I. e^+e^- annihilation experiments

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

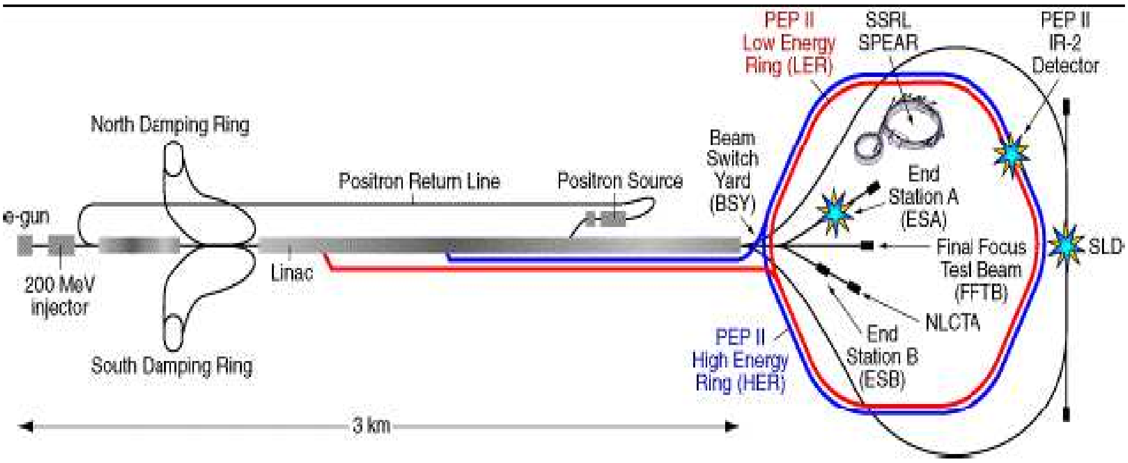
Lit.: H.U Martyn, "Test of QED …" in "Quantum Electrodynamics", T.Kinoshita (ed.)

1. Experimental methods

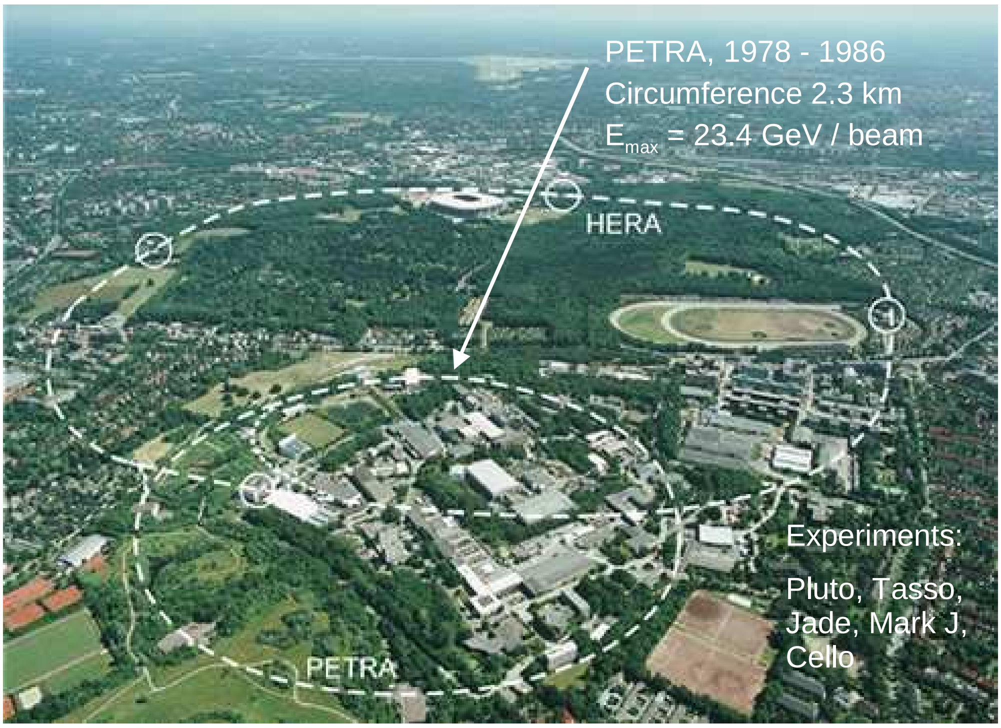
<u>e^+e^- accelerators</u> (selection)

Accelerator	Lab	$\sqrt{s}$, GeV	L_{int} , pb^{-1} / Exper.
SPEAR	SLAC	2 – 8	
DORIS	DESY	9	
CESR	Cornell	3 – 12	
PEP	SLAC	$\to$29	220 – 300
PETRA	DESY	12 – 47	~250
TRISTAN	KEK	50 – 60	~20
SLC	SLAC	100	
LEP	CERN	91$\to$209	~200

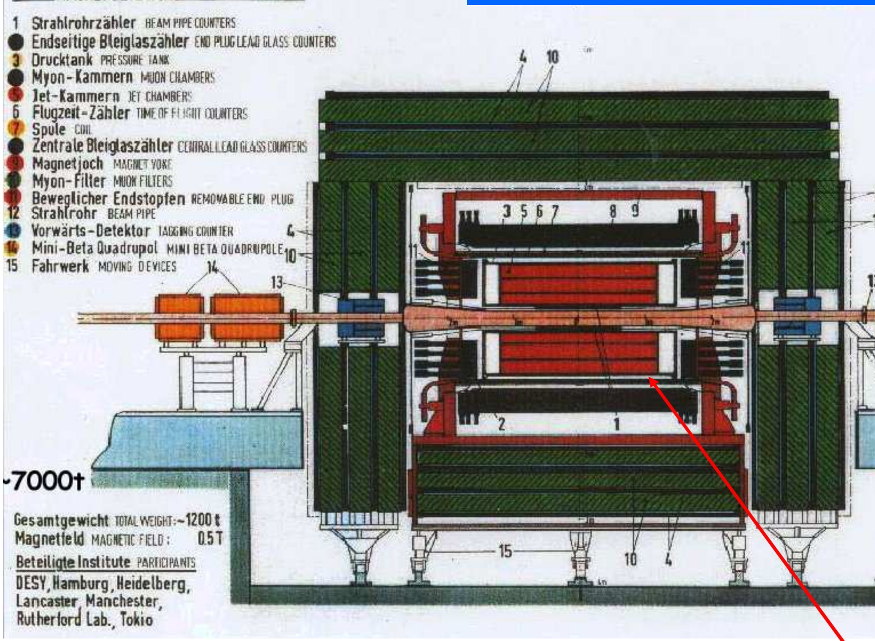
Stanford Accelerator Complex

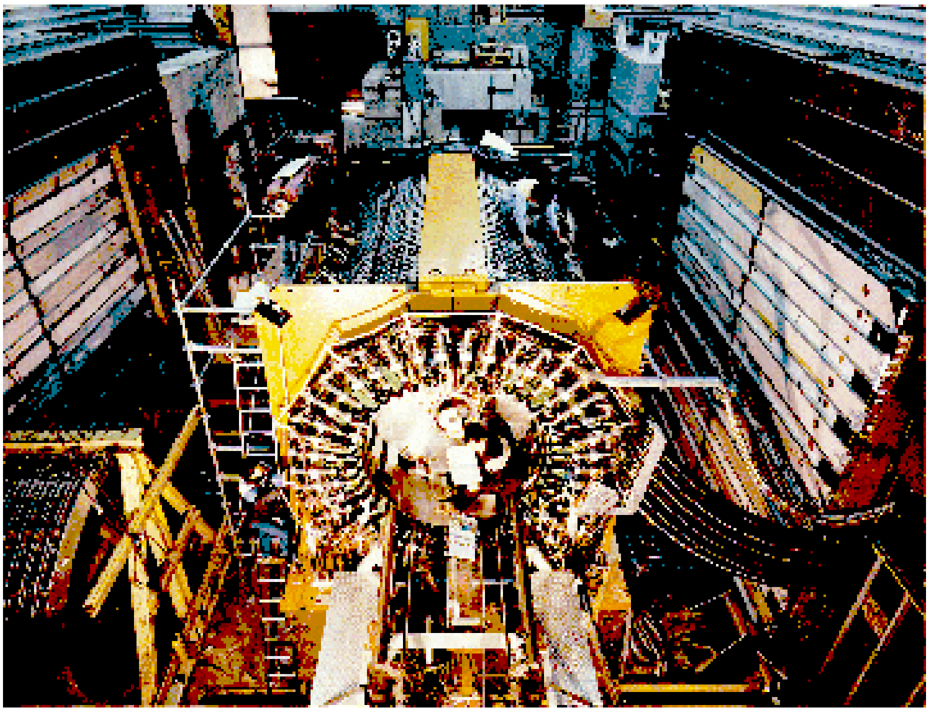


DESY Accelerator Complex

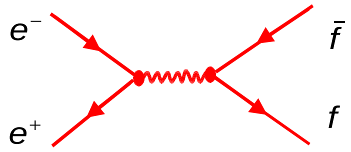


Japan – Deutschland – England

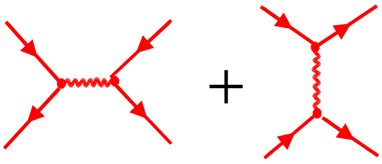




Experimental Signatures:

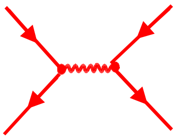


$f\,\bar{f} = e^-e^+$



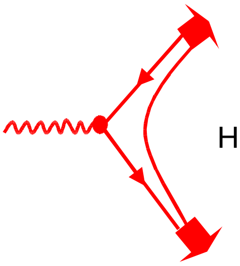
$\mu^-\mu^+$

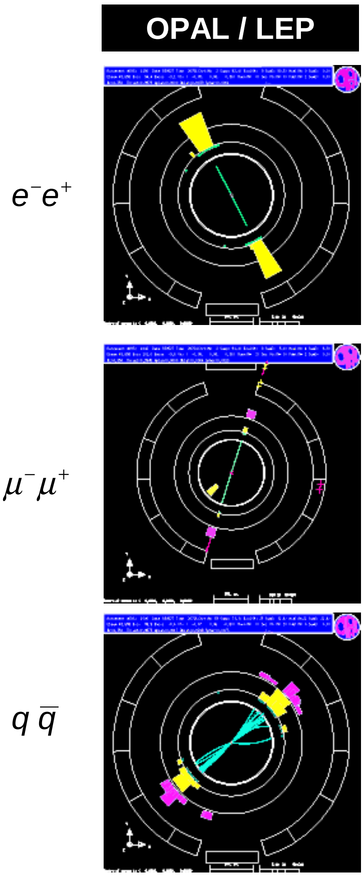
$\tau^-\tau^+$



$q\,\bar{q}$ mit

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





Cross section - Experimental determination

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

- N_{ff} - number of detected $e^+e^- \rightarrow ff$ events
- b - background fraction

∀ ε - acceptance / efficiency

- L_{int} - integrated luminosity of collider
- δ - radiative corrections

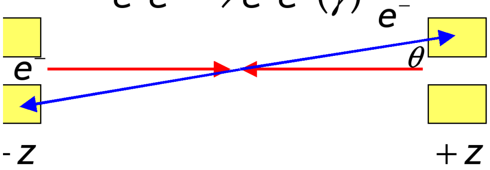
›etermination of integrated luminosity

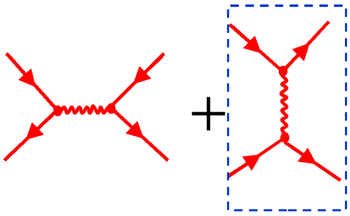
$$L_{\text{int}} = \int L_{ee}(t)dt$$

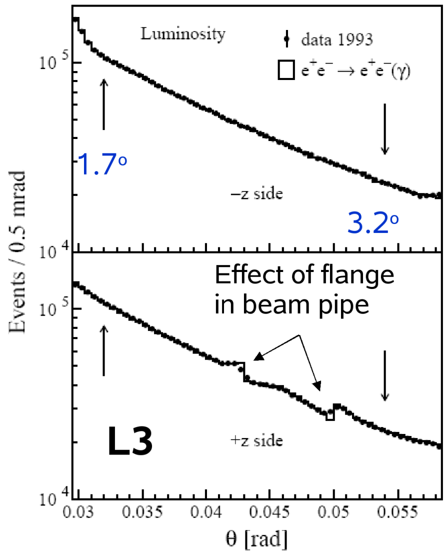
$$\sigma(e^+e^- \to f\bar{f}) = \frac{N_{ff}(1-b)}{\varepsilon L_{\text{int}}}$$

›mall angle Bhabha scattering
(low momentum transfer, QED works !!):

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





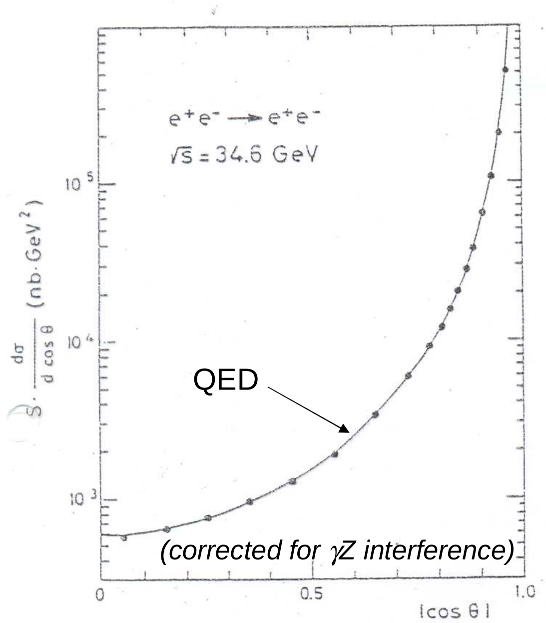


›all angle Bhabha scattering is
›hannel dominated: theoretical
›ss section σ_{theo} well known.

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

At LEP:
typ. errors < 0.5%

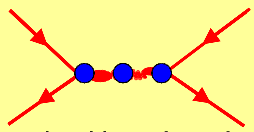
2. $e^+e^- \to e^+e^-(\gamma)$



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

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 at small distances:

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

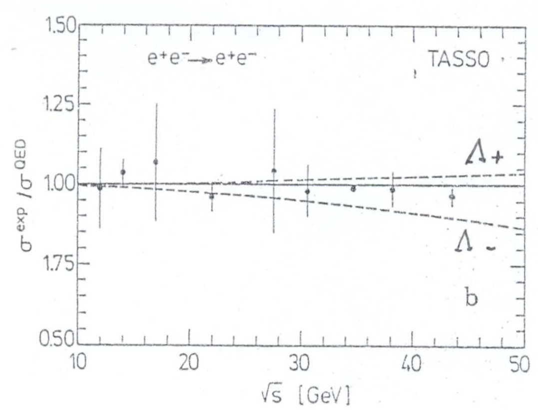
i.e. Λ measures point-like nature of $e\gamma$ interaction (size of electron).

$\Lambda > \sim 500$ GeV $\Leftrightarrow$ $r_e < 0.197/500$ fm

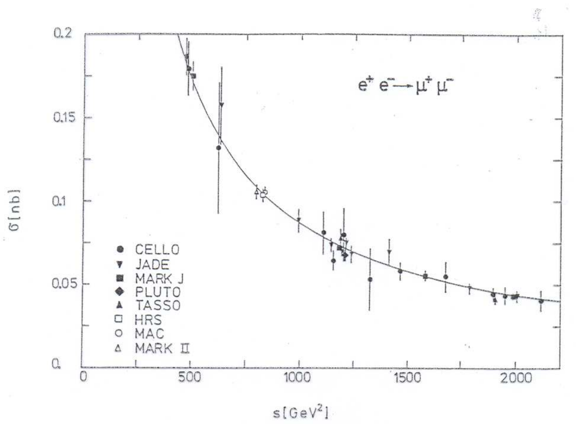
Electr. substructure $< 0.5 \times 10^{-18}$ m

Tasso: $\Lambda_+ > 370$ GeV

$\Lambda_- > 190$ GeV



2. $e^+e^- \to \mu^+\mu^-$

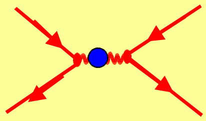


Good agreement with QED.

Also here, quantitative limit for new physics is set

Possible deviation from QED:

- additonal heavy photon



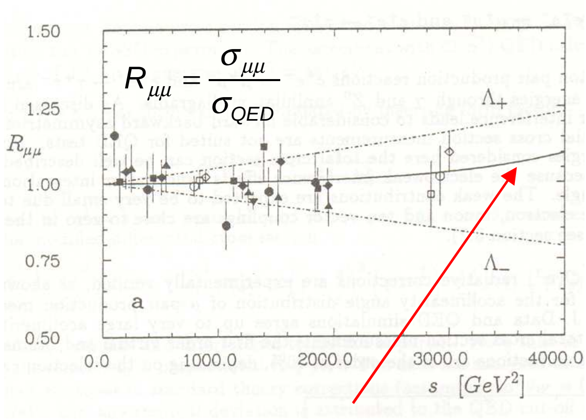
$$\frac{1}{q^2} \to \frac{1}{q^2} - \frac{1}{q^2-\Lambda^2} = \frac{1}{q^2}\left(1-\frac{q^2}{q^2-\Lambda^2}\right)$$

$$\approx \frac{1}{q^2}\left(1+\frac{q^2}{\Lambda^2}\right)$$

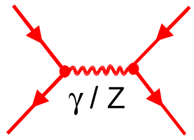
Λ corresponds to the mass of new photon

To also account for possible lower cross sections:

$$\frac{1}{q^2} \to \frac{1}{q^2}\left(1 \mp \frac{q^2}{q^2-\Lambda_\pm^2}\right)$$



$$\frac{\sigma_{\mu\mu}^{theo}}{\sigma_{QED}}$$



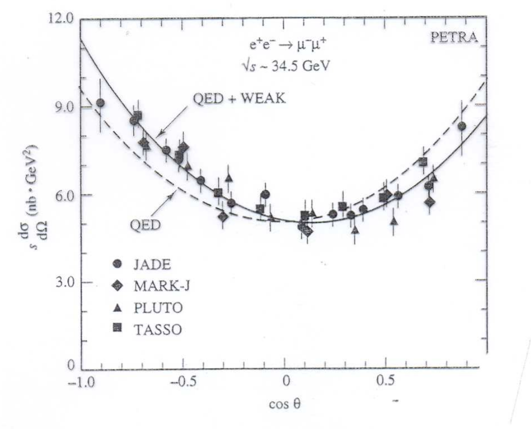
Additional heavy photon:

$$\sigma_{\mu\mu} = \frac{4\pi\alpha^2}{s}\left(1 \mp \frac{s}{s-\Lambda_\pm}\right)^2$$

$\longrightarrow\ \Lambda_\pm > 200\,\text{GeV}$

Effect of Z boson exchange

„heavy photon w/ different couplings“



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\cdot(1+\cos^2\theta)\Big|_{QED}$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\cdot(1+\cos^2\theta + A\cos\theta)\Big|_{\gamma+Z}$$

Clear deviation from QED:

⇒Effect of electro-weak γ/Z interference

3. Discovery of the Tau-Lepton

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

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

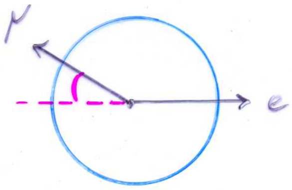
for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, K_L^0 mesons, or neutrinos. Most of these events are observed at center-of-mass energies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

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

Nobel Prize 1995 for M.Perl

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



Explanation:

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

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

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

Cross checks: e and μ momentum spectrum

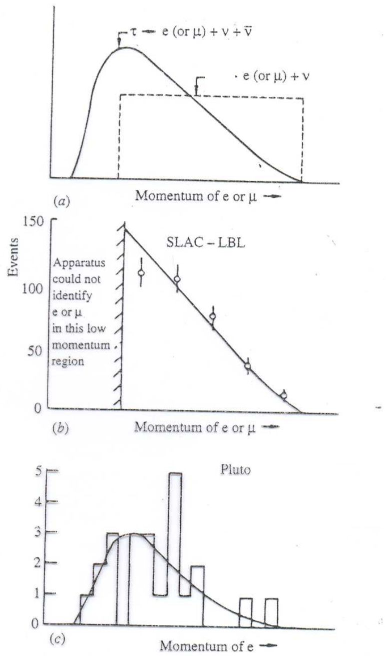


Fig. 14.2. Momentum spectra of e or μ from τ decay: (a) expected spectra of two-body and three-body decays, (b) and (c) SLAC-LBL and PLUTO data, respectively, compared with three-body spectrum. (From Perl, 1978.)

← Two body decay

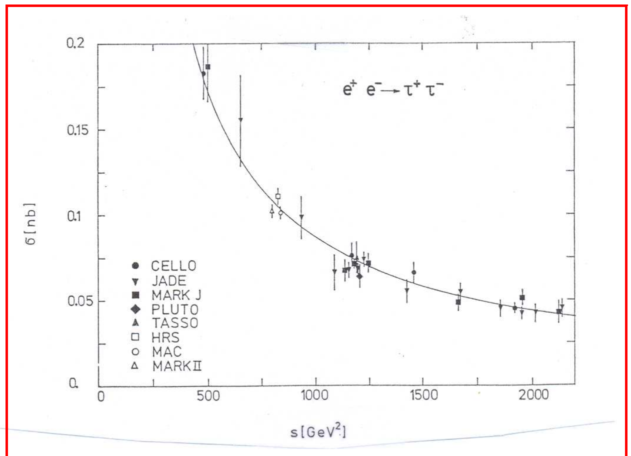
← τ hypothesis:

$$\tau \to \ell \nu_\tau \bar{\nu}_\ell$$

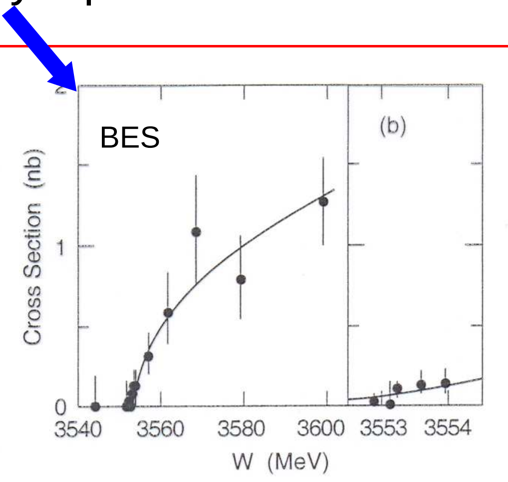
← PLUTO (DESY), 1976

confirms τ hypothesis.

Tau lepton: a sequential heavy lepton



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



Tau pair production threshold:

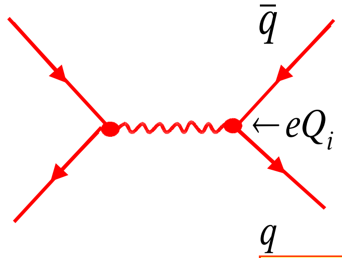
$$\sigma = \frac{4\pi}{3s} \cdot \frac{\beta(3-\beta^2)}{2} \quad \text{with} \quad \beta = \frac{v}{c}$$

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

BES, 1994

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

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



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

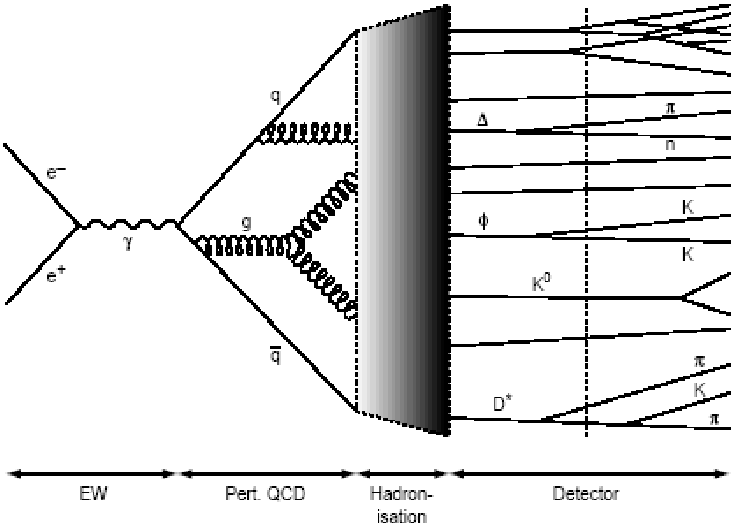
Additional color factor N_C

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

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

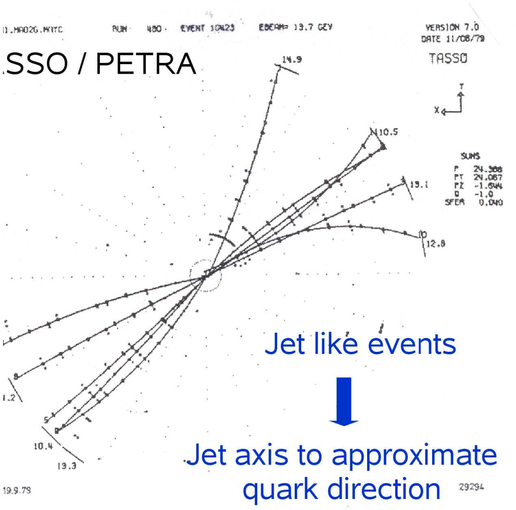
$\sqrt{s}$	Quarks
< ~3 GeV	uds
< ~10 GeV	udsc
< ~350 GeV	udscb
> ~350 GeV	udscbt

From Quarks to Jets

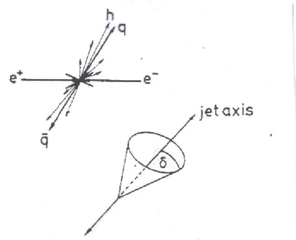


~ 20 particles
at 90 GeV

Quark jets and angular distribution



ig.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.



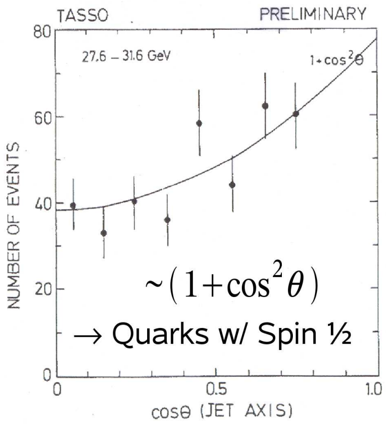


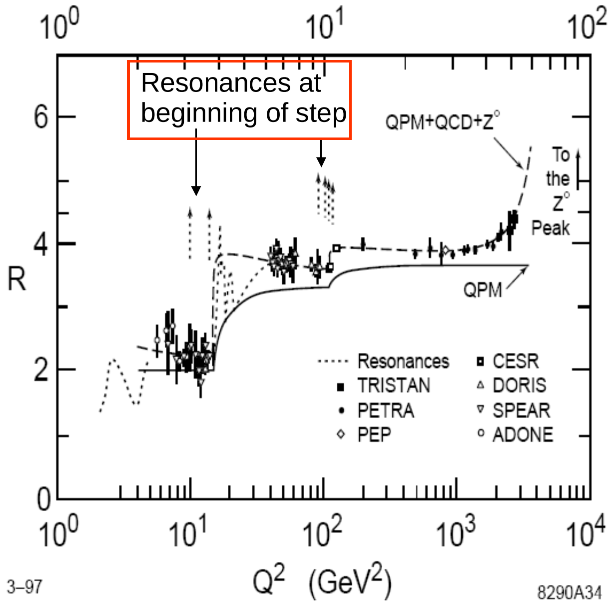
Fig.7 Angular distribution of the jet axis with respect to the beam.

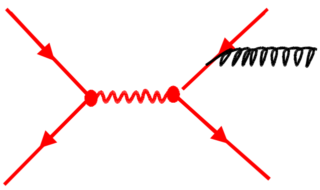
Definition:

$$R_{had} = \frac{\sigma(ee \to hadrons)}{\sigma(ee \to \mu\mu)} = 3 \cdot \sum_i Q_i^2$$

$\sqrt{s}$	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.





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

~ 7%

Hadronic resonances: Discovery of the c quarks

Until 1974

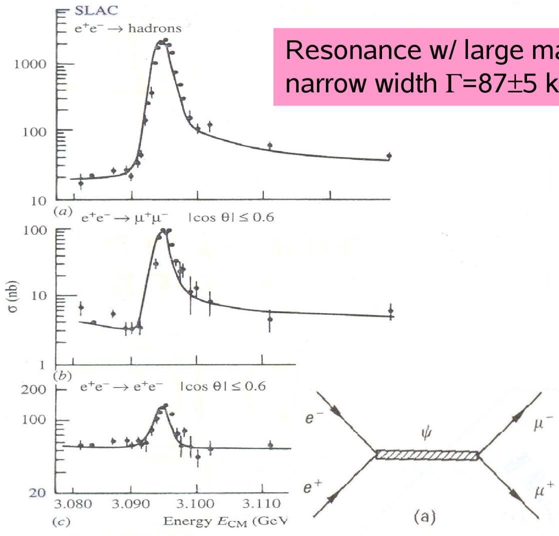
- hadronic states explained as bound states of 3 quarks (u, d, s)
- Prediction of a forth quark by theoreticians (e.g. GIM)

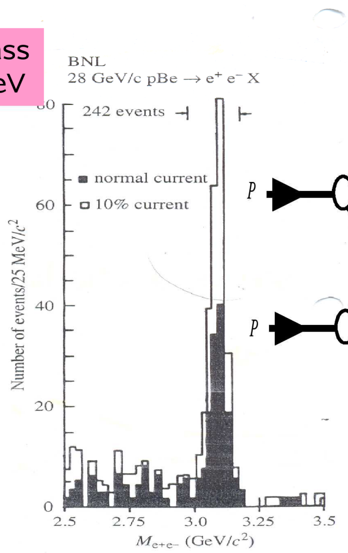
1974: "November Revolution" – Discovery of the J/ψ, bound state of new quark

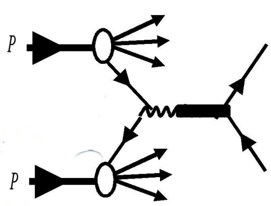
SLAC $e^+e^- \to$ hadrons, $e^+e^-, \mu^+\mu^-$

BNL p(28 GeV)+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.

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

B. Richter et al.

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‡
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ice 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.

.C.C. Ting et al.

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

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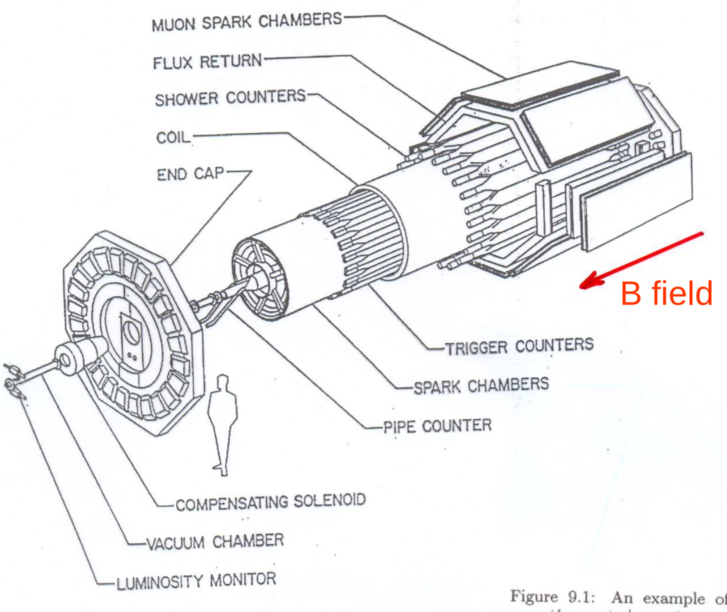
Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

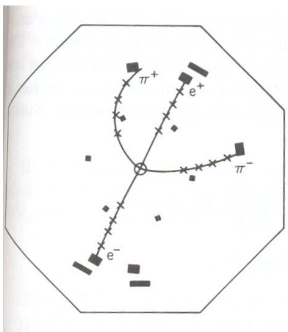
We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's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

MARK-I Detector



= prototype of a compact 4π detector

Figure 9.1: An example of the decay $\psi' \rightarrow \psi\pi^+\pi^-$ 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.



New particle J/ψ (bound c$\bar{c}$ state): $J^{PC}(J/\psi) = J^{PC}(\gamma) = 1^{--}$

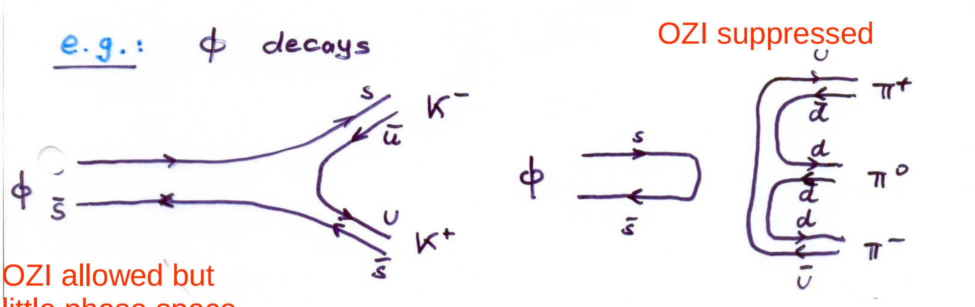
Width of resonance:

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

→ Extremely narrow !

ρ	Γ=149 MeV
ω	Γ= 8.4 MeV
ϕ	Γ= 4.3 MeV

<u>**OZI** (**O**kubo, **Z**weig, **I**izuka) rule:</u>



OZI suppressed

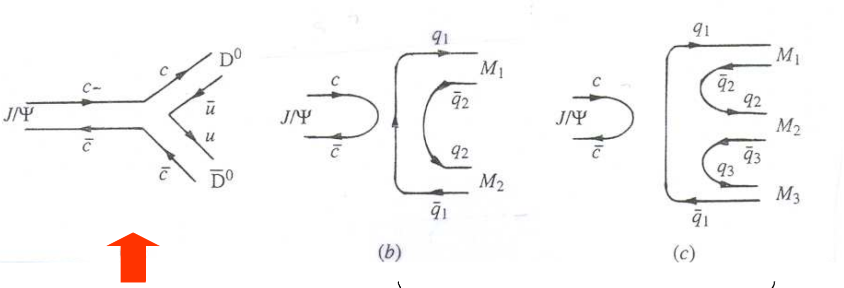
OZI allowed but
little phase space

$Br(\varphi \rightarrow K^+ K^-) = 49$ $Br(\varphi \rightarrow \pi^+ \pi^- \pi^0) = 15.5$

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

Width of J/ψ

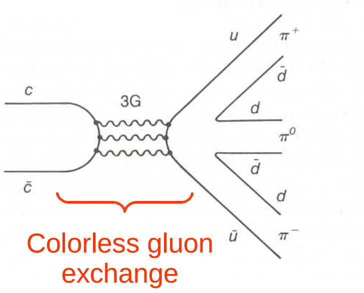
- Narrow J/ψ peak cannot be explained in the 3 quark picture: would expect large hadronic width if particle consists of u,d,s quarks
- J/ψ was interpreted as a quark-antiquark bound state of a new heavy quark c-quark.



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

OZI suppressed

OZI rule in QCD



1 gluon exchange: not possible (color)

2 gluon exchange: not possible (C=1)

since ψ couples to γ, it has C = -1

3 gluon exchange: possible

(similar to positronium)

Suppression ~ α_s^3