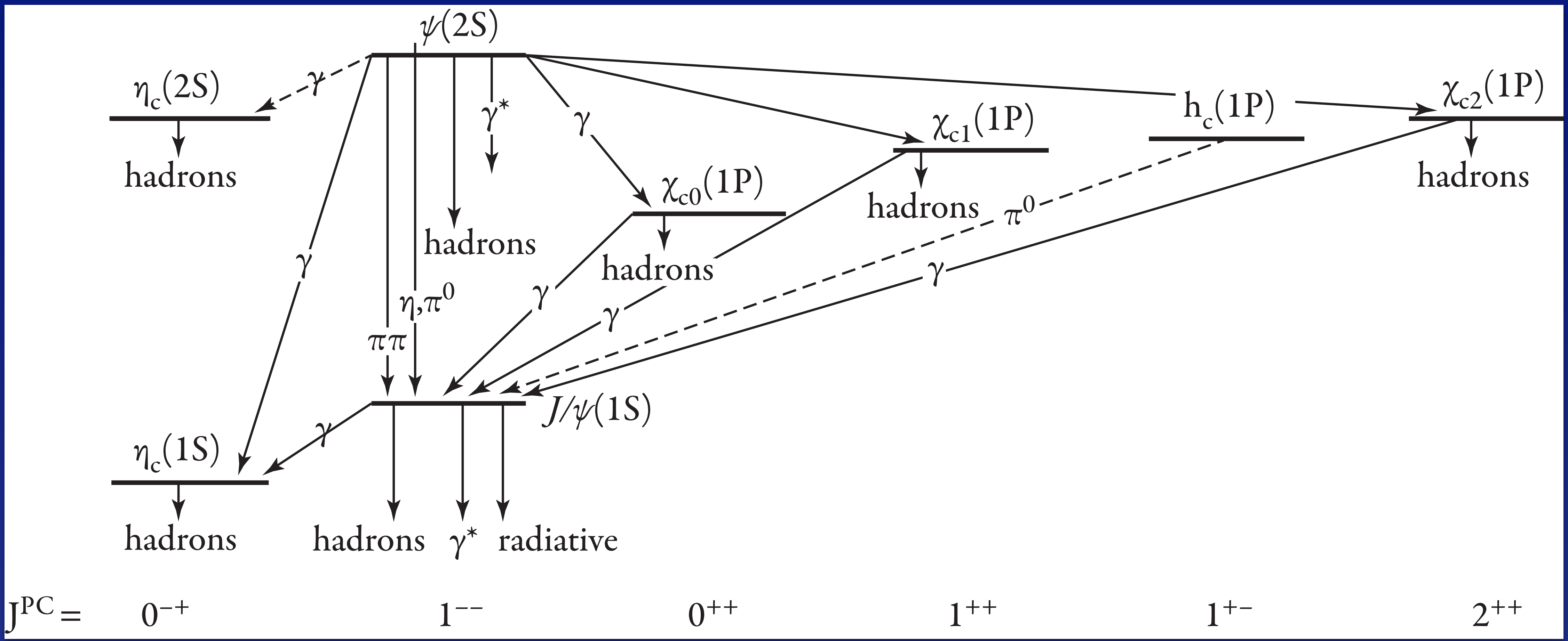
$\mathrm{BR}(\psi(2S) \to \pi^+\pi^- \, J/\psi) \approx 34\%$

$\mathrm{BR}(\psi(2S) \to \pi^0\pi^0 \, J/\psi) \approx 18\%$

<u>Soft-pion theorems</u>
<u>Gottfried's color multipole expansion</u>

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," hep-ph/9811359

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, …

$J/\psi \to \gamma + \text{Gluonium?}$

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

Non-$q\overline{q}$ Candidates

OMITTED FROM SUMMARY TABLE

For a review on gluonium and other non-$q\overline{q}$ candidates see PDG 06, Journal of Physics (generic for all A,B,E,G) **G33** 1 (2006). See also the "Note on scalar mesons" in the $f_0(500)$ Particle Listings, our note "New charmonium-like states" in PDG 08, Physics Letters **B667** 1 (2008), and the extensive chapter on Spectroscopy in N. Brambilla *et al.* (Quarkonium Working Group), The European Physical Journal **C71** 1534 (2011).

BRAMBILLA	11	EPJ C71 1534	N. Brambilla *et al.*	(Quarkonium Working Group)
PDG	08	PL B667 1	C. Amsler *et al.*	(PDG Collab.)
PDG	06	JP G33 1	W.-M. Yao *et al.*	(PDG Collab.)

General review: Ochs (2013)

E. Bloom, 1982: "… the experimental search for such states has proven to be a difficult and confusing one, with a number of guiding principles losing credibility as the field has matured."

Initial Charmonium Lessons

Quarks are real mechanical objects

Constituents are spin-1/2

Charm exists; $\psi(3770)$

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°, B°.

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.

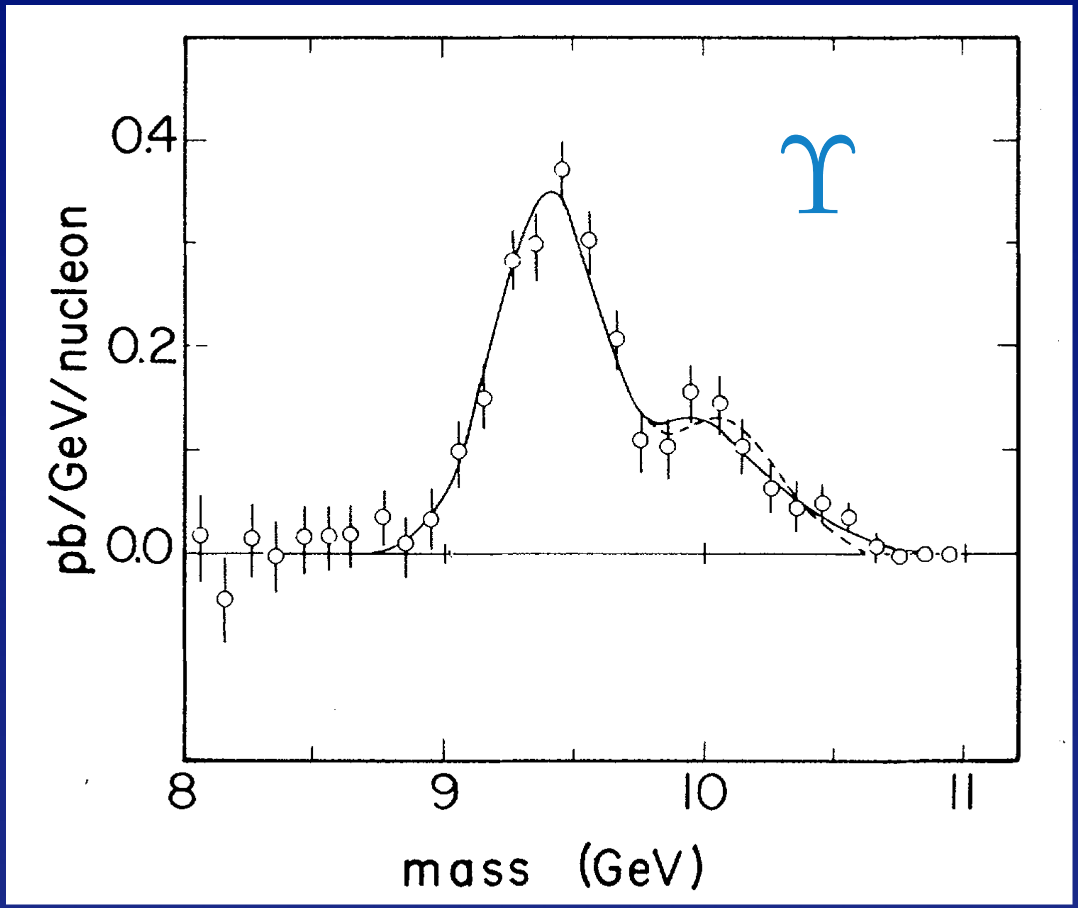
5. Extend the Experiment #70 study of single leptons in the double arm arrangement, i.e. $W^\pm$ etc. Publish these and become famous.

6. Look at $\pi^\circ\pi^\circ$ pairs by double conversion of π°- γ's 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).

CERN COURIER

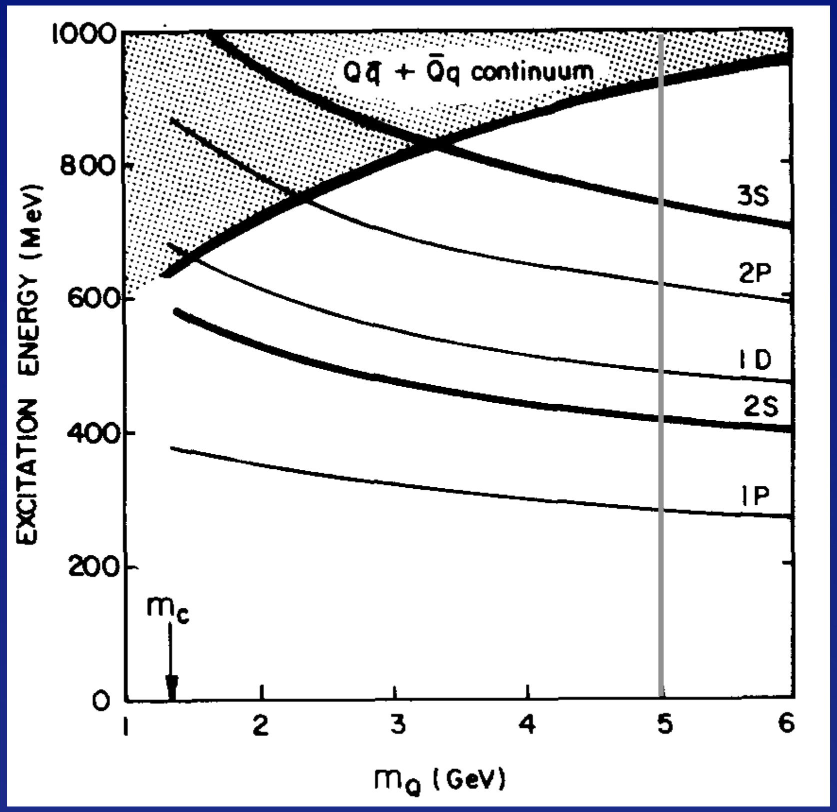
NO. 7/8 VOL. 17 JULY/AUGUST 1977

EPS Budapest 1977



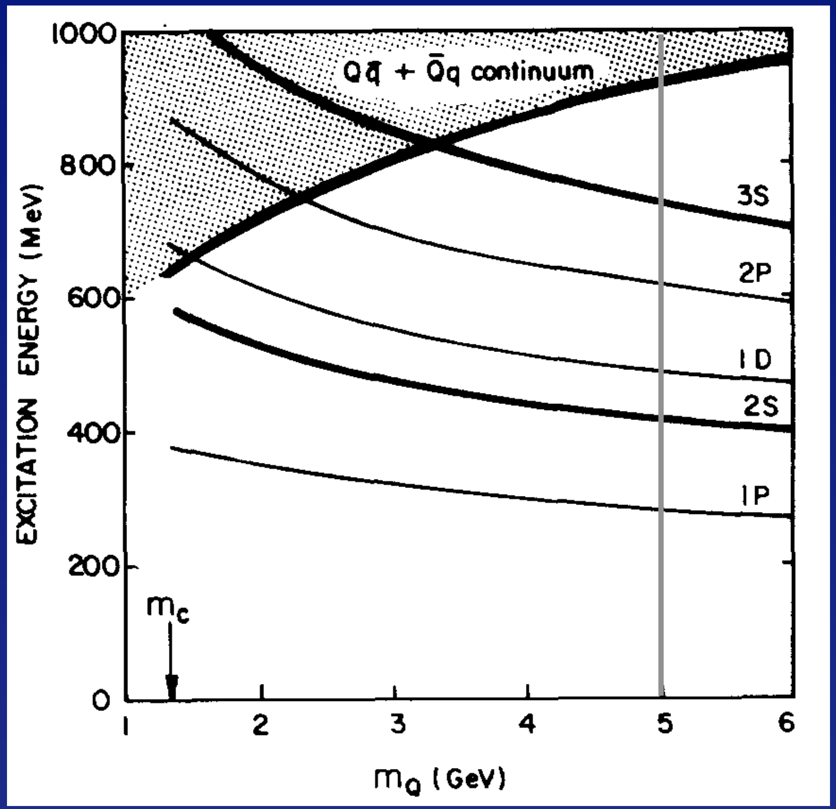
E288	$M(\Upsilon') - M(\Upsilon)$	$M(\Upsilon'') - M(\Upsilon)$
Two-level fit	650 ± 30 MeV	
Three-level fit	610 ± 40 MeV	1000 ± 120 MeV
$M(\psi') - M(\psi)$	≈ 590 MeV	

Eichten & Gottfried: CESR Proposal (November 1976)



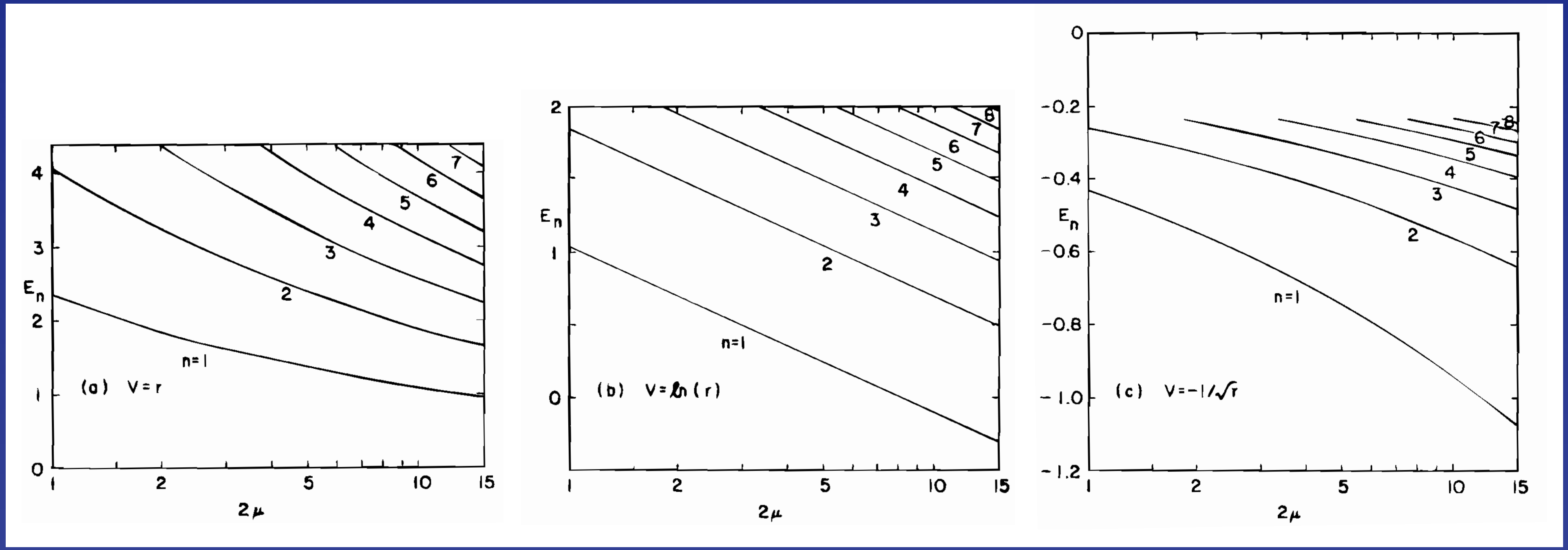
E(2S)–E(1S) = 420 MeV

Eichten & Gottfried: CESR Proposal (November 1976)



E(2S)–E(1S) = 420 MeV

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



Why choose 5 GeV?

Excess events at high inelasticity in

$$\bar{\nu}_\mu \mathrm{N} \to \mu^+ + \ldots$$

HPWF "high-y anomaly" explained by

$$\begin{pmatrix} u \\ b \end{pmatrix}_{\mathrm{R}} \quad \mathrm{m}_b \approx (4-5)\ \mathrm{GeV} \quad \text{Barnett}$$

Why choose 5 GeV?

Excess events at high inelasticity in

$$\bar{\nu}_\mu \mathrm{N} \to \mu^+ + \ldots$$

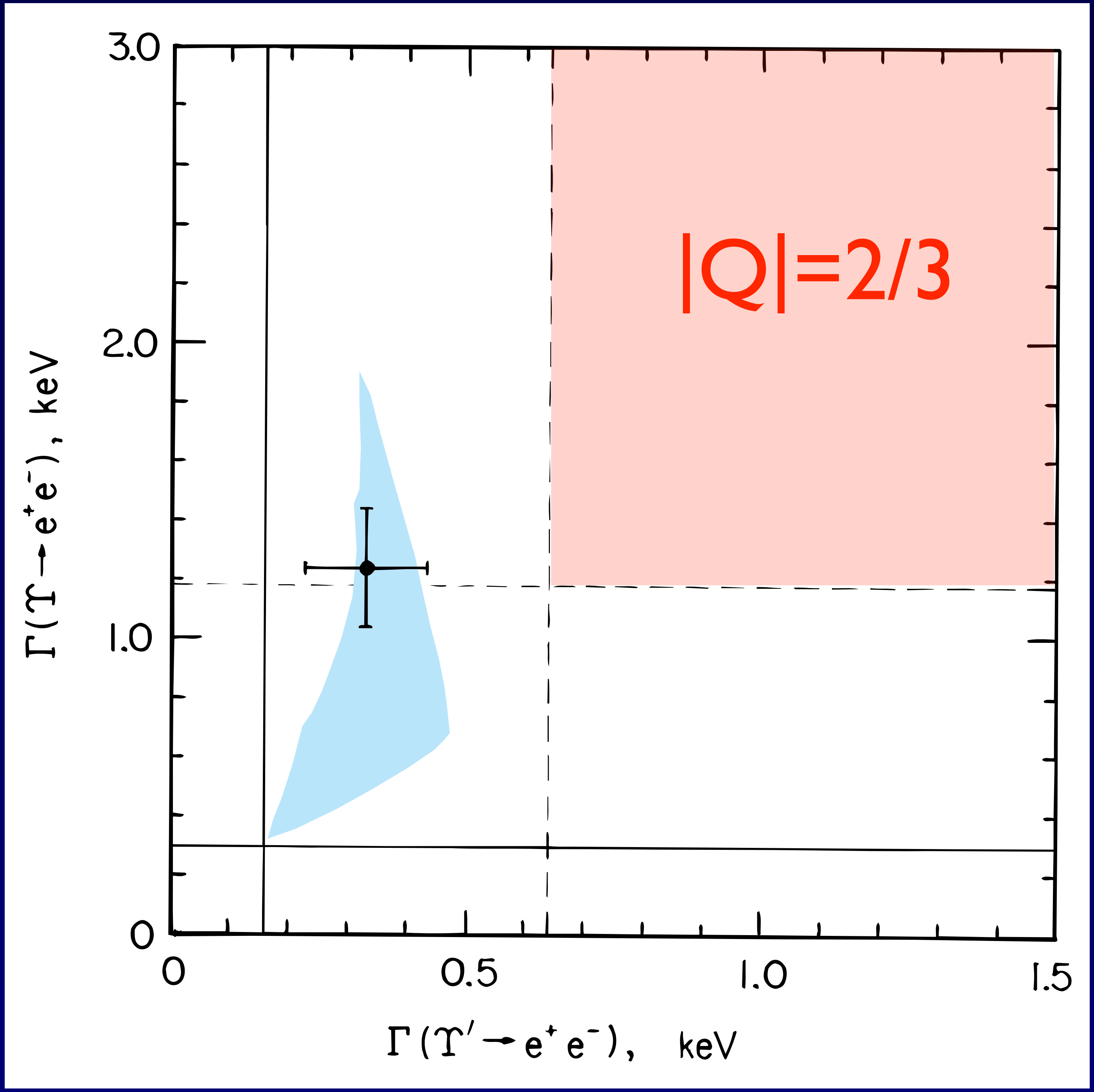
HPWF "high-y anomaly" explained by

$$\begin{pmatrix} u \\ b \end{pmatrix}_{\mathrm{R}} \quad \mathrm{m}_b \approx (4-5)\ \mathrm{GeV} \quad \text{Barnett}$$

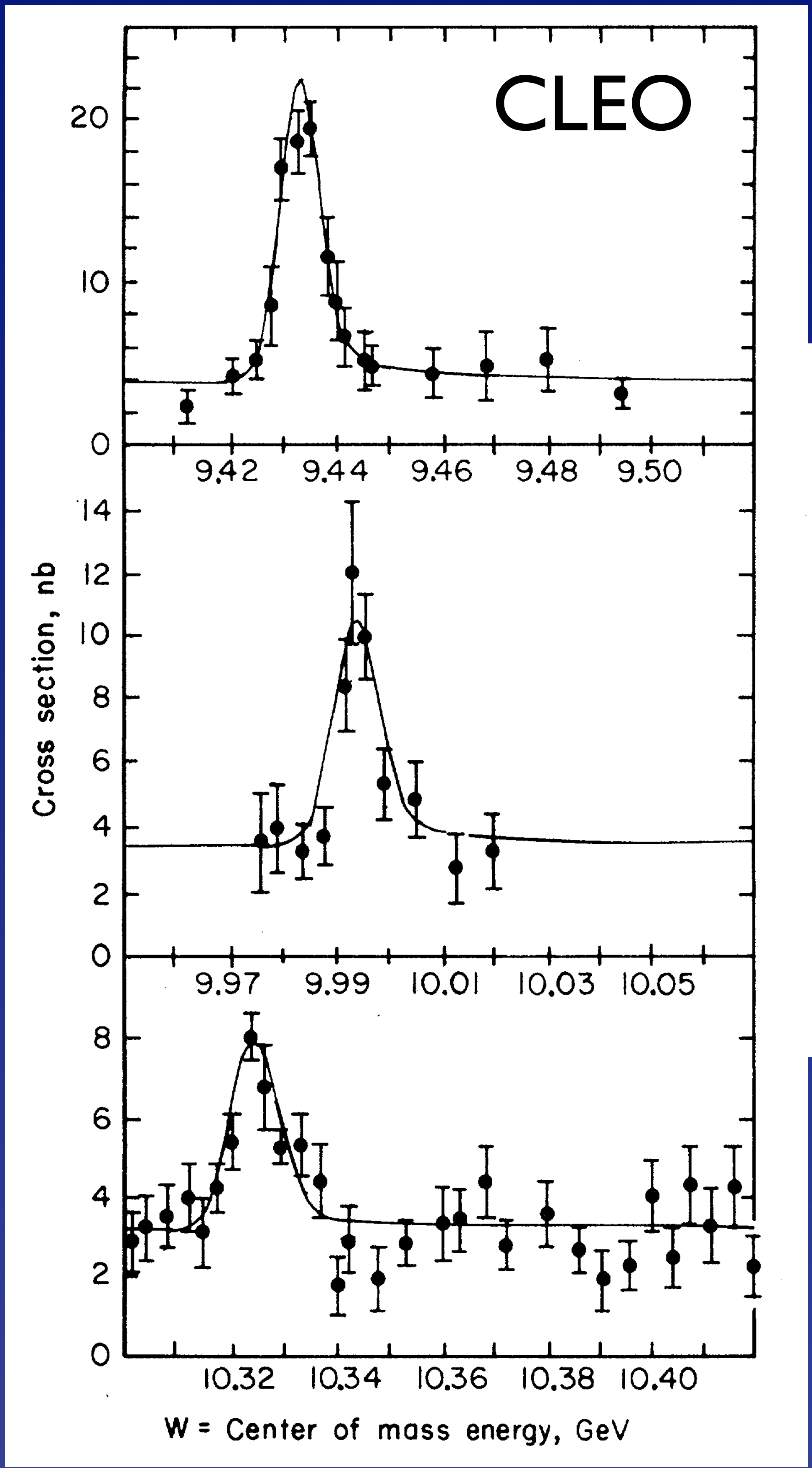
Also at Budapest …

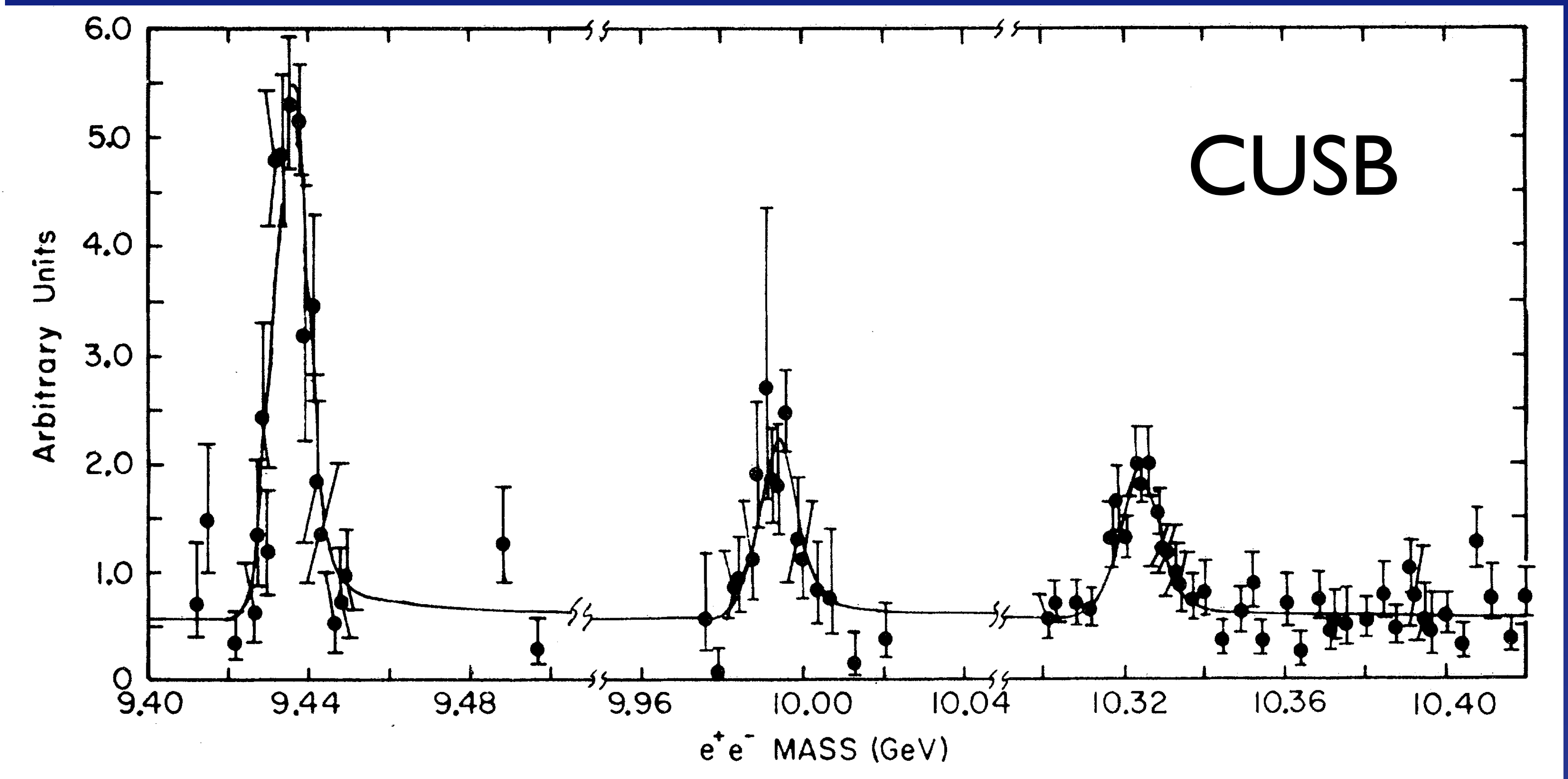
CDHS Experiment ruled out high-y anomaly

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



CESR resolves 3 ϒ levels 1979-80



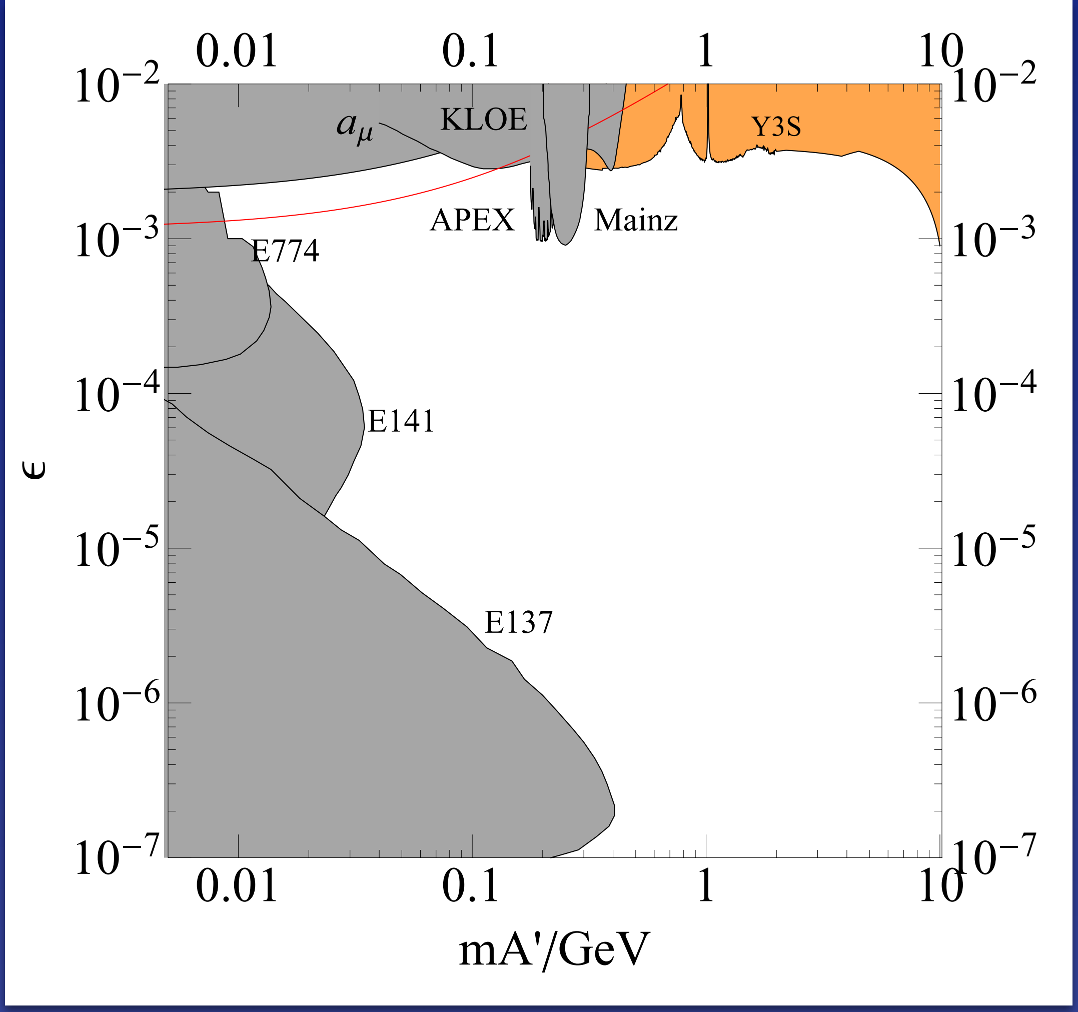


ϒ(4S) launches B physics 1980

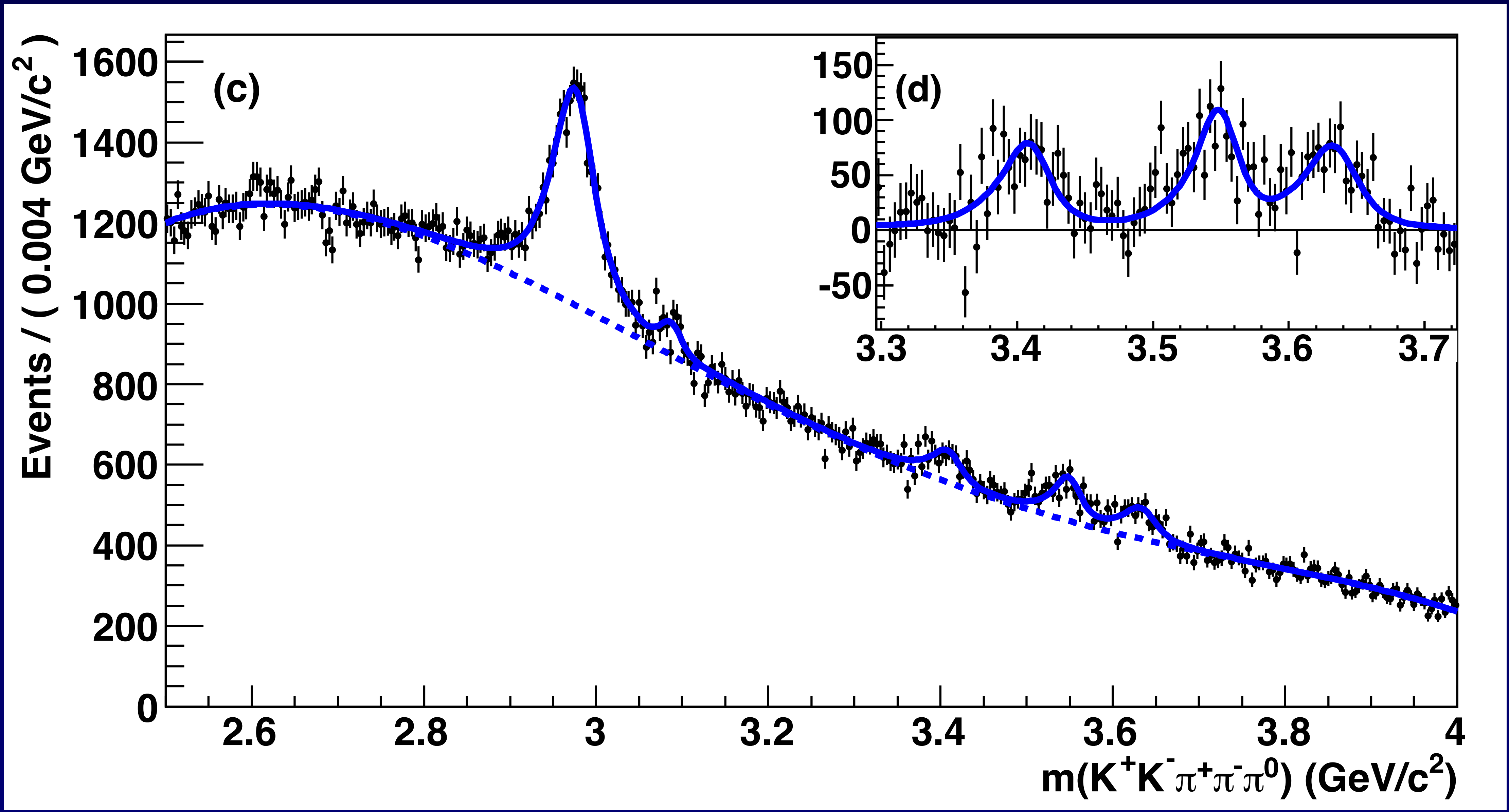
Quarkonium decay into new particles?

BaBar light-Higgs & dark-photon searches

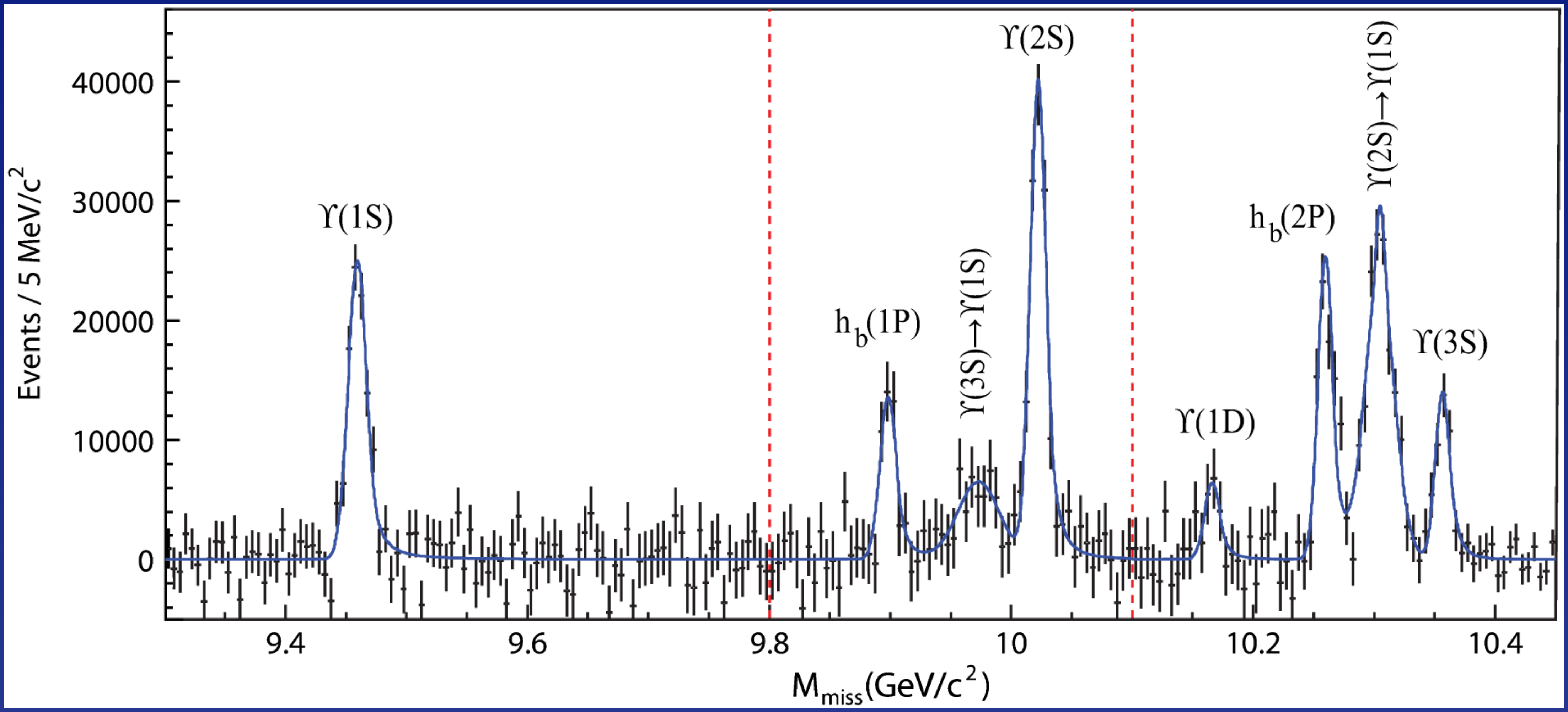
Mode	Mass range (GeV)	BF upper limit (90% CL)
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	$0.21 < m_A < 9.3$	$(0.3 - 8.3)\times 10^{-6}$
$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	$4.0 < m_A < 10.1$	$(1.5 - 16)\times 10^{-5}$
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ hadrons	$0.3 < m_A < 7.0$	$(0.1 - 8)\times 10^{-5}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to \chi\bar{\chi}$	$m_\chi < 4.5$ GeV	$(0.5 - 24)\times 10^{-5}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible	$m_A < 9.2$ GeV	$(1.9 - 37)\times 10^{-6}$
$\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible	$m_A < 9.2$ GeV	$(0.7 - 31)\times 10^{-6}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to g\bar{g}$	$m_A < 9.0$ GeV	$10^{-6} - 10^{-2}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to s\bar{s}$	$m_A < 9.0$ GeV	$10^{-5} - 10^{-3}$



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



BELLE h_b(1P) and h_b(2P): $\pi^+\pi^- + \mathrm{MM}$ at $\Upsilon(5S)$



Initial Upsilon Lessons

Requires *one* new quark species

Interquark interaction is flavor-independent

Potential shape measured

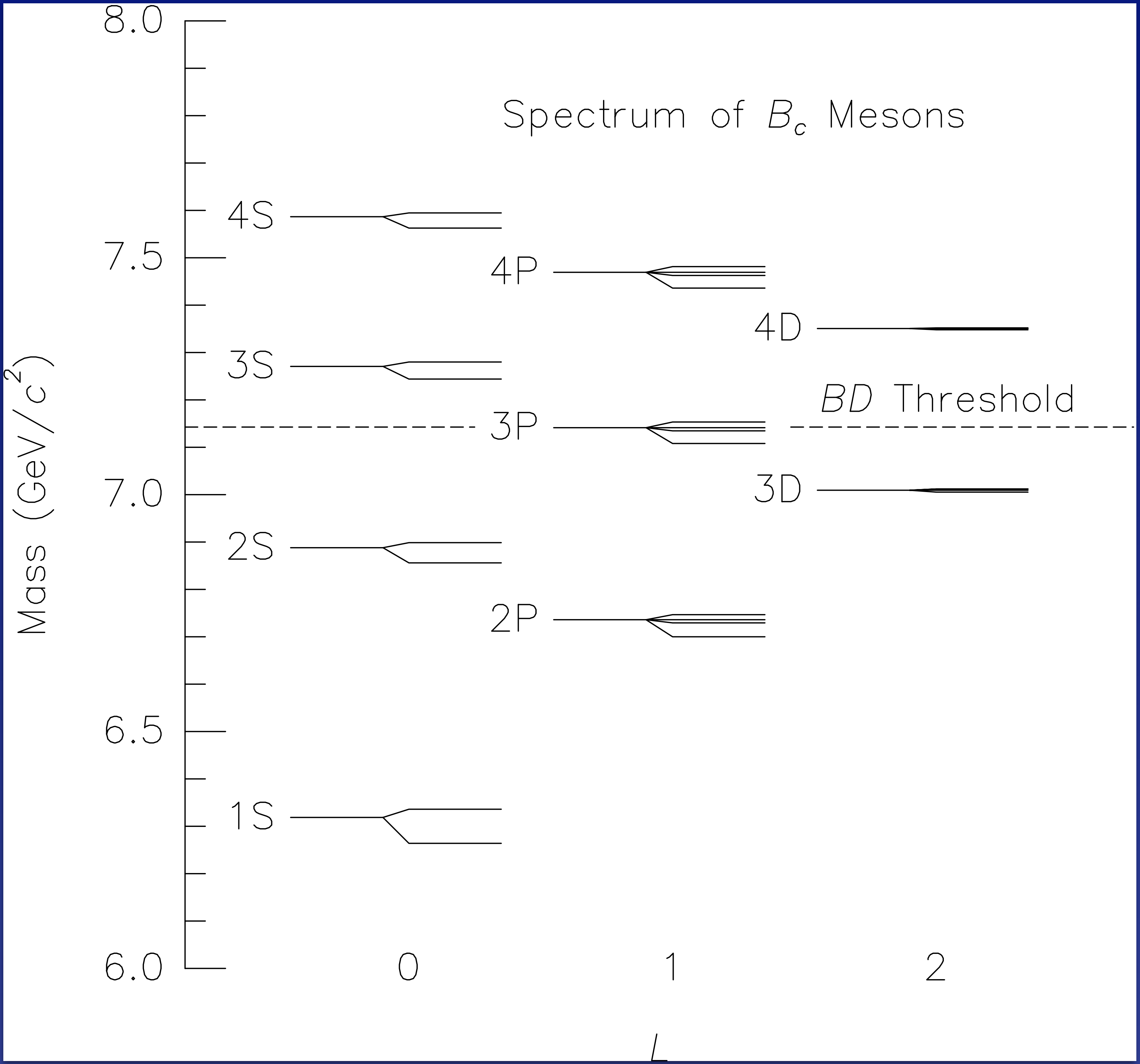
$\Upsilon(4S)$ is a fountain of *B* mesons

Υ decays allow new-particle searches

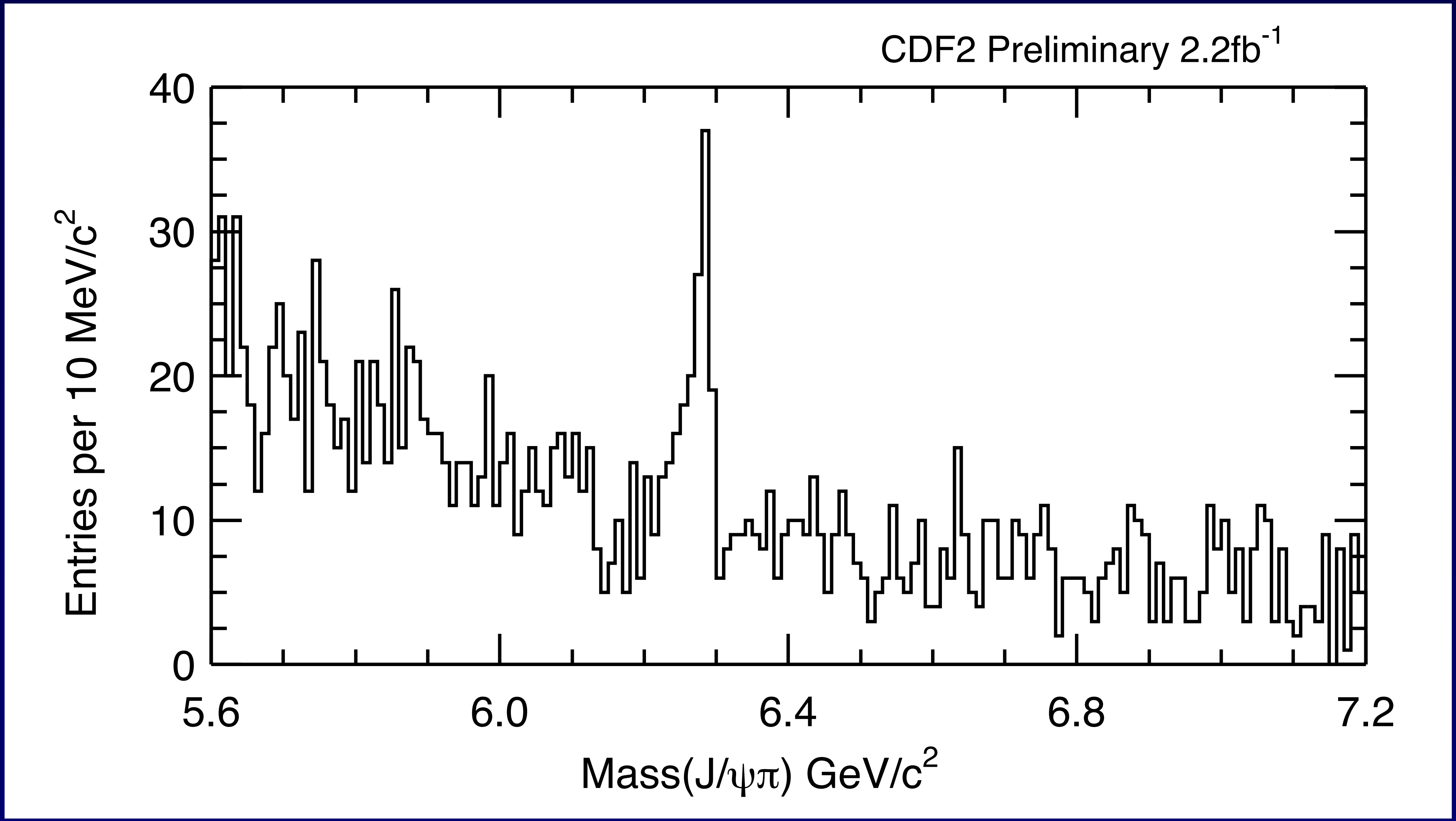
$\Upsilon(5S)$ a source of B_s mesons

. . .

Anticipating B_c (1994)

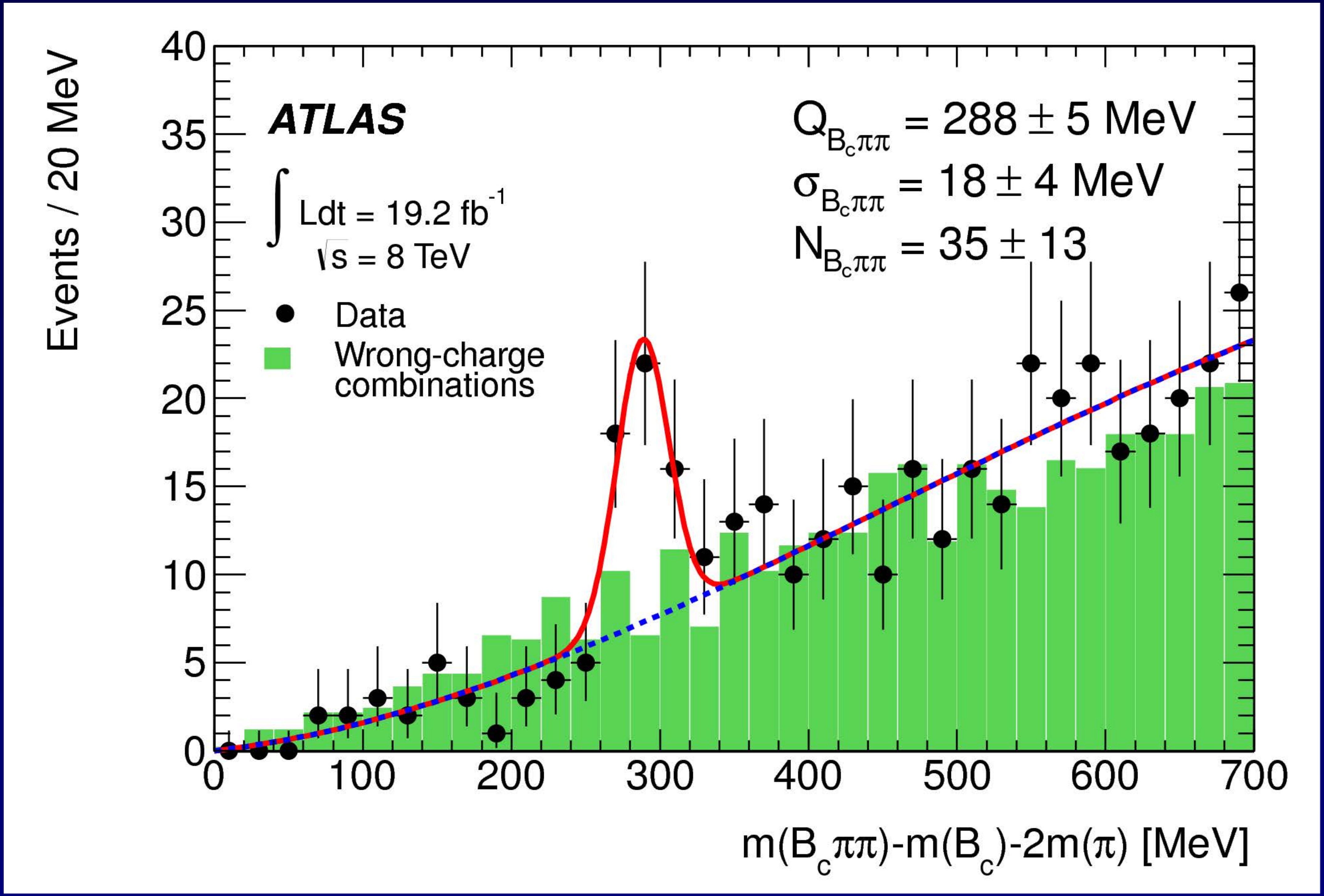


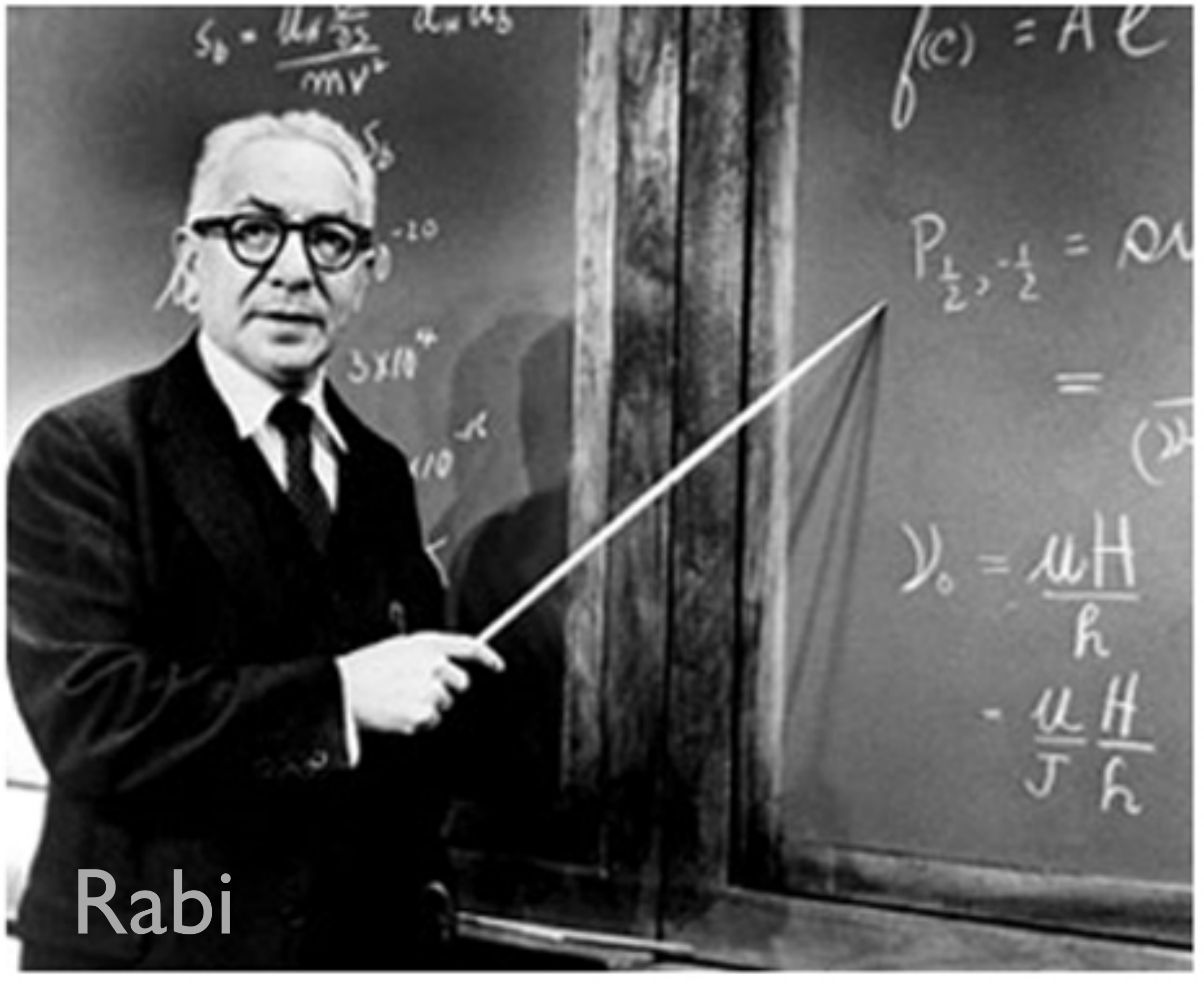
B_c (6276)



Quarkonium transmutation

B_c' (6842 ± 7)

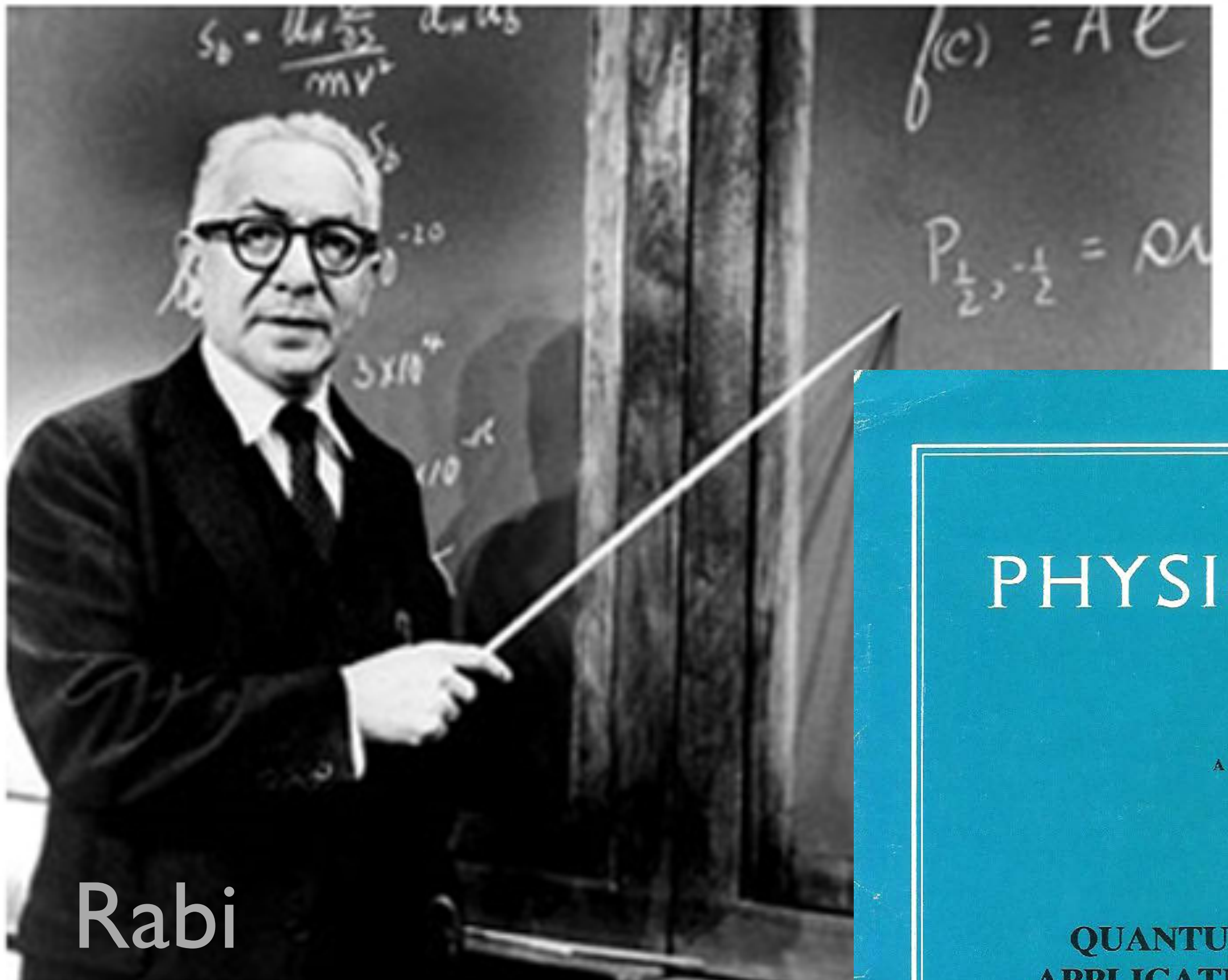

ATLAS
∫ Ldt = 19.2 fb⁻¹
√s = 8 TeV
Data
Wrong-charge combinations
Q_{B_cππ} = 288 ± 5 MeV
σ_{B_cππ} = 18 ± 4 MeV
N_{B_cππ} = 35 ± 13
Events / 20 MeV
m(B_cππ)-m(B_c)-2m(π) [MeV]
0
100
200
300
400
500
600
700
5
10
15
20
25
30
35
40

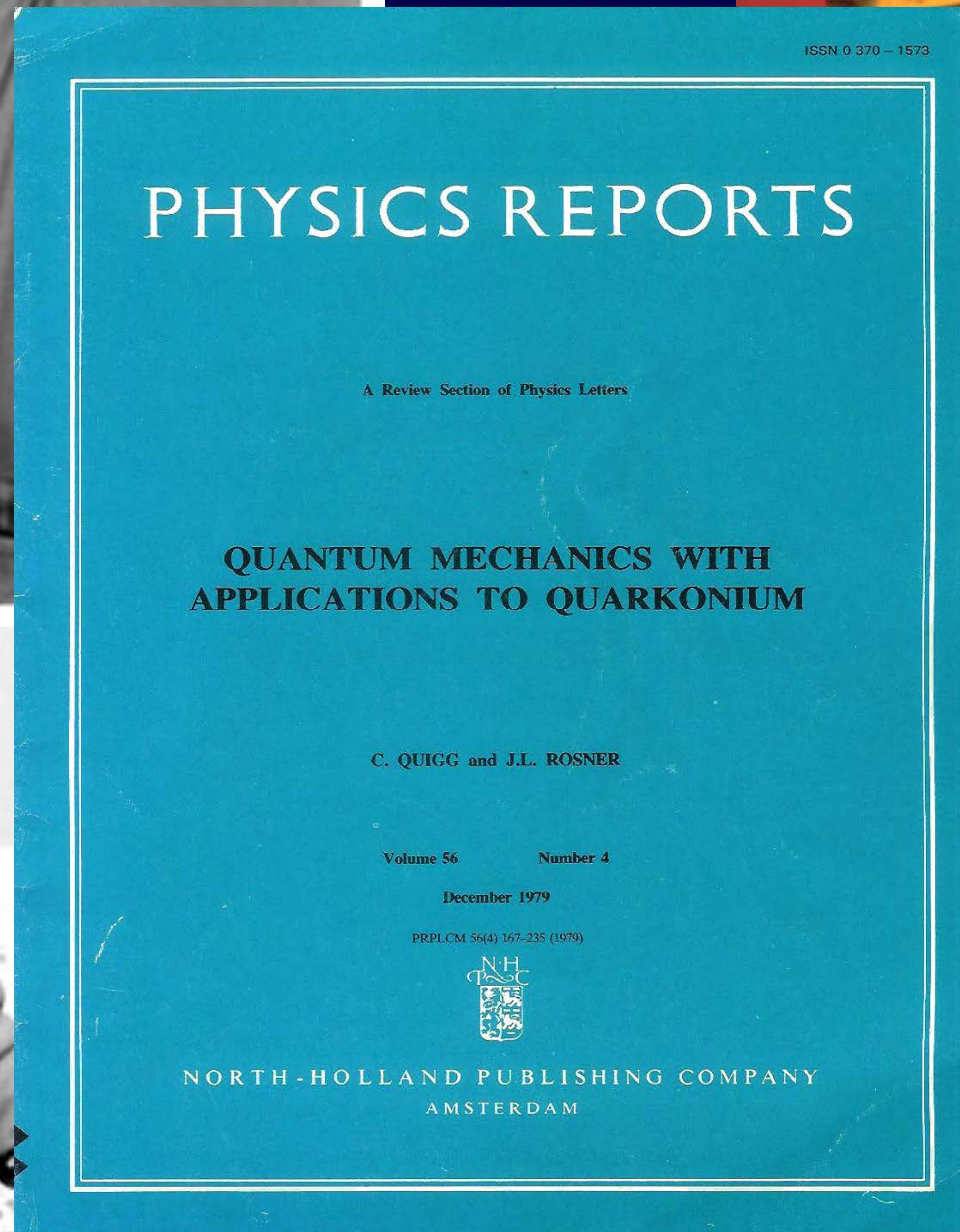

Rabi


Bell


Segrè


Fano




ISSN 0 370 – 1573

PHYSICS REPORTS

A Review Section of Physics Letters

QUANTUM MECHANICS WITH APPLICATIONS TO QUARKONIUM

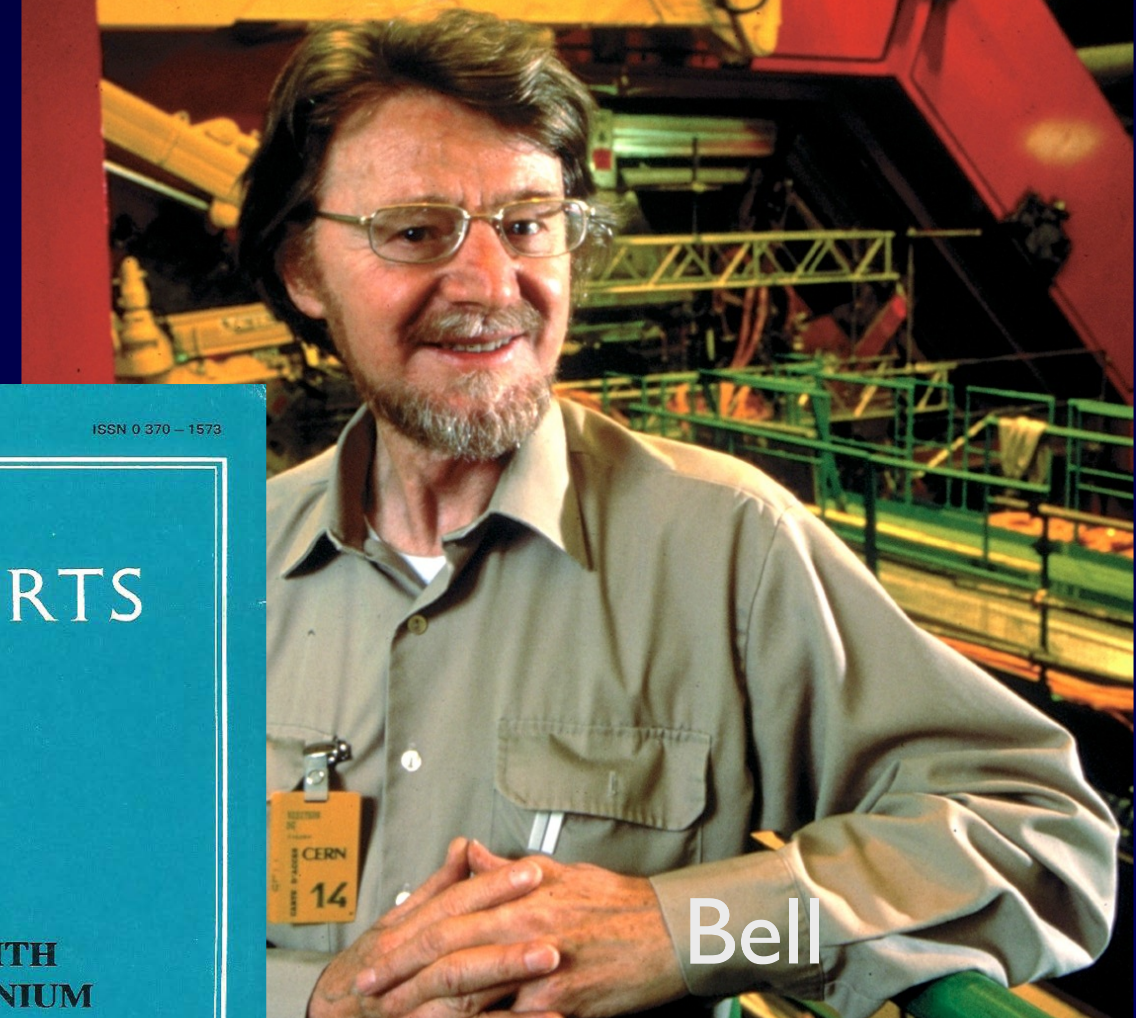
C. QUIGG and J.L. ROSNER

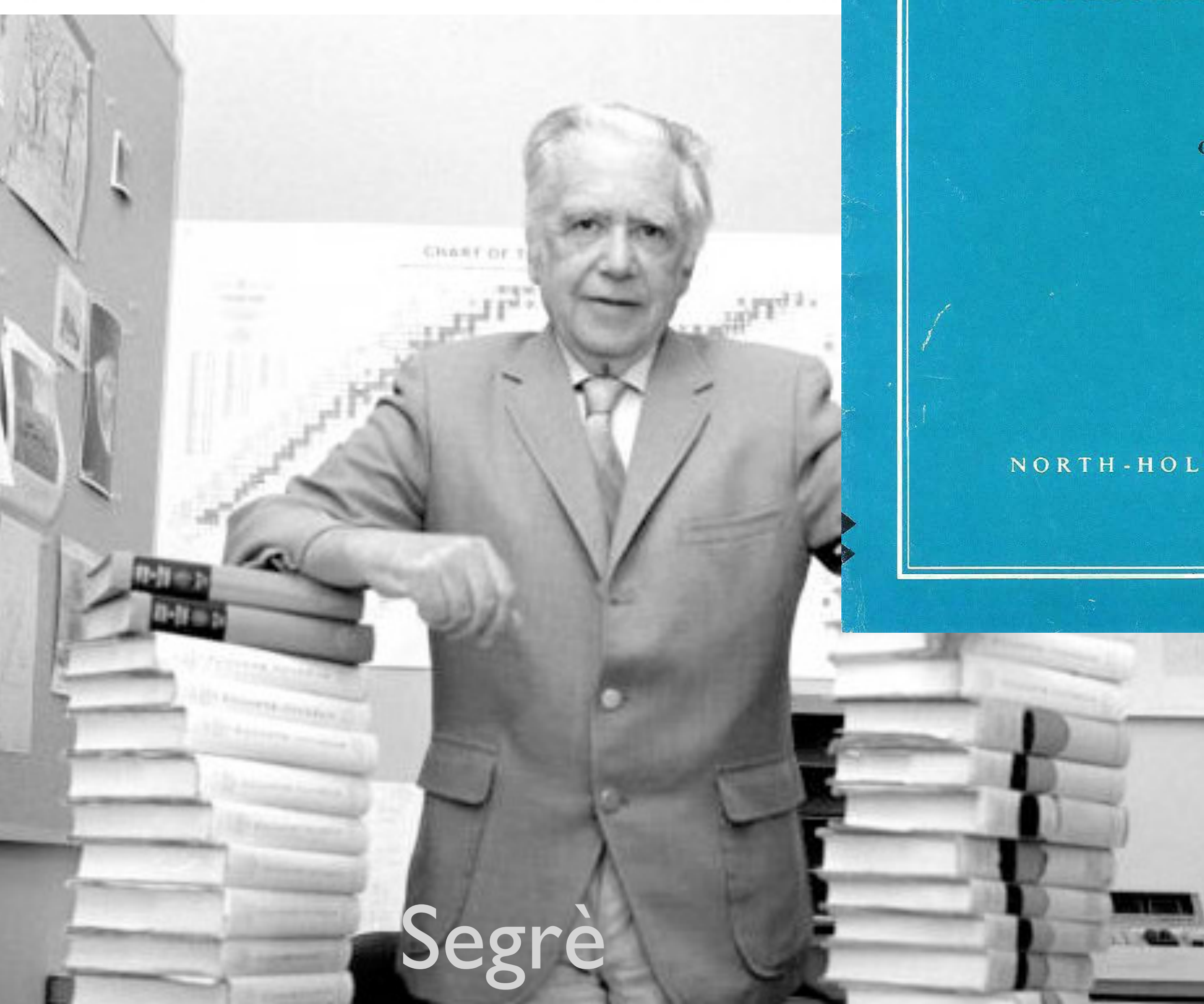
Volume 56 Number 4

December 1979

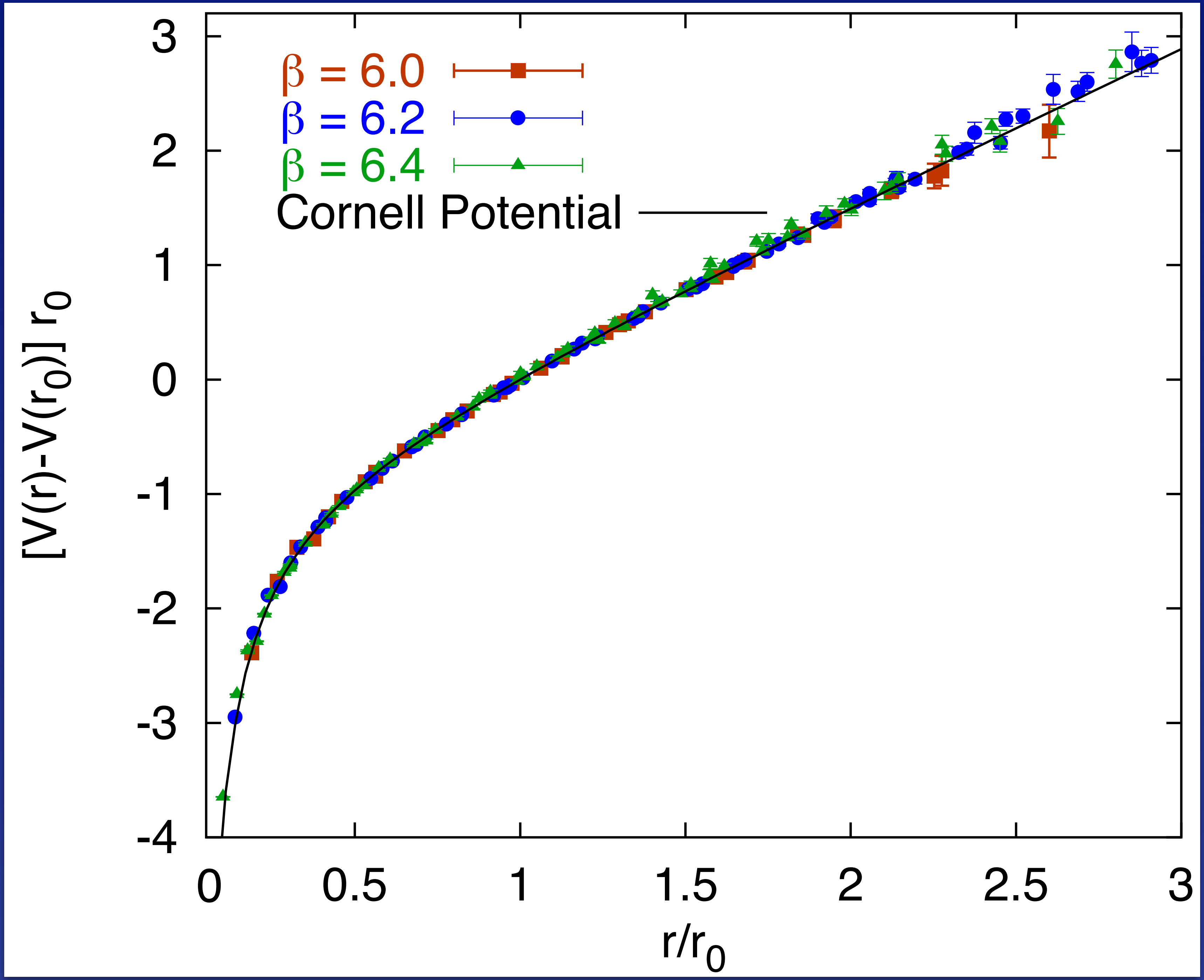
PRPLCM 56(4) 167–235 (1979)

NORTH-HOLLAND PUBLISHING COMPANY
AMSTERDAM



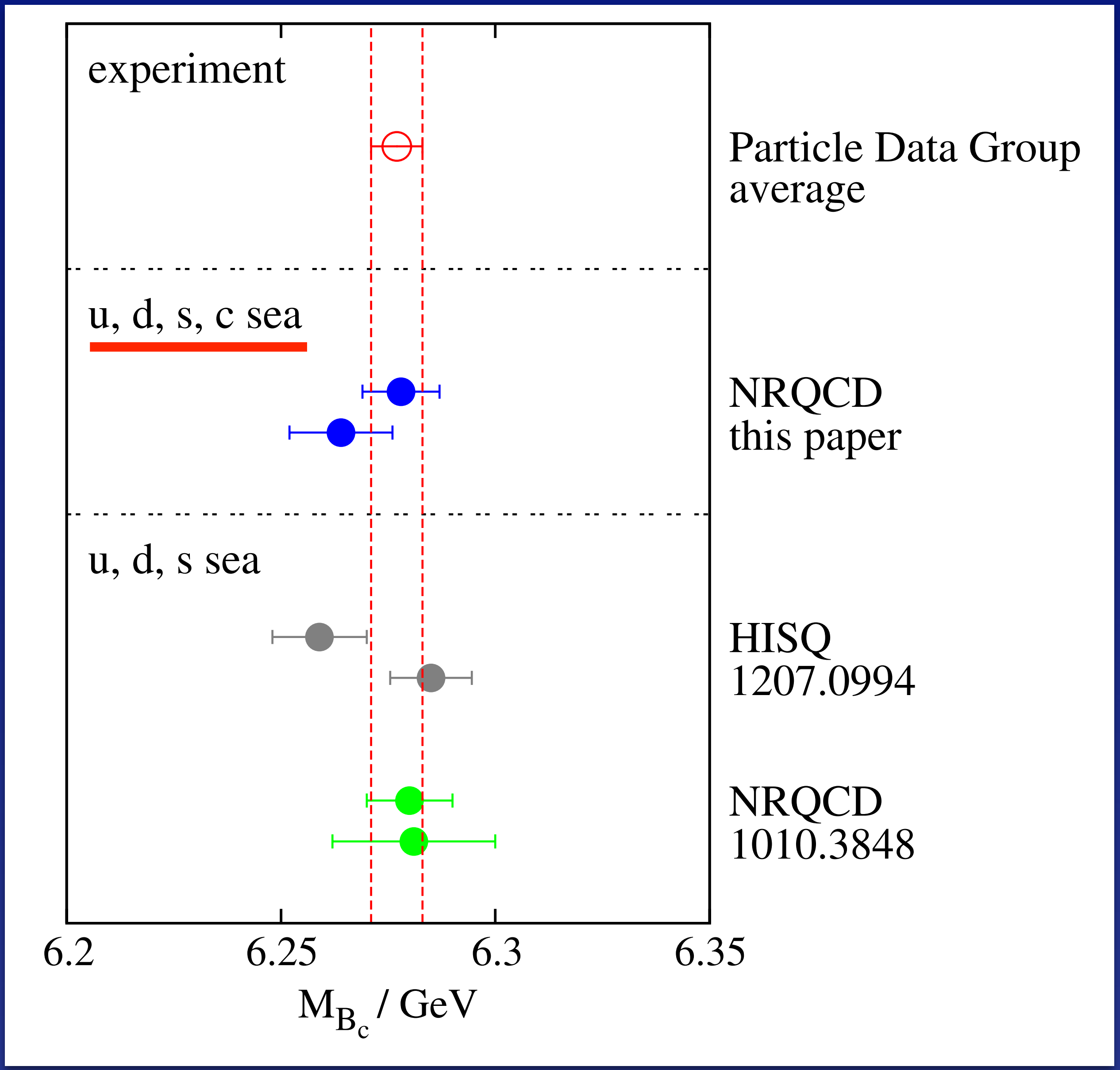


Lattice QCD: V(r) between static color sources



Early example, no dynamical quarks

Lattice QCD now:



$$M(B_c) = 6278 \pm 10 \text{ MeV}$$

$$M(B_c') = 6894 \pm 21 \text{ MeV}$$

Quarkonium production: many scales

M_Q, Λ_{QCD}, factorization, renormalization, …

and multiple mechanisms

direct, via P-states, fragmentation, *B* decay …

$$M_Q \gg p \sim 1/\langle r \rangle \sim M_Q v \gg E \sim M_Q v^2$$

Important instrumental development: CDF SVX

separate prompt component

begin controlled polarization studies

Effective field theories: NRQCD, pNRQCD

Caswell & Lepage, "Effective lagrangians for bound state problems in QED, QCD, and other field theories"

Applications to Lattice QCD, prefigured SCET

Bodwin, Braaten, Lepage, "Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium"

Brambilla, Pineda, Soto, Vairo, "Potential NRQCD: an effective theory for heavy quarkonium"

Quarkonium as a tool: Determining parameters of QCD Lagrangian that we will need to make the most of precision Higgs-boson studies

α_s	m_b	m_c

Refs. a b c

Quarkonium as a tool:
Determining parameters of QCD Lagrangian that we will need to make the most of precision Higgs-boson studies

α_s m_b m_c Refs. a b c

Higgs-boson couplings to fermions:

only have evidence for 3rd generation, t, b, τ

Can $H \to (J/\psi, \Upsilon)\gamma$ probe $HQ\bar{Q}$?

Quarkonium as a tool: Melting quarkonium in hot media

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

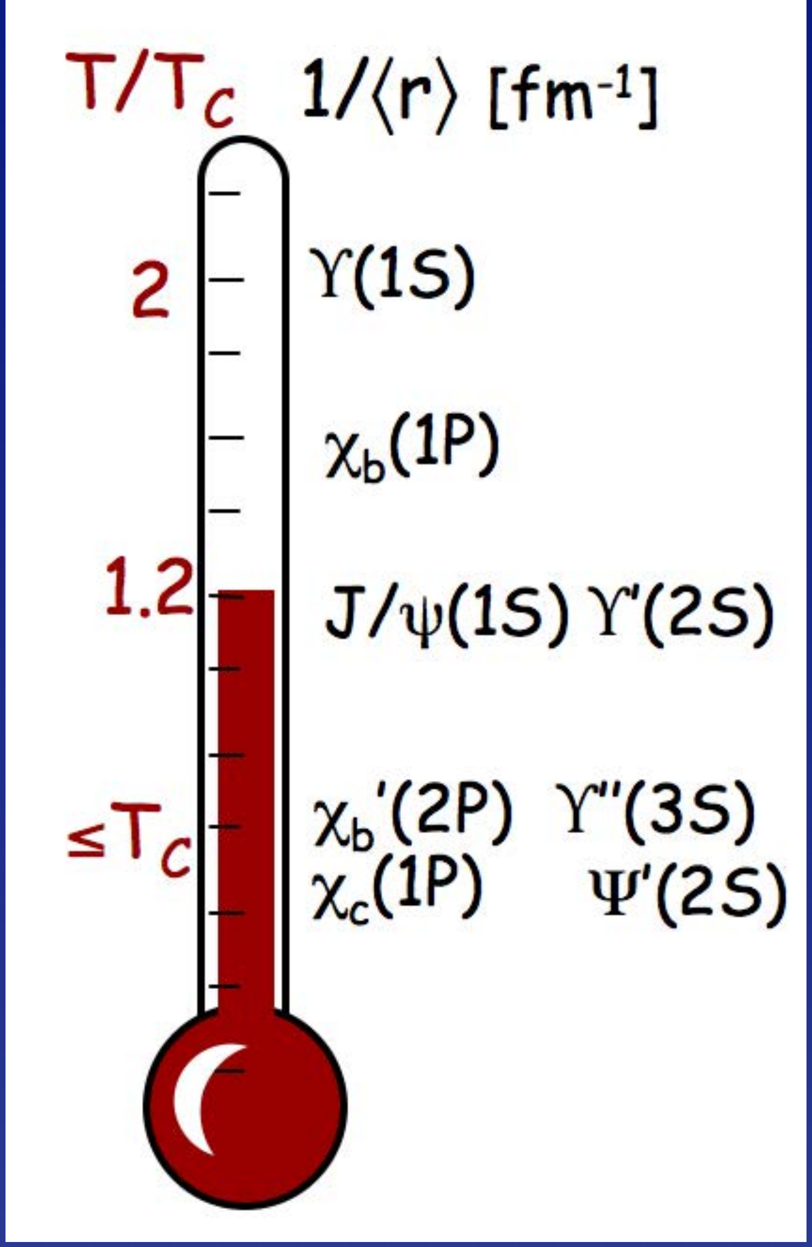
T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

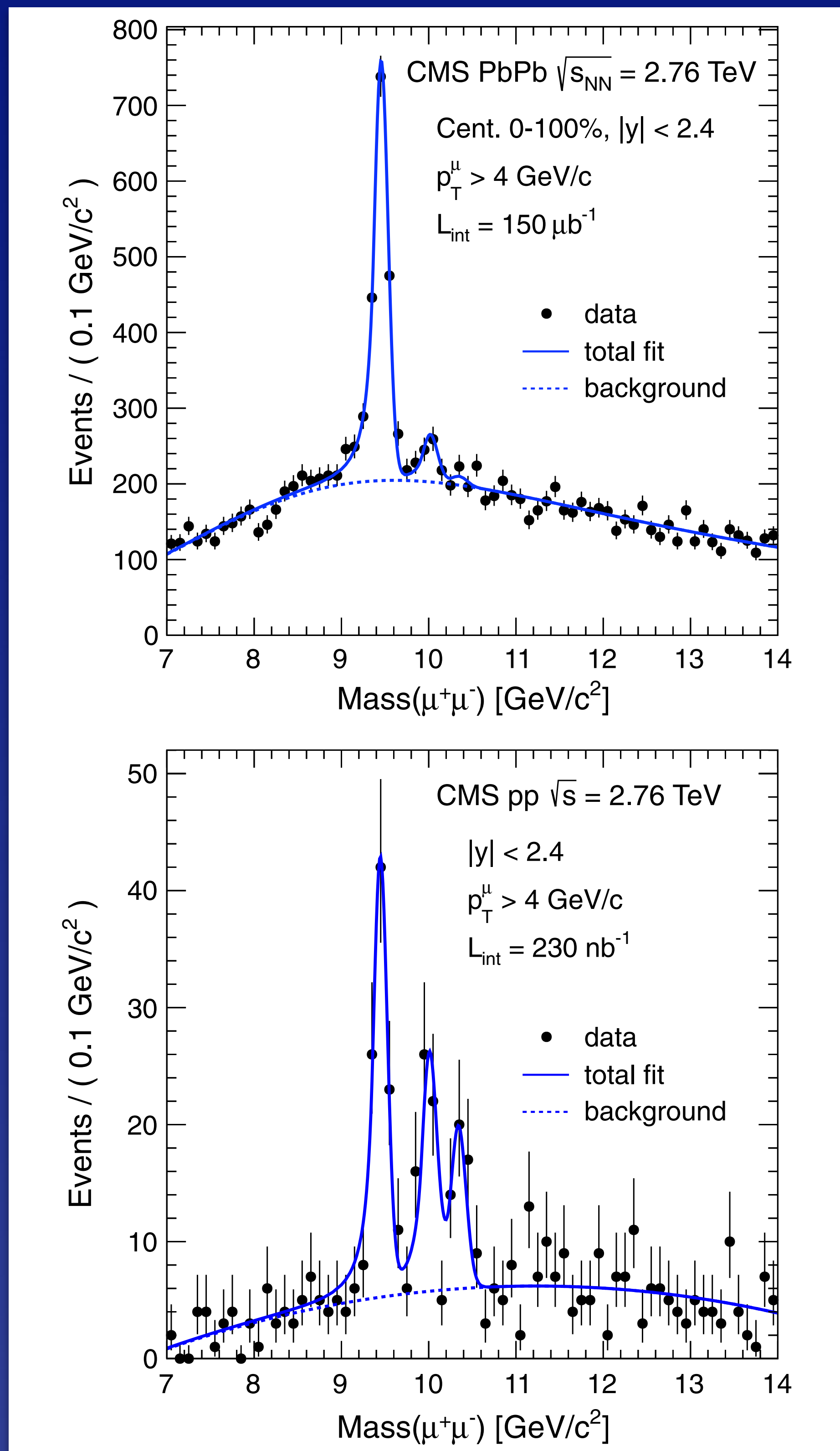
H. SATZ
Fakultät für Physik, Universität Bielefeld, D-4800 Bielefeld, Fed. Rep. Germany and Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.



Sequential Υ suppression in PbPb @ LHC



$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{\text{PbPb}}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07(\text{stat}) \pm 0.02(\text{syst}),$$

$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{\text{PbPb}}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} = 0.06 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})$$

$$< 0.17(95\%\text{CL}).$$

Decades of effort at
SPS & RHIC

Issues

Sequential melting of 3S, 2S

Role of P-states

Recombination

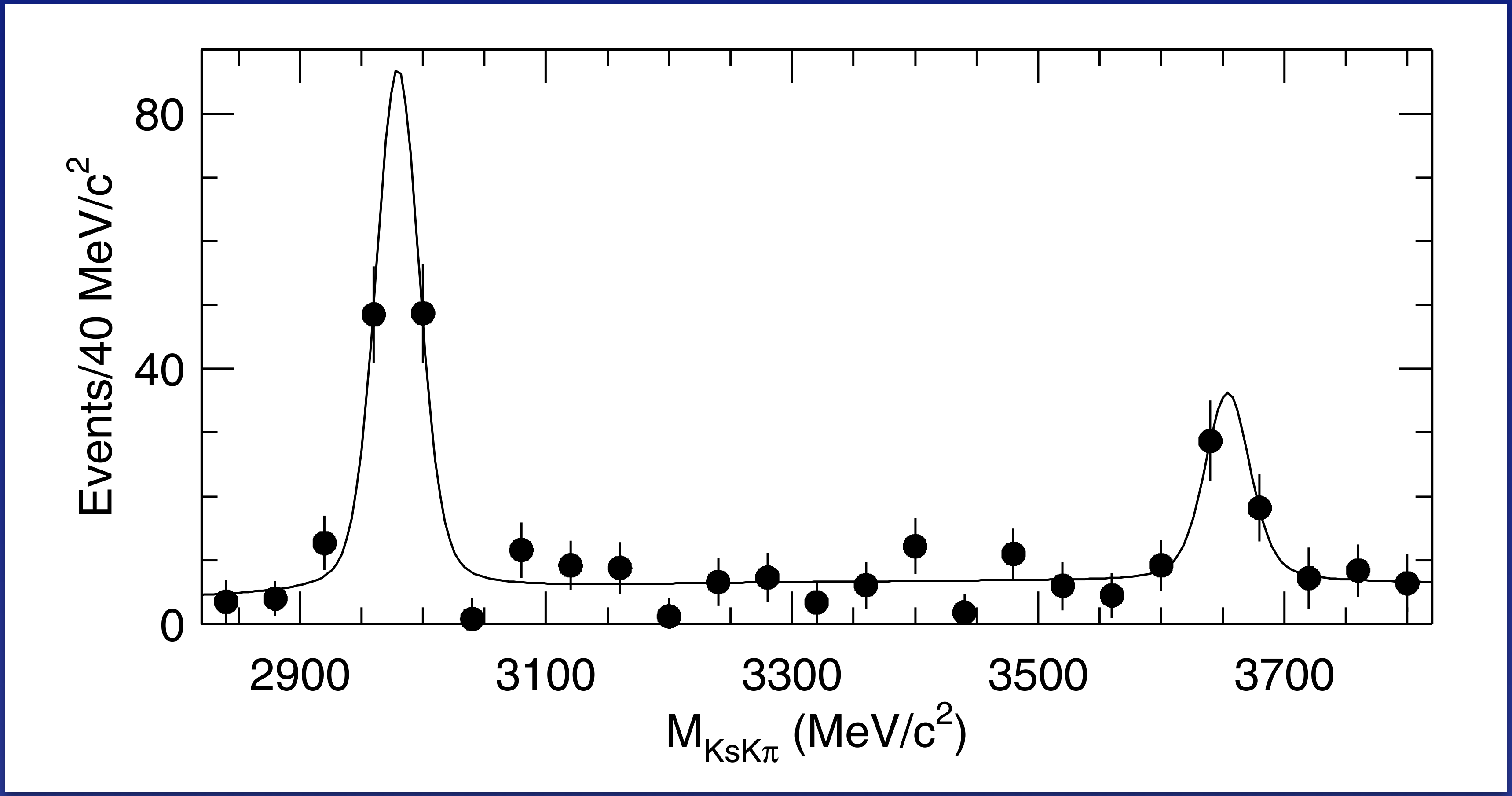
Dependence on centrality

Thermal regime in pp

Feed-down from B (for J/ψ)

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

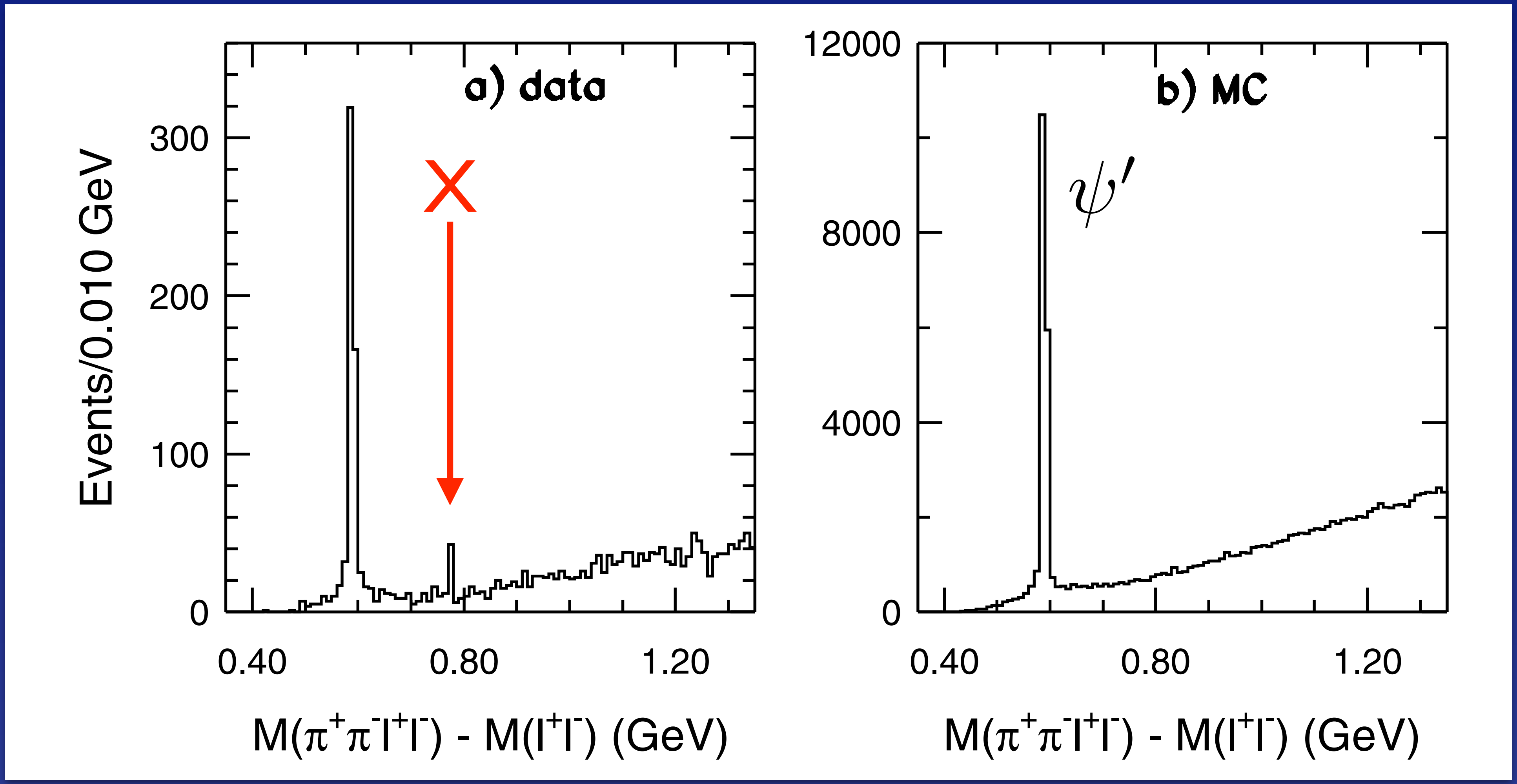
Belle discovers η_c' in $B \to K\, K_S K^{\mp}\pi^{\pm}$ (2002)



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

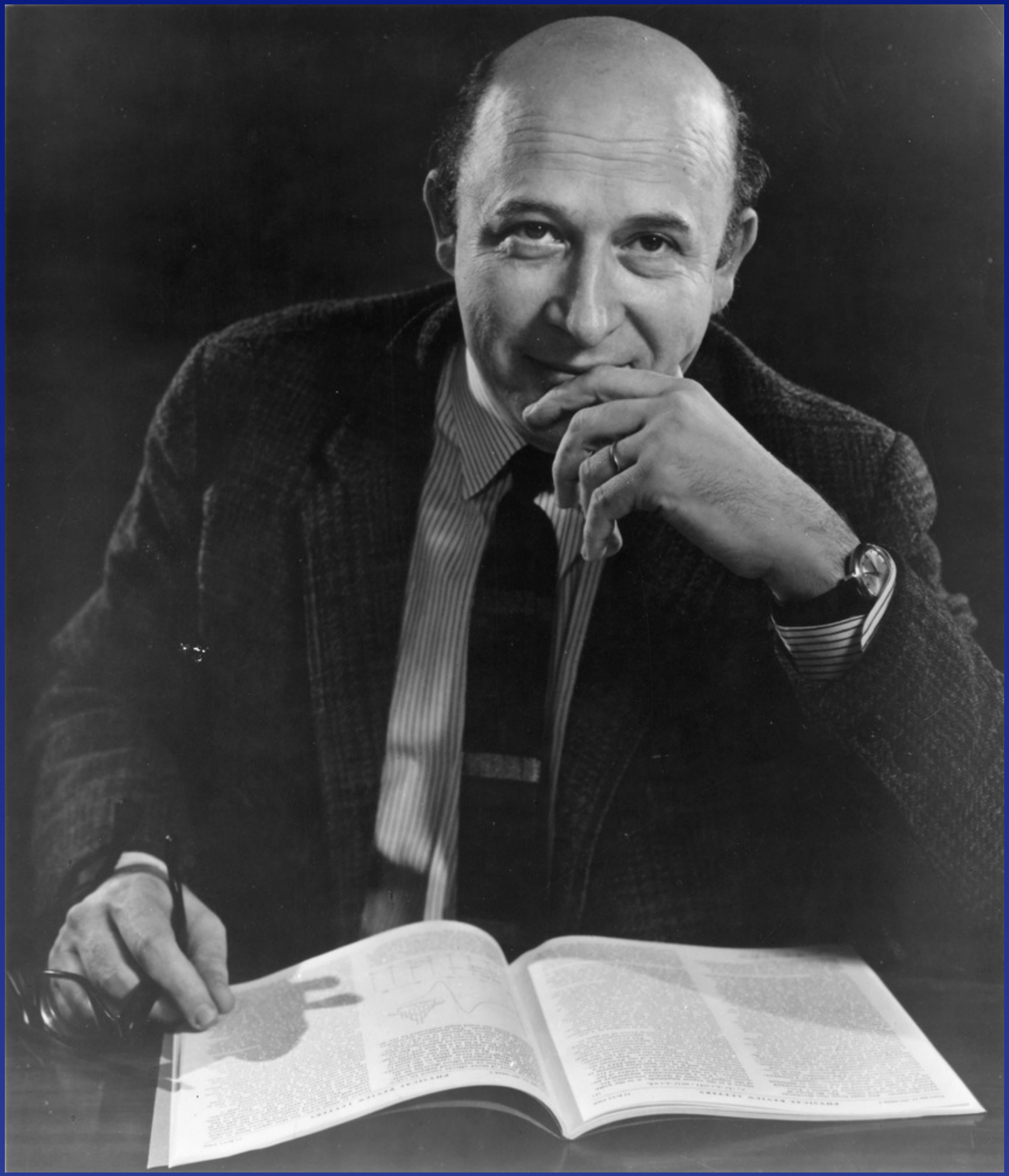
tetraquarks

diquarkonium

hadroquarkonium

and superpositions!

"Yesterday's sensation is today's calibration … and tomorrow's background."



Chicago *Maroon* photo

V. L. Telegdi

?

Quarkonium Working Group Publications

“Heavy quarkonium: progress, puzzles, and opportunities”

“Heavy quarkonium physics”

“QCD & Strongly Coupled Gauge Theories: Challenges and Perspectives”