Charm Before (and Slightly After) the Revolution

Incomplete & Idiosyncratic

First: A Brief Pre-History

J/ψ 50th Anniversary
SLAC, November 8, 2024

SLAC Theory Group, July 1969

Missing: Bj, Stan Brodsky, Joel Primack

Fall 1970 →

Harvard Particle Theory Group

1970/71: Sydney Coleman } Away
Sheldon Glashow
Joel Primack

1971/72: Helen Quinn
David Politzer (GS)
Erick Weinberg (GS)

1972/73: Howard Georgi
Michael Peskin (UG)

1973/74: Steven Weinberg (from MIT)
Alvaro DeRujula
Michael Barnett
R. Shankar

Spring 1973: Yang-Mills Asymptotic Freedom
David Politzer, D. Gross and F. Wilczek

Color SU(3)
Fritszch, Gell-Mann
1972 ICHEP

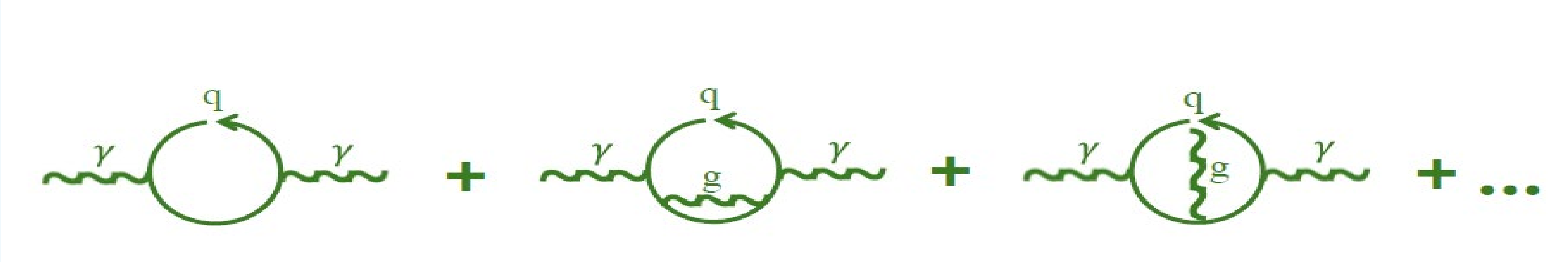
→

QCD:
$\alpha_s(q) \sim 1 / \ln(-q^2/\Lambda^2)$

e+ e- → Hadrons:

Howard Georgi & TA, June 1973
Tony Zee, June 1973

$\sigma_{TOT} \sim \mathrm{Im}$



RG Equations:
Peskin & Schroeder

$$R\,(E_{CM}) = \sum Q_i^2 \{ 1 + \alpha_s(E_{CM}) / \pi + \ldots\ldots \}$$

u,d,s: 2
u,d,s,c:10/3

Slow Approach
From Above

→ Jets

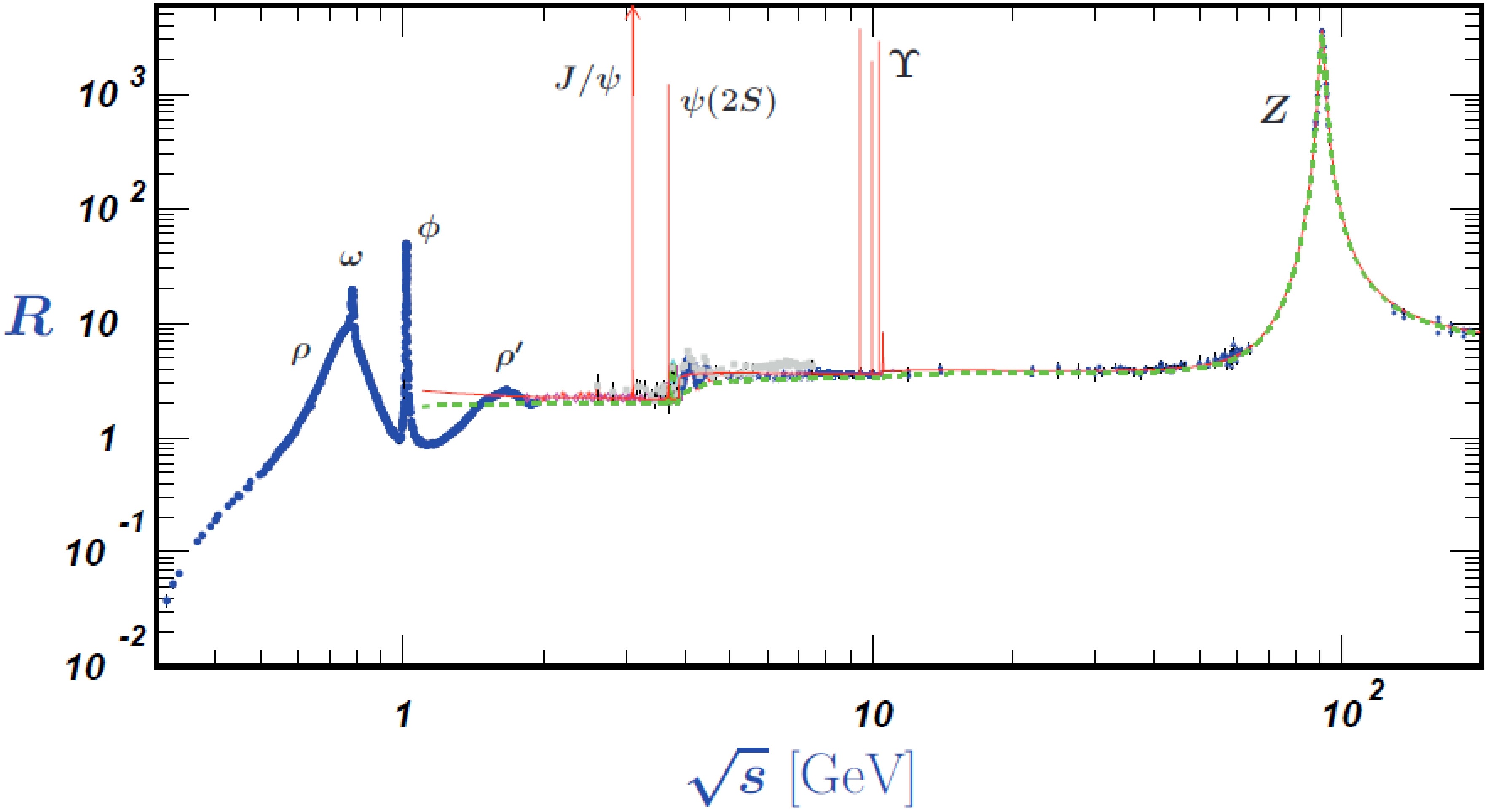


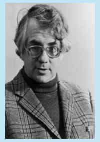
Figure 53.2: World data on the total cross section of $e^+e^- \to hadrons$ and the ratio $R(s) = \sigma(e^+e^- \to hadrons, s)/\sigma(e^+e^- \to \mu^+\mu^-, s)$. $\sigma(e^+e^- \to hadrons, s)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^- \to \mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model prediction, and the solid one (red) is 3-loop pQCD prediction (see "Quantum Chromodynamics" section of this *Review*, Eq. (9.7) or, for more details [99], Breit-Wigner parameterizations of J/ψ, $\psi(2S)$, and $\Upsilon(nS), n = 1, 2, 3, 4$ are also shown. The full list of references to the original data and the details of the R ratio extraction from them can be found in [100]. Corresponding computer-readable data files are available at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2021. Corrections by P. Janot (CERN) and M. Schmitt (Northwestern U.))

Charm

- 1964, Bjorken and Glashow:

Bj

SU(3) → SU(4) u,d,s,c
“Charm”
“Similarity to the Leptons”



Shelly

- Spring 1970, Glashow, Iliopoulos, Maiani (GIM)

Weak interactions: $G_f\, J_+^{\mu}\, J_{-\mu}$

Expectation: $G_f\, J_0^{\mu}\, J_{0\mu}$

Hadrons: $J_+^{\mu} = \bar{u}_L \gamma^{\mu} [d_L \cos\theta_c + s_L \sin\theta_c]$ → $J_0^{\mu} = \bar{s}_L \gamma^{\mu} d_L \sin\theta_c \cos\theta_c + \ldots$

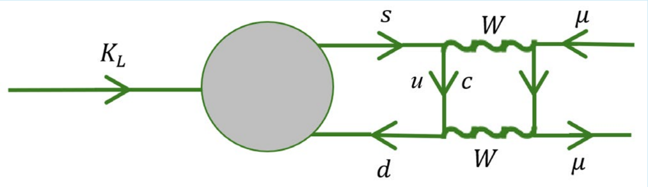
But !! $\Gamma(K_L^0 \rightarrow \mu^+\mu^-) / \Gamma(K_L^0 \rightarrow \text{all}) \sim 10^{-8}$ etc

$$J_+^{\mu} = \bar{u}_L \gamma^{\mu} [d_L \cos\theta_c + s_L \sin\theta_c] + \bar{c}_L \gamma^{\mu} [s_L \cos\theta_c - d_L \sin\theta_c]$$

→ J_0^{μ} = Flavor Neutral !

- M. K. Gaillard & B. Lee Spring 1974 :

Analysis of K Mesons
Higher order Effects



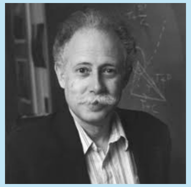
Progenitor: SO(3)
Lee, Primack, Treiman
1972

Abstract: $m_c < 5$ GeV
$\Delta m(K_L, K_S)$: $m_c \approx 1.5$ GeV !

- M.K. Gaillard, B. Lee, J. Rosner August,1974 :

"Search for Charm"

Φ_c ($\bar{c}c$): Γ ("OZI Rule") ≈ 2 MeV



ICHEP, London, July 1974

Burt Richter

“Subject of great intrinsic interest”

“Results flatly contradict all known models of hadron production available up to about half a year ago.”

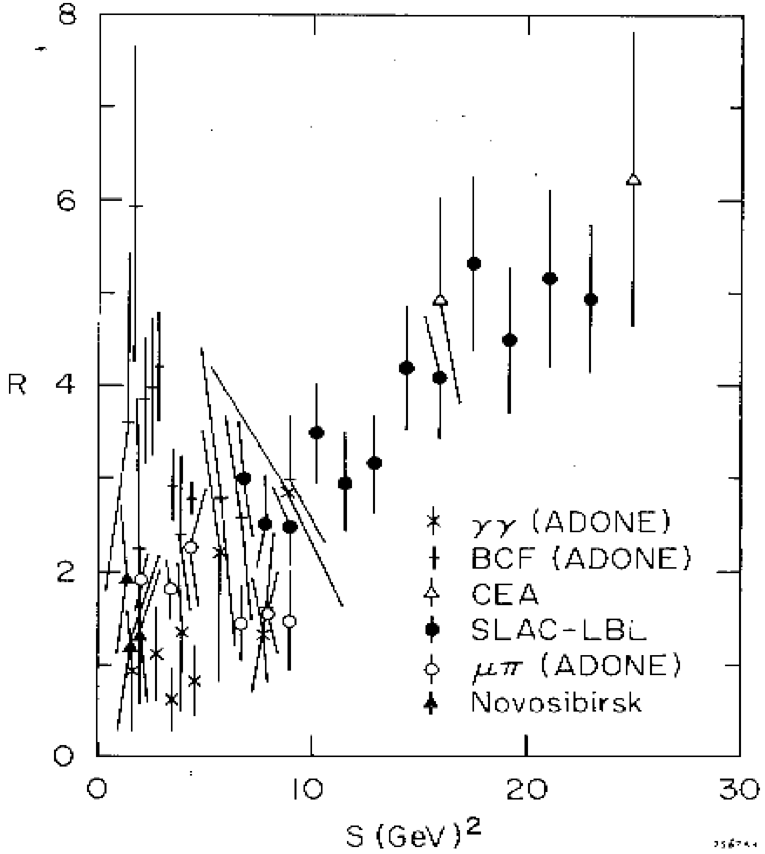


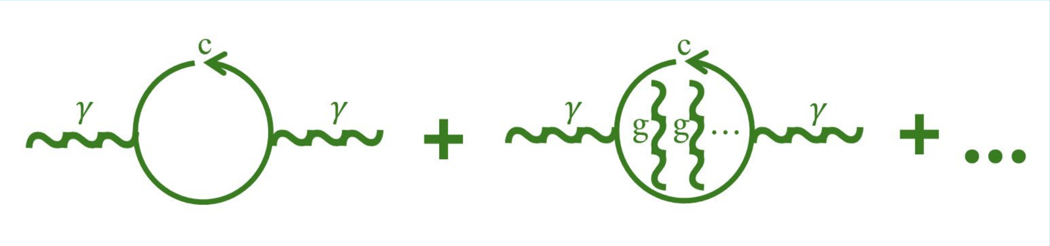
Fig. 4

Aspen Summer, 1974
QCD Workshop

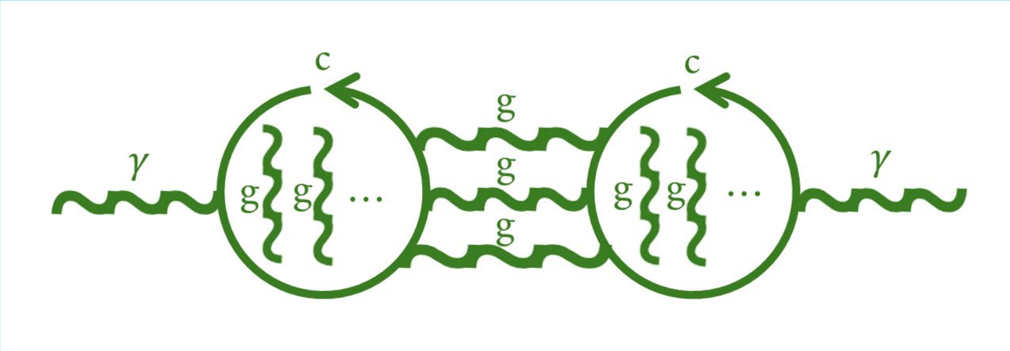
David Politzer, TA

What happens at a $c\bar{c}$ threshold in e^+e^- annihilation?

- Just Above 2 m_c: Im



- Below 2 m_c: Im



- # Orthocharmonium (1^{--})

$\sim \alpha_s^3(2m_c)$ Narrow !

  - $\Gamma_{\text{ortho h}} = |\Psi(0)|^2 \; |M_h|^2 \; + \ldots$

$\sim \alpha^2 = (1/137)^2$

  - $\Gamma_{\text{ortho ll}} = |\Psi(0)|^2 \; |M_l|^2 = \; + \ldots$

$$\boxed{\Gamma_{\text{ortho ll}} / \Gamma_{\text{ortho h}} = [18\,\pi / 5\,(\pi^2 - 9)] \;\; \alpha^2 / \alpha_s^3(2m_c) + \ldots}$$

- # Paracharmonium (0^{-+})

$\sim \alpha_s^2(2m_c)$ Less Narrow

  - $\Gamma_{\text{para h}} = |\Psi(0)|^2 \, |M_h|^2 \; + \ldots$

  - $\Gamma_{\text{para } \gamma\gamma} = \ldots$

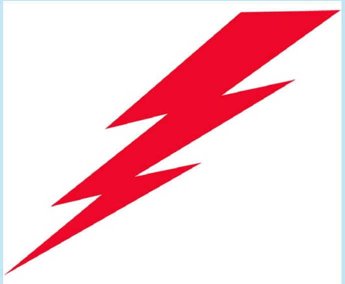
$$\boxed{\Gamma_{\text{ortho h}} / \Gamma_{\text{para h}} = [5\,(\pi^2 - 9)/27\,\pi] \;\; \alpha_s(2m_c) + \ldots}$$

October,1974 Seminars: Cornell, MIT

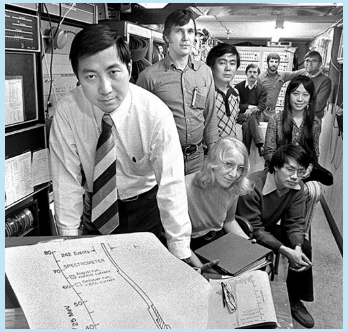
J /ψ Discovery

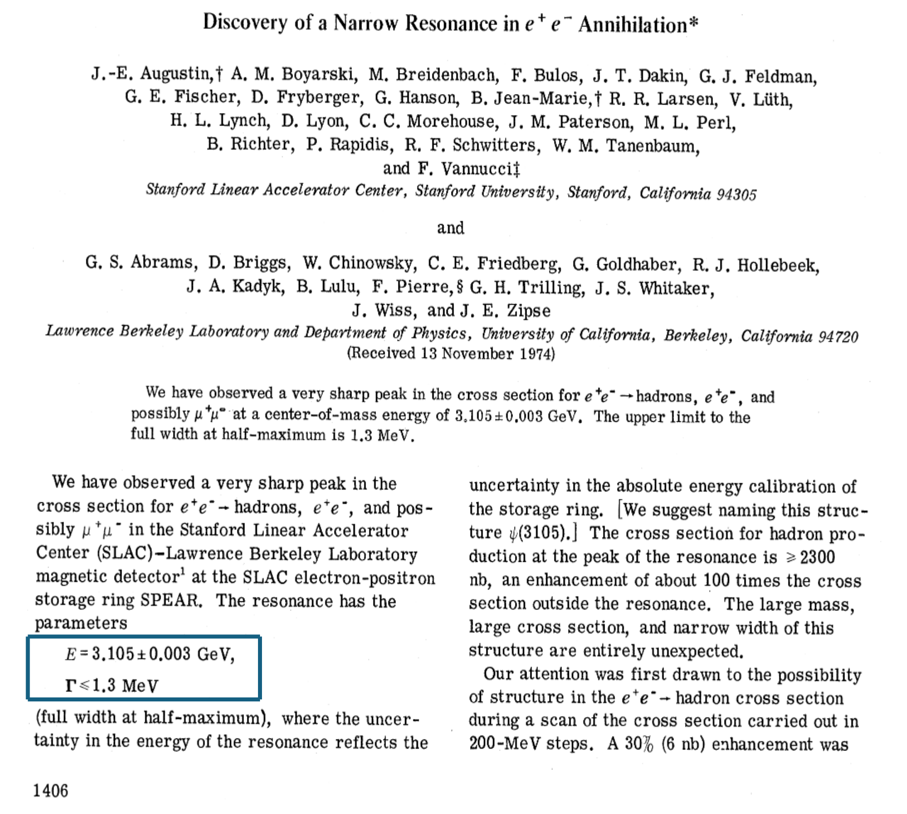
November 11, 1974

SLAC



BNL





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,
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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)

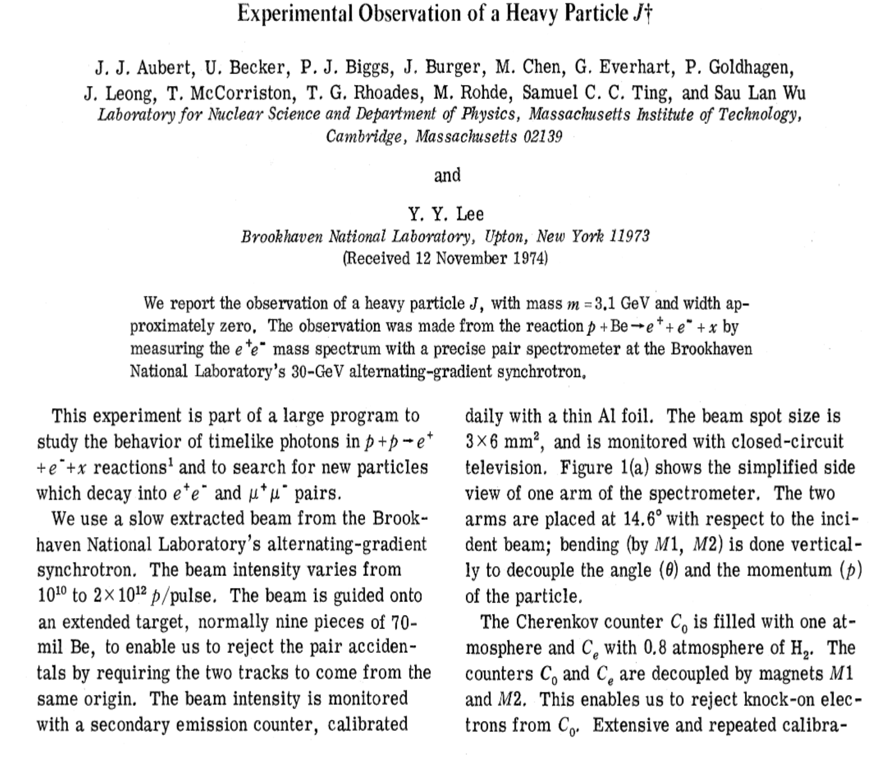
We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ in the Stanford Linear Accelerator Center (SLAC)–Lawrence Berkeley Laboratory magnetic detector[1] at the SLAC electron-positron storage ring SPEAR. The resonance has the parameters

$$\boxed{\begin{array}{l} E = 3.105 \pm 0.003 \text{ GeV}, \\ \Gamma \leq 1.3 \text{ MeV} \end{array}}$$

(full width at half-maximum), where the uncertainty in the energy of the resonance reflects the uncertainty in the absolute energy calibration of the storage ring. [We suggest naming this structure $\psi(3105)$.] The cross section for hadron production at the peak of the resonance is ≥ 2300 nb, an enhancement of about 100 times the cross section outside the resonance. The large mass, large cross section, and narrow width of this structure are entirely unexpected.

Our attention was first drawn to the possibility of structure in the $e^+e^- \rightarrow$ hadron cross section during a scan of the cross section carried out in 200-MeV steps. A 30% (6 nb) enhancement was



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

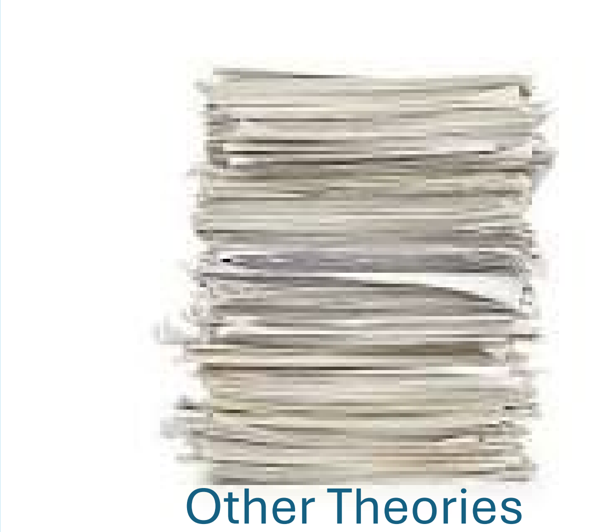
This experiment is part of a large program to study the behavior of timelike photons in $p + p \rightarrow e^+ + e^- + x$ reactions[1] and to search for new particles which decay into e^+e^- and $\mu^+\mu^-$ pairs.

We use a slow extracted beam from the Brookhaven National Laboratory's alternating-gradient synchrotron. The beam intensity varies from 10^{10} to 2×10^{12} p/pulse. The beam is guided onto an extended target, normally nine pieces of 70-mil Be, to enable us to reject the pair accidentals by requiring the two tracks to come from the same origin. The beam intensity is monitored with a secondary emission counter, calibrated daily with a thin Al foil. The beam spot size is 3×6 mm^2, and is monitored with closed-circuit television. Figure 1(a) shows the simplified side view of one arm of the spectrometer. The two arms are placed at 14.6° with respect to the incident beam; bending (by $M1$, $M2$) is done vertically to decouple the angle (θ) and the momentum (p) of the particle.

The Cherenkov counter C_0 is filled with one atmosphere and C_e with 0.8 atmosphere of H_2. The counters C_0 and C_e are decoupled by magnets $M1$ and $M2$. This enables us to reject knock-on electrons from C_0. Extensive and repeated calibra-

November 15, 1974:
"Orthocharmonium and e+e- Annihilation"
PRL 34 (1975)

+


Other Theories

$m_c \approx 1.5$ GeV $Q_c = 2/3$

$\alpha_s(2m_c) \approx 0.2$

Non-Relativistic , Non-Coulombic

2024 Actuals:

$\Gamma_{\text{ortho ll}} / \Gamma_{\text{ortho h}} \approx 0.09$

5.5 keV / 60 keV ≈ 0.09

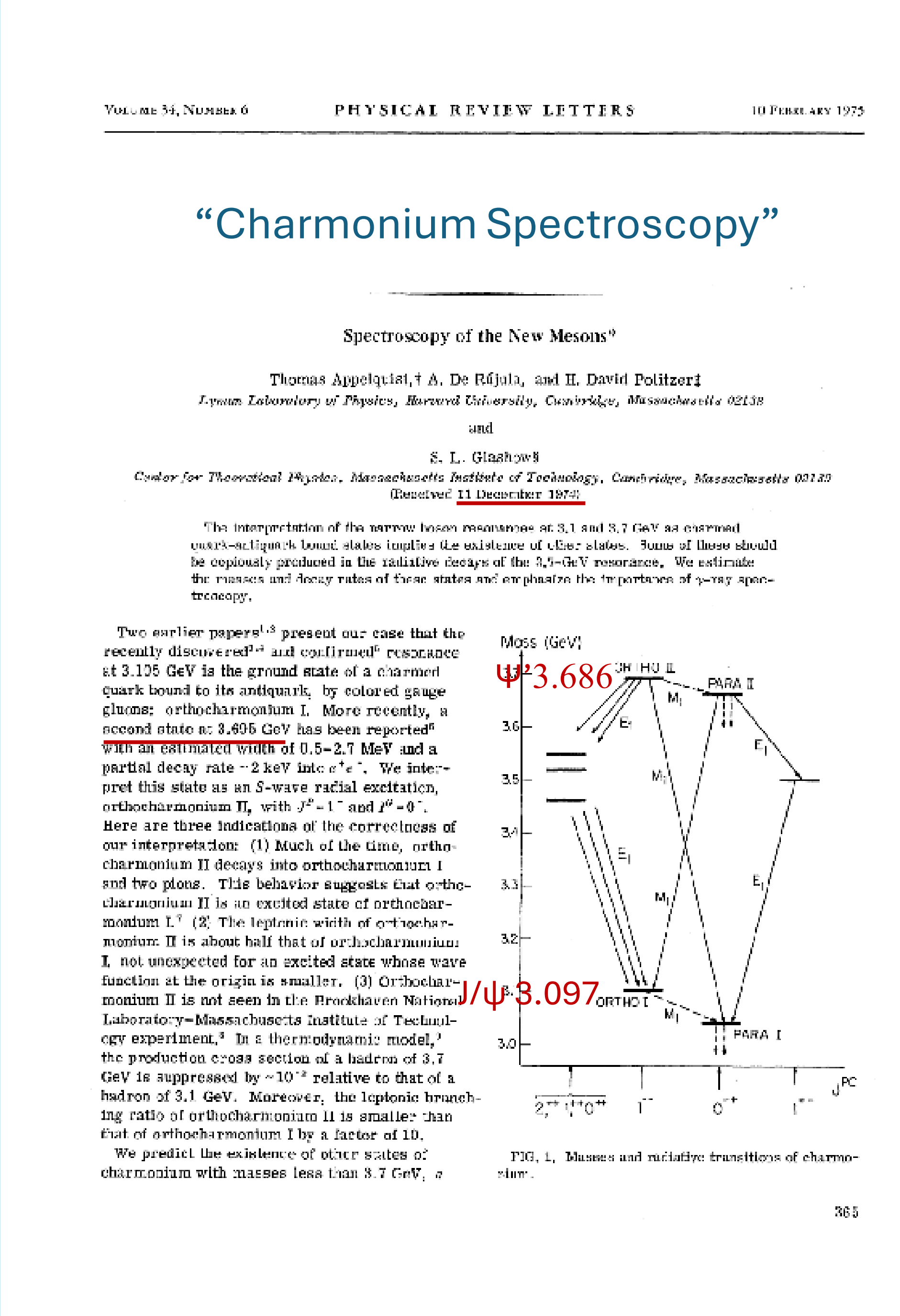
$\Gamma_{\text{ortho h}} / \Gamma_{\text{para h}} \approx 0.01$

60 keV / 32 MeV ≈ 0.002

→ $\Gamma_{\text{para h}} \approx$ 6-8 MeV

Long Literature

"Charmonium Spectroscopy"



Volume 34, Number 6 PHYSICAL REVIEW LETTERS 10 February 1975

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.

Two earlier papers[1,3] present our case that the recently discovered[2-4] and confirmed[5] resonance at 3.105 GeV is the ground state of a charmed quark bound to its antiquark, by colored gauge gluons: orthocharmonium I. More recently, a second state at 3.695 GeV has been reported[6] with an estimated width of 0.5–2.7 MeV and a partial decay rate ~2 keV into e^+e^-. We interpret this state as an S-wave radial excitation, orthocharmonium II, with $J^P = 1^-$ and $I^G = 0^-$. Here are three indications of the correctness of our interpretation: (1) Much of the time, orthocharmonium II decays into orthocharmonium I and two pions. This behavior suggests that orthocharmonium II is an excited state of orthocharmonium I.[7] (2) The leptonic width of orthocharmonium II is about half that of orthocharmonium I, not unexpected for an excited state whose wave function at the origin is smaller. (3) Orthocharmonium II is not seen in the Brookhaven National Laboratory–Massachusetts Institute of Technology experiment.[8] In a thermodynamic model,[9] the production cross section of a hadron of 3.7 GeV is suppressed by ~10^{-2} relative to that of a hadron of 3.1 GeV. Moreover, the leptonic branching ratio of orthocharmonium II is smaller than that of orthocharmonium I by a factor of 10.

We predict the existence of other states of charmonium with masses less than 3.7 GeV, a

FIG. 1. Masses and radiative transitions of charmonium.

ROM's

↓

$\eta_c{}'$ 3.670 PARA II 3.638

P-states ~ 3.500

η_c 3.050 PARA I 2.984

- Hadronic Decay Via Gluons
- Radiative Transitions
- Ortho II (ψ´) "Below Charm Threshold"
- Higher Excitations "Above Threshold"

The Cornell Group

“Spectrum of Charmonium”

2γ de-excitation of paracharmonium II.

[14]The value of $\alpha_s = 0.26$ at 3.1 GeV was obtained in Ref. 1 from the leptonic branching ratio of orthocharmonium I. Asymptotic freedom reduces this value to 0.22 at 3.7 GeV.

[15]E. Eichten *et al.*, Phys. Rev. Lett. 34, 369 (1975) (this issue). As pointed out by these authors in the transition orthocharmonium II → paracharmonium I + γ, the orthogonality of the wave functions may make our upper limit a gross overestimate.

Spectrum of Charmed Quark-Antiquark Bound States*

E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan†
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(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 4.5 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.

Recently two astonishingly narrow resonances have been discovered[1,2] at 3.105 and 3.695 GeV. In our view the most plausible explanation of this phenomenon is that of Appelquist and Politzer,[3] to wit, that they are $c\bar{c}$-bound states of charmed quarks c which lie below[4] the threshold M_c for the production of a pair of charmed hadrons.[5] Because of its similarity to positronium this system has been called charmonium.[3] This note is devoted to the spectrum of charmonium.[1] Many of the phenomena that we shall discuss are accessible to existing experimental techniques.

If the strong interactions are described by an asymptotically free theory, one may hope[3] that the short-distance structure of charmonium (in particular, its decay into leptons, and probably also hadrons) is adequately described by perturbation theory in terms of a small "running" coupling constant. In this regime the $c\bar{c}$ interaction would be Coulombic, with a small strong "fine-structure" constant α_s. At larger $c\bar{c}$ separation, on the other hand, there are rather compelling arguments that gauge theories provide for quark confinement.[7]

If α_s is small and the observed levels do not lie far below the threshold M_c, nonrelativistic quantum mechanics should provide a sound zeroth-order guide. Given[8] the sizable electronic widths Γ_e of $\psi(3695)$ and $\psi(3105)$, it is natural[9] to assign them to the states $2\,^3S_1$ and $1\,^3S_1$, respectively. This being said, it is at once clear that there should be other levels below M_c, for any confining potential will raise[10] the $2S$ Coulomb level above its previously degenerate partner $2P$. One must therefore expect a multiplet of narrow P states below $\psi(3695)$, fed from the latter by $E1$ γ transitions, and decaying in turn into $\psi(3105)$. If 3.7 GeV is not too close to M_c, bound D states could also exist.

It goes without saying that many qualitative features of the spectrum can be surmised without resorting to a detailed model. Nevertheless, we have found it informative to simulate the intricate $c\bar{c}$ interaction by a simple potential that incorporates both the Coulomb and confinement forces:

$$V(r) = -(\alpha_s/r)[1-(r/a)^2]. \qquad (1)$$

That the interaction is far from Coulombic follows from the large $2S$-$1S$ mass difference, and the fact that[8]

$$\eta = \left|\frac{\psi(1\,^3S; r=0)}{\psi(2\,^3S; r=0)}\right|^2 \approx \left(\frac{3.1}{3.7}\right)^2 \frac{\Gamma_e(3105)}{\Gamma_e(3695)} \approx 1.4, \qquad (2)$$

in contrast to Ref. 8 for a Coulomb field.[11] In analogy with electrodynamics there must also be spin-spin, spin-orbit, and tensor forces, but hopefully they play a secondary role. Near M_c a treatment that accounts for coupling to decay channels is necessary.

We have determined α_s, a, and the charmed-quark mass m_c by solving the wave equation numerically,[12] and by imposing the constraints (a) $M(2\,^3S) - M(1\,^3S) = 0.59$ GeV; (b) $\Gamma_e(1\,^3S) = 5.5$ keV; (c) 1.5 GeV $\lesssim m_c \lesssim$ 2.0 GeV; and (d) $0.1 \lesssim \alpha_s \lesssim 0.4$. Constraint (c) is the requirement that the system be nonrelativistic, and that $\psi(3695)$ lie below M_c; naive quark phenomenology would set

Similar Spectrum
More Work

$$\boxed{V(r) = -\alpha_s/r\,[\,1 - r^2/a^2\,]}$$

“Cornell Potential”

Fit: $m_c = 1.600$
$\alpha_s = 0.2$
$a = 0.2$ fm

- Avoided:
  Hadronic Decay via Gluons
  Spin Dependent ROM’s
- P States ≈ 3.450
- Radiative Transitions
- Charm Threshold “Nearby”

Coupling to Decay Channels (D, D_s)

Charm(onium) Theory After the Revolution

M. B. Voloshin 2008: “Charmonium” 0711.4556

1. Spectrum

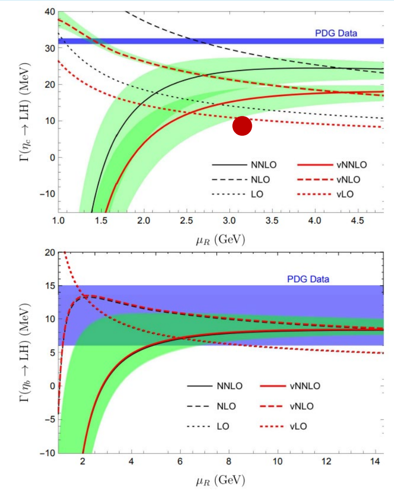
Spin-Dependence
NRQCD
Lattice Calculations

Nora Brambilla
“50 Years of QCD” 2212.11107

2. Hadronic Width via Gluons in Higher Orders:

$\Gamma(J/\psi)$ Looks Under Control
$\Gamma(\eta_c)$ Large Increase
$\Gamma(\eta_b)$ Looks Much Better

Feng, Jia, Sang 1707.05758



$\Gamma(\eta_c)$ 2.984 GeV

$\Gamma(\eta_b)$ 9.399 GeV

Early Spring 1975

Charm Status

- Hidden Charm Established. Quarks Real !
- m_c in Gaillard-Lee Range
- Non-Relativistic but Non- Coulombic Hadrons (Charmonium) J/ψ , ψ´

  (Asymptotic Freedom, Confinement
  Modeling, Textbook Quantum Mechanics)

- Predictions for Many Other $c\bar{c}$ States

Near Horizon

- 1975: P States, Lepton-Photon Conference, August
- 1976: Charmed Particles, G. Goldhaber et al, August
- 1977: Paracharmonium η_c, W. Braunschweig et al

……

Quark Jets: December 1975

Tau Lepton: December 1975

Upsilon ($b\bar{b}$): 1977

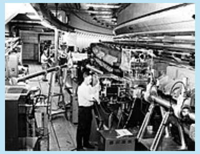
Summary

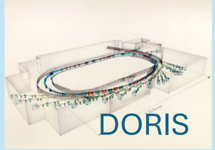
1. Early → Mid Seventies :

Depressing in Many Ways

Golden Age of Particle Physics

2. Stunning Experimental Discoveries





. . . .

3. Emergence of the Standard Model

& Effective-Field-Theory Framework

$$SU(3)_c \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_c \times U(1)_{EM}$$