IV. e^+e^- annihilation experiments

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

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}
LEP	CERN	90 GeV	~200 pb^{-1}

Cross section (experimental definition)

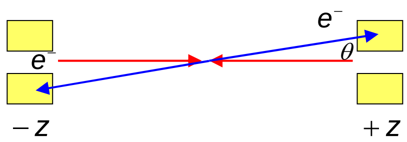
$$\sigma(e^+e^- \to f\,\bar{f}) = \frac{N_{ff}(1-b)}{\varepsilon\, L_{int}}$$

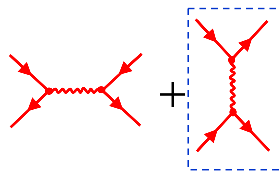
- N_{ff} number of detected $e^+e^- \to$ ff events
- b background fraction
- ε acceptance / efficiency
- L_{int} integrated luminosity of collider

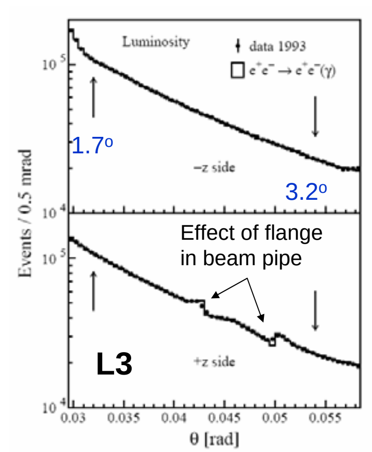
Determination of integrated luminosity $L_{\text{int}} = \int L_{ee}(t)dt$

Small angle Bhabha scattering

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



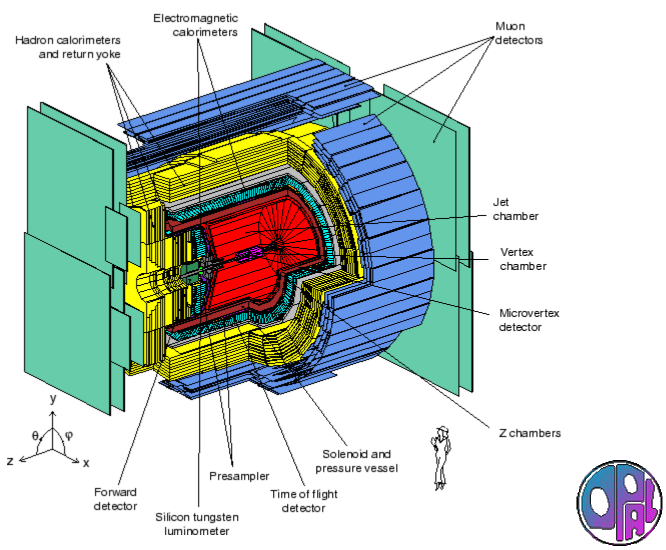




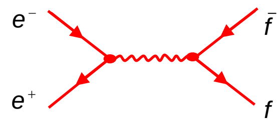
Small angle Bhabha scattering is t channel dominated: theoretical cross section σ_{theo} well known.

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

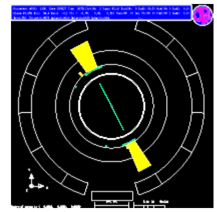
Typical detector:



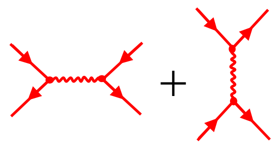
Fermion pair production:



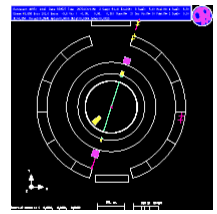
e^-e^+



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

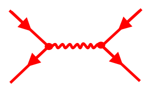


$\mu^-\mu^+$

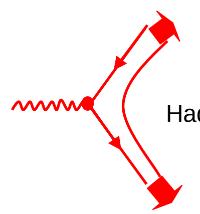


$\mu^-\mu^+$

$\tau^-\tau^+$

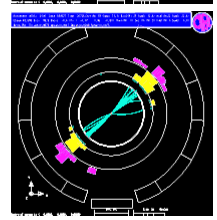


$q\bar{q}$ mit
$q = u,d,s,c,b,(t)$

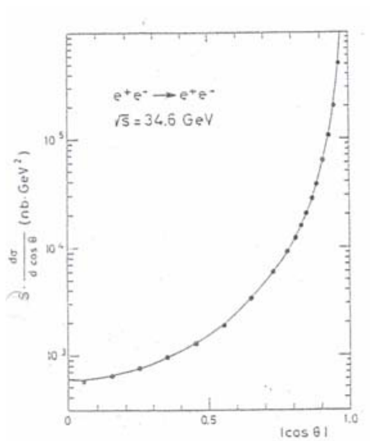


Hadron jets

$q\bar{q}$



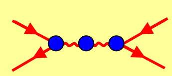
2. $e^+e^- \to e^+e^-(\gamma)$



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

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:
Λ+ >435 GeV @ 95% CL
Λ- > 590 GeV

In the "space picture" form factor corresponds to modified Coulomb potential: $\frac{1}{r} \rightarrow \frac{1}{r}(1+e^{-\Lambda r})$

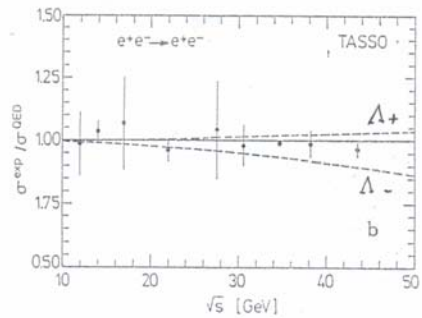
= extended charge

Λ> ~500 GeV $\Leftrightarrow$ r_e< 0.197/500 fm

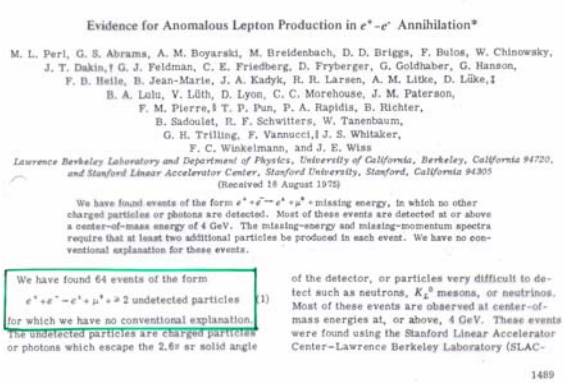
Substructure < 0.5 $\times 10^{-18}$ m

Tasso: Λ_+ >370 GeV

Λ_- > 190 GeV



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

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(Received 18 August 1975)

We have found events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + 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

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

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

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

Nobel Prize 1995 for M.Perl

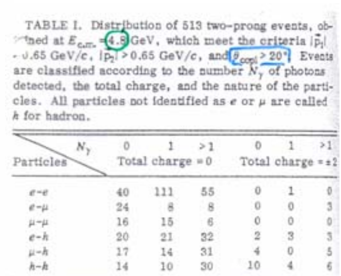
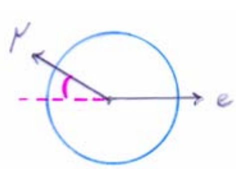


TABLE I. Distribution of 513 two-prong events, obtained at $E_{c.m.}$ = 4.8 GeV, which meet the criteria $|\vec{p}_1|$ > 0.65 GeV/c, $|\vec{p}_2|$ > 0.65 GeV/c, and θ_{copl} > 20°. Events are classified according to the number N_γ of photons detected, the total charge, and the nature of the particles. 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:

$$e^+e^- \rightarrow \tau^+\tau^-$$

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

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

Cross checks: e and μ momentum spectrum

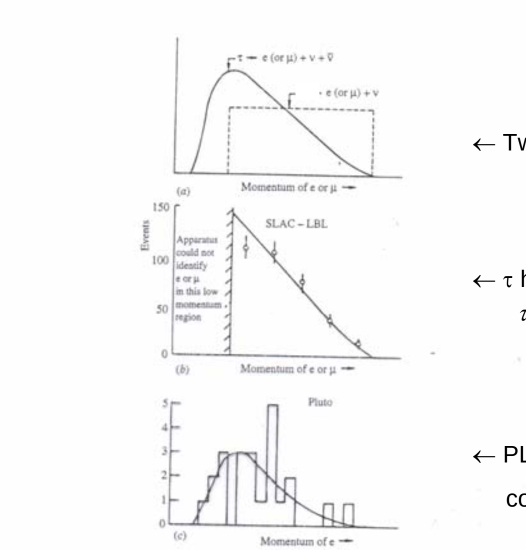
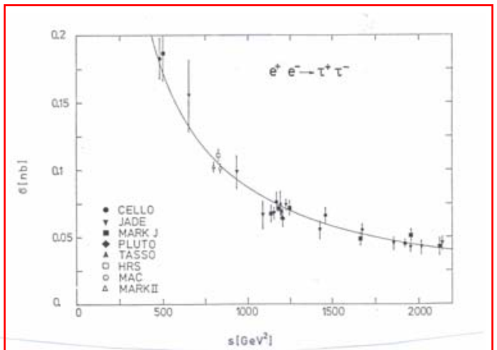
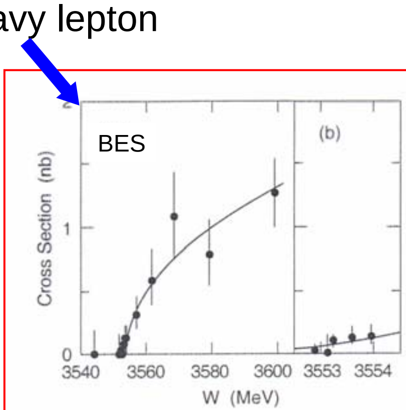


Fig. 14.2. Momentum spectra of e or μ from τ decay: (a) expected spectra of two-body and three-body decays, (b) and (c) SLAC-LBL and PLUTO data, respectively, compared with three-body spectrum. (From Perl, 1978.)

Tau lepton: a sequential heavy lepton



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



Tau pair production threshold:

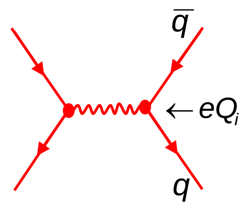
$$\sigma = \frac{4\pi}{3s} \cdot \frac{\beta(3-\beta^2)}{2} \quad \text{with} \quad \beta = \frac{v}{c}$$

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

BES, 1994

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

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



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

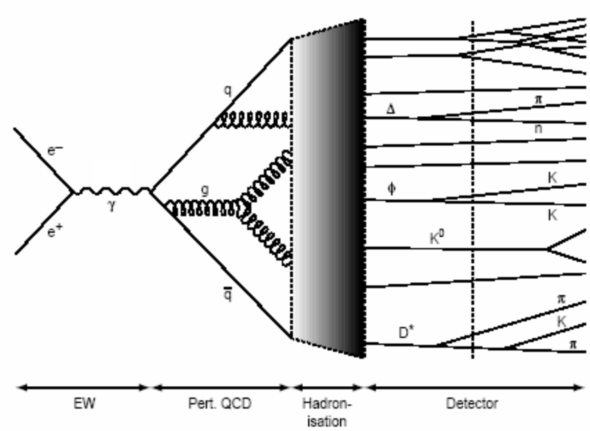
Additional color factor N_C

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

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

TASSO / PETRA

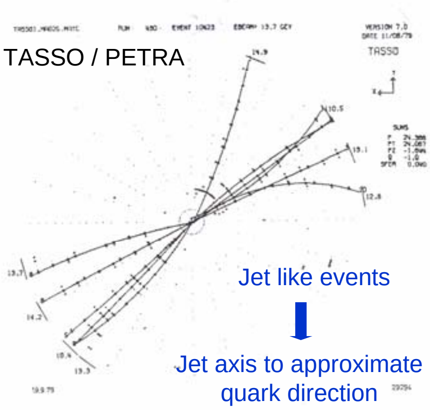
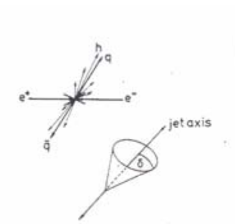


Fig.2 A typical multihadron event at 27.4 GeV recorded in the central detector. The inner 4 layers belong to the proportional chamber, the following 9 are zero degree layers of the drift chamber. The solid bars at the periphery mark time-of-flight counters.

Jet like events

⬇

Jet axis to approximate quark direction



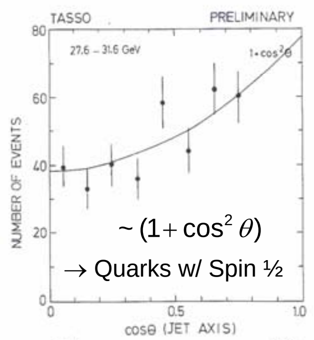


Fig.7 Angular distribution of the jet axis with respect to the beam.

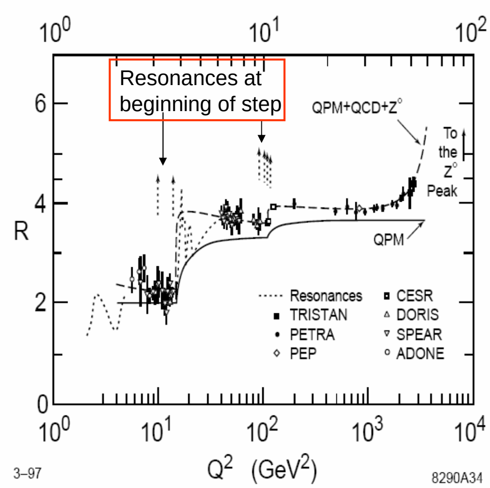
$\sim (1+\cos^2\theta)$

$\rightarrow$ Quarks w/ Spin ½

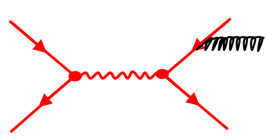
Definition:

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

$\sqrt{s}$	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) $\rightarrow$ gluon bremsstrhl.



$$\sigma(s) = \sigma_{QED}(s)\left[1 + \underbrace{\frac{\alpha_s(s)}{\pi} + 1.411 \cdot \frac{\alpha_s(s)^2}{\pi^2} + \ldots}_{\sim 7\%}\right]$$

U. Uwer