IV. e^+e^- annihilation experiments

1. Experimental methods
2. $e^+e^- \to e^+e^-(\gamma)$
3. $e^+e^- \to \mu^+\mu^-(\gamma)$
4. Discovery of the Tau-Lepton
5. $e^+e^- \to$ hadrons
6. Hadronic resonances

Lit.: H.U Martyn, "Test of QED …" in "Quantum Electrodynamics", T.Kinoshita (ed.)

1. Experimental methods

e^+e^- accelerator (selection)

Accelerator	Lab	$\sqrt{s}$	L_{int} / Exper.
SPEAR	SLAC	2 – 8 GeV	
PEP	SLAC	→29 GeV	220 - 300 pb^{-1}
PETRA	DESY	12 - 47 GeV	~20 pb^{-1}
TRISTAN	KEK	50 – 60 GeV	~20 pb^{-1}

Cross section (experimental definition)

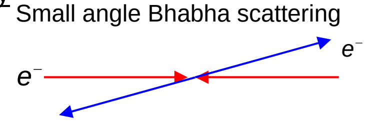
$$\sigma(e^+e^- \to f\,\bar{f}) = \frac{N_{ff}(1-b)}{\varepsilon\, L_{int}}$$

- N_{ff} number of detected $e^+e^- \to$ ff events
- b background fraction
- ε acceptance / efficiency
- L_{int} integrated luminosity of collider

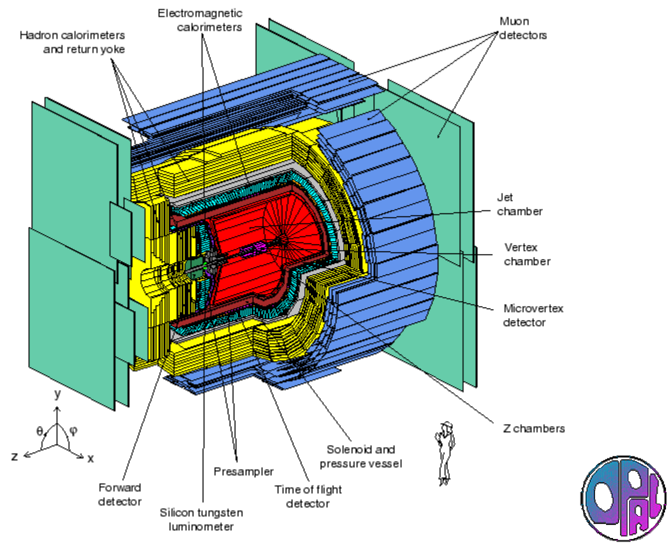
Determination of integrated luminosity

$$L_{int} = \frac{N_{ee}}{\sigma_{theo}}$$

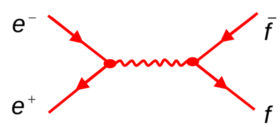
Small angle Bhabha scattering

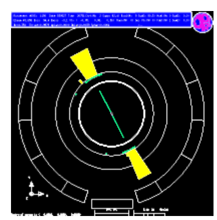


Typical detector:



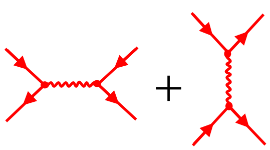
Fermion pair production:





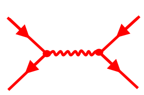
e^-e^+

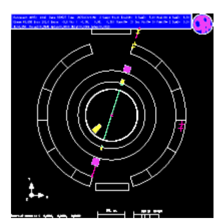
$f\,\bar{f} = e^-e^+$



$\mu^-\mu^+$

$\tau^-\tau^+$

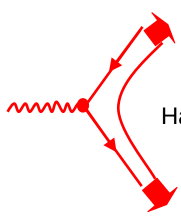




$\mu^-\mu^+$

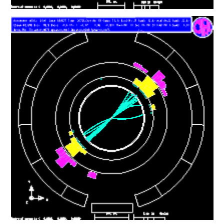
$q\,\bar{q}$ mit

$q = u, d, s, c, b, (t)$

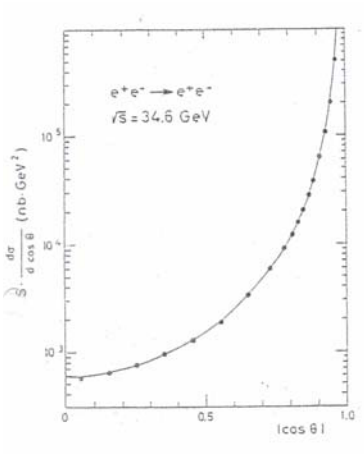


Hadron jets

$q\,\bar{q}$



2. $e^+e^- \to e^+e^-(\gamma)$

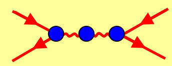


Differential cross section:

- Effect of t channel
- Perfect agreement with prediction

Possible deviation from QED:

- Finite size of electrons
- Modified photon propagator



Parametrized by a form factor:

$$F(q^2) = 1 \pm \frac{q^2}{q^2 - \Lambda_\pm^2}$$

(usual choice of form factor parametrization)

$F(q^2)$ describes an additional massive photon which modifies the propagator:

$$\frac{1}{q^2} \to \frac{1}{q^2} \pm \frac{1}{q^2 - \Lambda_\pm^2}$$

$\Lambda_\pm$ corresponds to the new photon's mass

Form factor modifies differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\left(\frac{u^2+s^2}{t^2}|F(t)|^2 + \frac{2u^2}{ts}|F(t)F(s)| + \frac{u^2+t^2}{s^2}|F(s)|^2\right)$$

Fit to combined PETRA e^+e^- data:
$\Lambda+$ >435 GeV @ 95% CL
$\Lambda-$ > 590 GeV

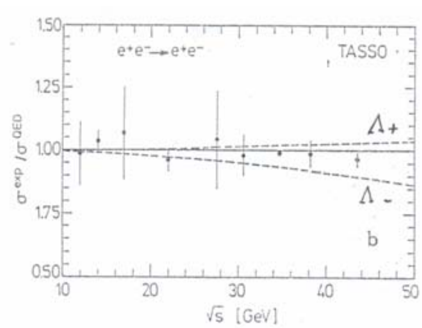
In the "space picture" form factor corresponds to modified Coulomb potential:

$$\frac{1}{r} \to \frac{1}{r}(1 + e^{-\Lambda r})$$

= extended charge

Λ> ~500 GeV ⇔ r_e< 0.197/500 fm
< 0.5 $\times 10^{-18}$ m

Tasso: Λ_+ >370 GeV
Λ_- > 190 GeV



3. $e^+e^- \to \mu^+\mu^-(\gamma)$

Total cross section

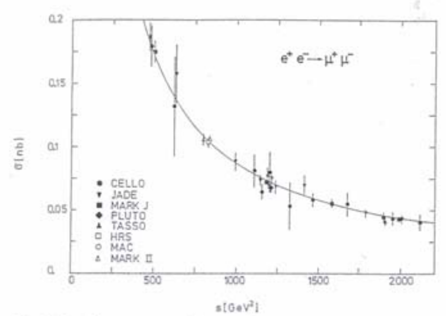
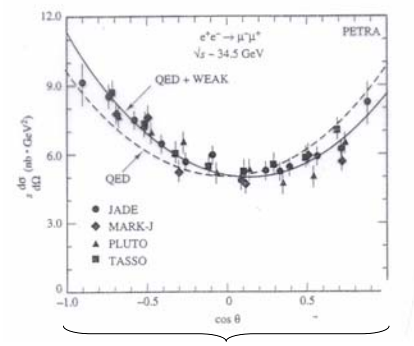


Fig. 3.21. Measurements of the total cross section for the reaction e^+e^- ... function for the square of the centre of mass energy. The lowest order QE... drawn as a solid line

Differential cross section



Clear deviation from QED:

⇒ Effect of electro-weak interference

Possible deviations from QED:

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}\left(1 \mp \frac{s}{s-\Lambda\pm}\right)$$

$\Lambda_\pm > 250\ \mathrm{GeV} \Leftrightarrow$ muon substructure $< 10^{-18} m$

4. Discovery of the Tau-Lepton

MARK I (SLAC), 1975, M.Perl et al.

Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ 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 18 August 1975)

We have found events of the form $e^+ + e^- \to e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

We have found 64 events of the form

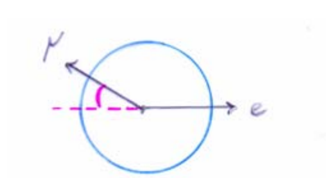
$$e^+ + e^- \to e^\pm + \mu^\mp + \geq 2 \text{ undetected particles} \quad (1)$$

for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, K_L^0 mesons, or neutrinos. Most of these events are observed at center-of-mass energies at, or above, 4 GeV. These events were found using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-

1489

TABLE I. Distribution of 513 two-prong events, obtained at $E_{c.m.}$ = 4.8 GeV, which meet the criteria $|\vec{p}_1| > 0.65$ GeV/c, $|\vec{p}_2| > 0.65$ GeV/c, and $\theta_{copl} > 20°$. Events are classified according to the number N_γ of photons detected, the total charge, and the nature of the particles. All particles not identified as e or μ are called h for hadron.

Particles \ N_γ	0	1	>1	0	1	>1
	Total charge = 0			Total charge = ±2		
e-e	40	111	55	0	1	0
e-μ	24	8	8	0	0	3
μ-μ	16	15	6	0	0	0
e-h	20	21	32	2	3	3
μ-h	17	14	31	4	0	5
h-h	14	10	30	10	4	6



Explaination

$e^+e^- \to \tau^+\tau^-$

$\tau^- \to e^-\bar{\nu}_e\nu_\tau$

$\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$

visible only $e^-\mu^+$!

Cross checks: e and μ momentum spectrum

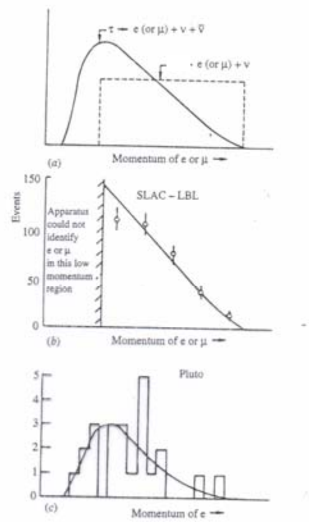


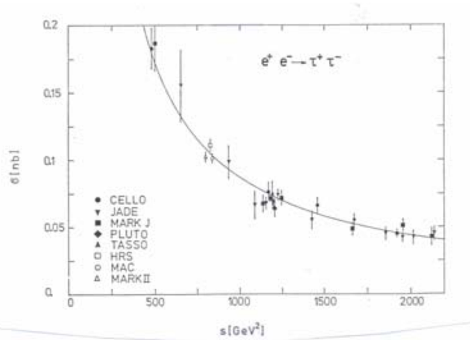
Fig. 14.2. Momentum spectra of e or μ from τ decay: (a) expected spectra of two-body and three-body decays, (b) and (c) SLAC-LBL and PLUTO data, respectively, compared with three-body spectrum. (From Perl, 1978.)

← Two body decay

← τ hypothesis:
$\tau \to \ell \upsilon_\tau \overline{\upsilon}_\ell$

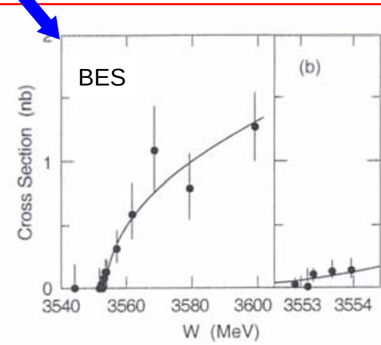
← PLUTO (DESY), 1976
confirms τ hypothesis.

Tau lepton: a sequential heavy lepton



as for $e^+e^- \to \mu^+\mu^-$

$\Lambda_\pm > 200$ GeV $r_\tau < 10^{-18}\,m$



Tau pair production threshold:

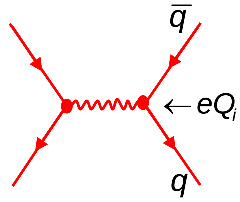
$$\sigma = \frac{4\pi}{3s} \cdot \frac{\beta(3-\beta^2)}{2} \quad \text{with} \quad \beta = \frac{v}{c}$$

$m_\tau = 1776.96^{+0.18+0.20}_{-0.19-0.16}\ MeV$

BES, 1994

5. $e^+e^- \to$ hadrons

e^+e^- annihilation to a pair of quarks with subsequent hadronization.



$$Q_i = \begin{cases} +\frac{2}{3} \\ -\frac{1}{3} \end{cases}$$

Additional color factor N_C

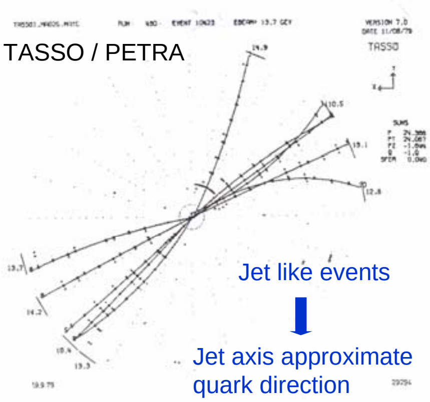
$$\left.\frac{d\sigma}{d\Omega}\right|_{ee \to hadrons} = \frac{\alpha^2}{4s} \cdot N_C \cdot \sum_{quarks\ i} Q_i^2 (1 + \cos^2\theta)$$

Sum over all possible quarks: $4m_q^2 < s$

$\sqrt{s}$	Quarks
< ~3 GeV	uds
< ~10 GeV	udsc
< ~350 GeV	udscb
> ~350 GeV	udscbt

Quark jets and angular distribution

TASSO / PETRA

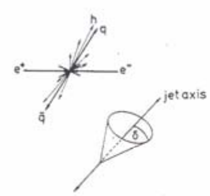


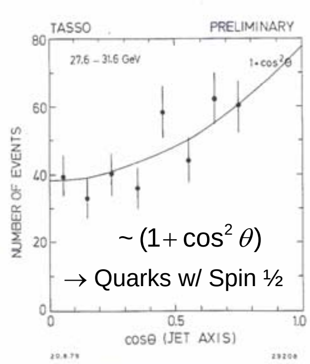
Jet like events

⬇

Jet axis approximate quark direction

Fig.2 A typical multihadron event at 27.4 GeV recorded in the central detector. The inner 4 layers belong to the proportional chamber, the following 9 are zero degree layers of the drift chamber. The solid bars at the periphery mark time-of-flight counters.





$\sim (1+\cos^2\theta)$

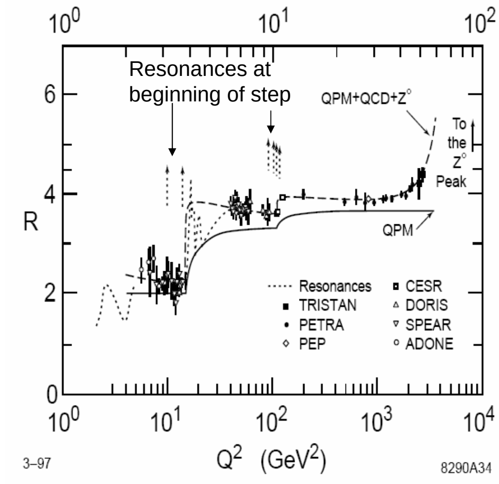
$\to$ Quarks w/ Spin ½

Fig.7 Angular distribution of the jet axis with respect to the beam.

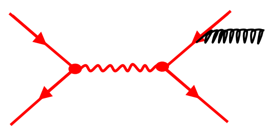
Definition:

$$R_{had} = \frac{\sigma(ee \to hadrons)}{\sigma(ee \to \mu\mu)}$$

$\sqrt{s}$	Quarks	$R_{had} = 3 \cdot \sum_i Q_i^2$
< ~3 GeV	uds	3·6/9=2.00
< ~10 GeV	udsc	3·10/9=3.33
< ~350 GeV	udscb	3·11/9=3.67
> ~350 GeV	udscbt	3·15/9=5.00



Data lies systematically higher that the prediction from Quark Parton Model (QPM) → gluon bremsstrhl.



$$\sigma(s) = \sigma_{QED}(s)\left[1 + \frac{\alpha_s(s)}{\pi} + 1.411 \cdot \frac{\alpha_s(s)^2}{\pi^2} + \ldots\right]$$

~ 5%

6. Hadronic resonances: Discovery of c and b quarks

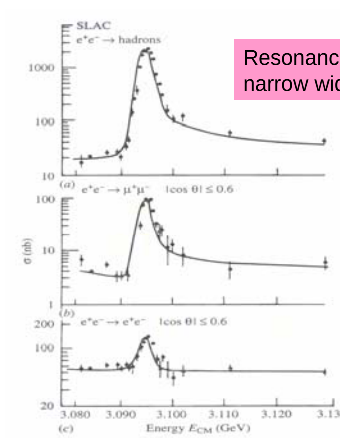
Until 1974

- hadronic states explained as bound states of 3 quarks (u, d, s)
- Prediction of a forth quarks (e.g. GIM) by theoreticians

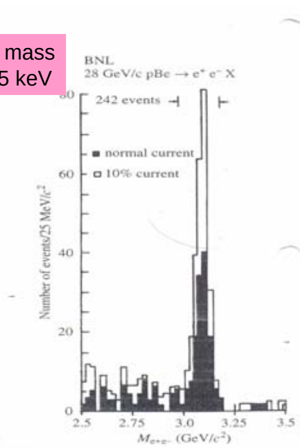
1974: "November Revolution" – Discovery of the J/ψ, bound state of new quark

SLAC $e^+e^- \to \text{hadrons}, e^+e^-, \mu^+\mu^-$

BNL p(28GeV)+Be → e^+e^-X



Resonance w/ large mass narrow width Γ=87±5 keV



Both articles appeared in the same issue of Phys. Rev. Let.

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.

B. Richter et al.

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

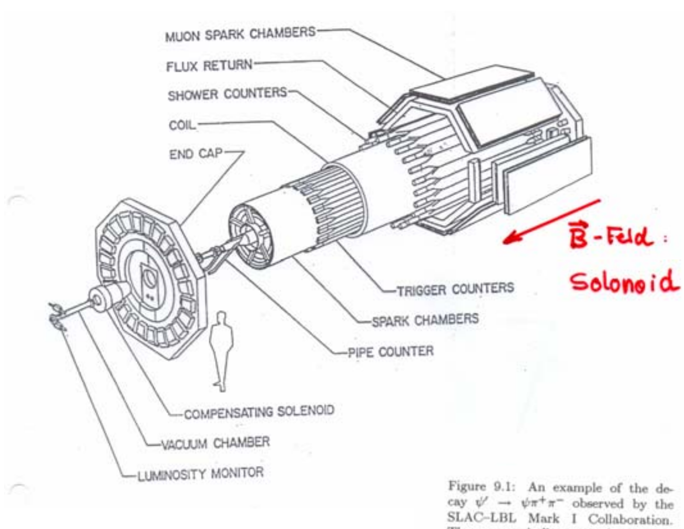
and

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

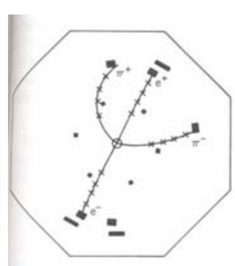
S.C.C. Ting et al.

MARK-I Detector



= prototype of a compact 4π detector

Figure 9.1: An example of the decay $\psi' \to \psi\pi^+\pi^-$ observed by the SLAC-LBL Mark I Collaboration. The crosses indicate spark chamber hits. The outer dark rectangles show hits in the time-of-flight counters. Ref. 9.5.



BNL Detector

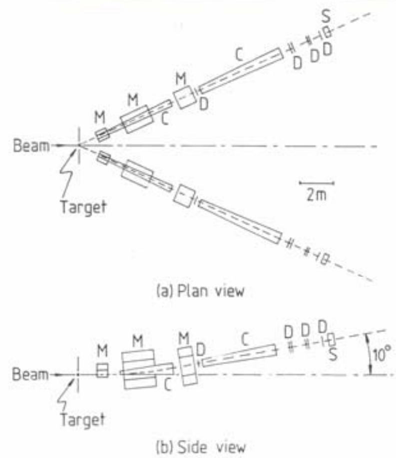


Fig. 3.12 Schematic diagram of the apparatus used in the Brookhaven experiment showing the locations of the dipole magnets M, Čerenkov counters C, electromagnetic shower counters S, and multiwire proportional chambers D. The scale is indicated by a 2 m bar line. (After J. J. Aubert *et al.*, *Physical Review Letters* **33** (1974) 1404.)

Breit-Wigner Resonance

$$\sigma = \frac{2J+1}{(2s_1+1)(2s_2+1)} \frac{\pi}{p_{cm}^2} \frac{\Gamma_{in}\Gamma_{out}}{(E-E_0)^2 + \Gamma_{tot}^2/4}$$

Spin of resonance and incoming particles

<u>Measurement of the total decay width:</u>

- Width of resonance much smaller than the detector resolution
- Use integrated cross section to determine the width:

$$\text{Area} = \int \sigma(E)dE \quad \Rightarrow \quad \text{Area} = \frac{6\pi^2}{M_\psi^2}\left(\frac{\Gamma_{ee}}{\Gamma}\right)^2 \Gamma$$

BR

Γ=87±5 keV

- Idea: total area is independent of detector resolution

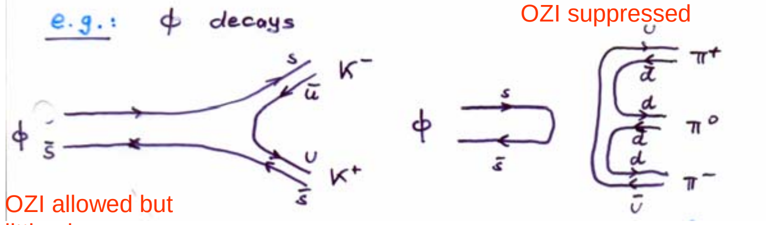
Width of resonances

J/ψ Γ=87±5 keV compared to know resonances:

ρ	Γ=149 MeV
ω	Γ= 8.4 MeV
ϕ	Γ= 4.3 MeV

<u>OZI</u> <u>(Okubo, **Zweig**, Iizuka) rule:</u>

OZI suppressed



OZI allowed but
little phase space

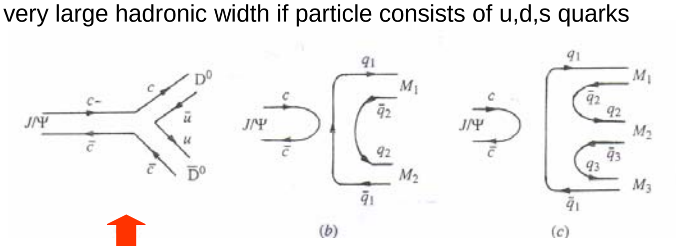
$Br(\phi \to K^+K^-) = 49\%$

$Br(\phi \to \pi^+\pi^-\pi^0) = 15.5\%$

Decays with disconnected quark lines are suppressed relative to decays where the quark lines are connected.

Width of J/ψ

Narrow J/ψ peak cannot be explained in the 3 quark picture:
very large hadronic width if particle consists of u,d,s quarks



OZI allowed but
kinematically not possible:
Charmed D mesons too
heavy (>1865 MeV)

OZI suppressed

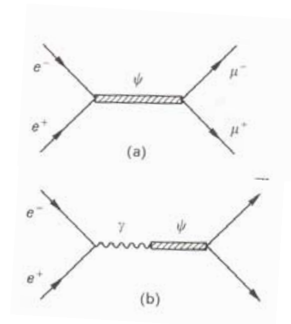
- J/ψ was interpreted as a quark-antiquark bound state of a new heavy quark c-quark.

Quantum numbers

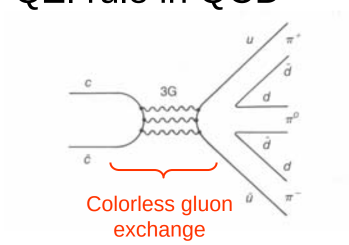
It can be shown that there are two interfering amplitudes contributing to the resonance production:

- Direct channel
- Intermediate virtual photon

$$J^{PC}(J/\psi) = J^{PC}(\gamma) = 1^{--}$$



QZI rule in QCD



1 gluon exchange: not possible (color)

2 gluon exchange: not possible (C=1)

3 gluon exchange: possible (similar to positronium)

➡ Suppression ~ α_s^3

Spectroscopy

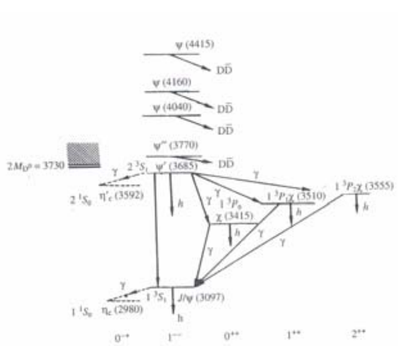


Fig. 11.7. Level diagram for J/Ψ family (see text).

Particle	$I^G(J^{PC})$	Mass(MeV/c^2)	Γ(MeV)	Γ_e(keV)	Main decay modes
$\eta_c(2980)$	$0^+(0^{-+})$	2978.8±1.9	$10.3\ ^{+3.8}_{-3.4}$		Mostly hadrons $\gamma\gamma$
$\Psi(1S) \equiv J/\Psi(3097)$	$0^-(1^{--})$	3096.93±0.09	0.086±0.006	5.36±0.29	e^+e^- $\mu^+\mu^-$ direct hadrons
$\chi(3415)$	$0^+(0^{++})$	3415.1±1.0	13.5±1.0		$\gamma J/\Psi(3097)$ hadrons
$\chi(3510)$	$0^+(1^{++})$	3510.6±0.5	0.88 ± 0.14		$\gamma J/\Psi(3097)$ hadrons
$\chi(3555)$	$0^+(2^{++})$	3556.17±0.13	2.00 ± 0.18		$\gamma J/\Psi(3097)$ hadrons
$\Psi(2S) \equiv \Psi'(3685)$	$0^-(1^{--})$	3686.00±0.10	0.278±0.032	2.14±0.21	e^+e^- $\mu^+\mu^-$ $J/\Psi + X$ J/Ψ+neutrals $J/\Psi\pi^+\pi^-$ $J/\Psi\pi^0\pi^0$ $J/\Psi\eta$ $\gamma\chi(3415)$ $\gamma\chi(3510)$ $\gamma\chi(3550)$
$\Psi''(3770)$	$0^-(1^{--})$	3769.9±2.5	23.6±2.7	0.26±0.04	e^+e^- $D\bar{D}$
$\Psi(4040)$	$?(1^{--})$	4040.0±10.0	52.0±10.0	0.75±0.15	e^+e^- charm mesons
$\Psi(4160)$	$?(1^{--})$	4159.0±20.0	78.0±20.0	0.77±0.23	e^+e^- charm mesons
$\Psi(4415)$	$?(1^{--})$	4415±6	43±15	$0.47\ ^{+0.10}_{-0.09}$	e^+e^- charm mesons

$c\,\bar{c}$ can be treated similar to prositronium:

$$V_{em} = -\frac{\alpha}{r} \quad \Rightarrow \quad V_{QCD} = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

$$E_n \sim \frac{\alpha^2 mc^2}{4n^2}$$

➡ Effective strong coupling

$\alpha_s \sim 1$

1977 Discovery of the $\Upsilon(b\bar{b})$ resonance

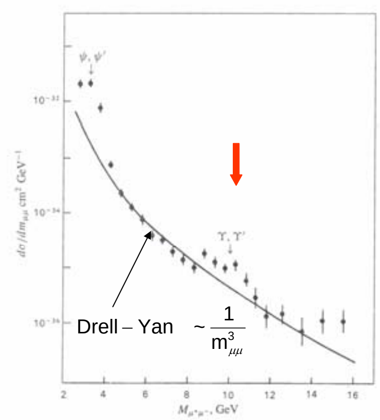


Fig. 4.6. First evidence for the upsilon resonances Υ, Υ′, obtained by Herb *et al.* (197 from the spectrum of muon pairs observed in 400 GeV proton–nucleus collisions Fermilab, near Chicago. The enhancement due to these resonances stands out agai the rapidly falling continuum background. The individual states Υ, Υ′ are not resolved.

<u>FNAL:</u> Herb et al.

$p(400\ GeV)+Cu \rightarrow \mu^+ \mu^- + X$

Detector resolution not sufficient to resolve the excited Υ states.

Confirmed by e^+e^- machines:

DESY/DORIS and Cornell/CESR

(resolved excited bb states)

$\Upsilon(9460)$ is a bound $b\bar{b}$ state: $J^{PC}=1^{--}$

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

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Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

We have observed a strong enhancement at 9.5 GeV in the mass spectrum of dimuons produced in 400-GeV proton-nucleus collisions. Our conclusions are based upon an analysis of 9000 dimuon events with a reconstructed mass $m_{\mu^+\mu^-}$ greater than 5 GeV corresponding to 1.6×10^{16} protons incident on Cu and Pt targets:

$$p + (Cu, Pt) \rightarrow \mu^+ + \mu^- + \text{anything}.$$

The produced muons are analyzed in a double-arm magnetic-spectrometer system with a mass resolution $\Delta m/m$ (rms) = 2%.

The experimental configuration (Fig. 1) is a modification of an earlier dilepton experiment in the Fermilab Proton Center Laboratory.[1-3] Narrow targets (~0.7 mm) with lengths corresponding to 30% of an interaction length are employed.

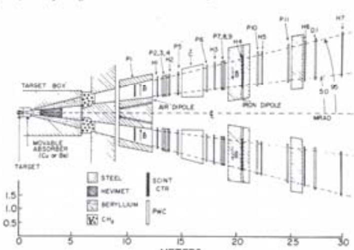

FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.

Υ Results from the e^+e^- machines

CESR

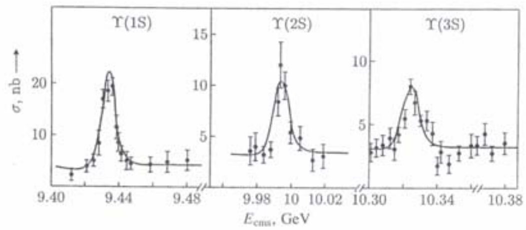

Fig. 4.7. The narrow Υ(1S), Υ(2S) and Υ(3S) resonances observed with the CLEO detector at the CESR storage ring. The data have not been corrected for radiative effects, which would bring up the masses to the values in Table 4.3 (from Andrews *et al.* 1980).

Remark: Only Υ(4s) (10.58 GeV) resonance decays into pairs of B mesons $\rightarrow$ B factories