

III. Introduction to QED

4.4 Bhabha scattering $e^+e^- \rightarrow e^+e^-$

$M =$
 $+$

$\overline{|M|^2} =$
 $+ \text{interference} +$

$\underbrace{\hspace{10em}}_{e^-\mu^- \rightarrow e^-\mu^- \text{ "s/t-crossing"}}$
 $\underbrace{\hspace{10em}}_{e^+e^- \rightarrow \mu^+\mu^-}$

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

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CM system:

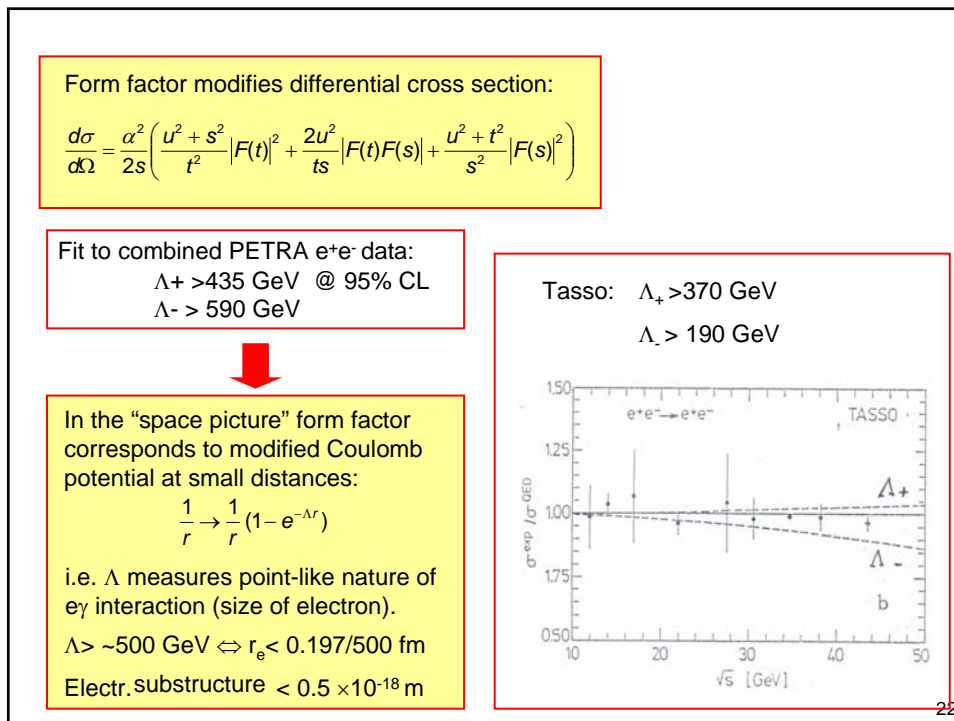
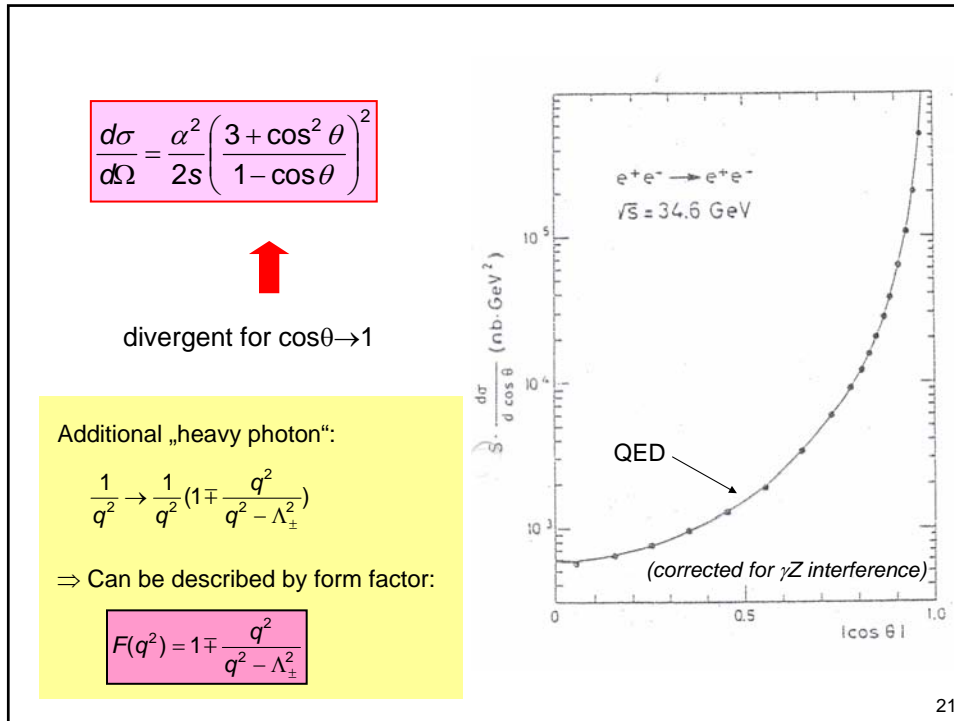
with $x = \cos\theta$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s} \left(\frac{4 + (1+x)^2}{(1-x)^2} - \frac{(1+x)^2}{1-x} + \frac{1+x^2}{2} \right)$$

$$= \frac{\alpha^2}{2s} \left(\frac{3 + \cos^2\theta}{1 - \cos\theta} \right)^2$$

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4.5 Discovery of the Tau-Lepton

MARK I (SLAC), 1975, M. Perl et al.
Nobel Prize 1995 for M. Perl

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

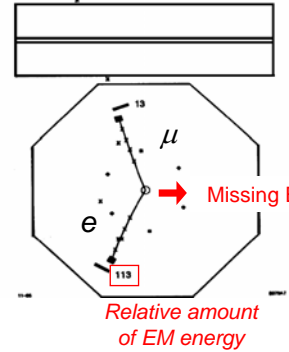
M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Daku, J. G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Loke, I. B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre, I. 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 19 August 1975)

We have found events of the form $e^+e^- \rightarrow e^\pm + \mu^\pm + \text{missing energy}$, 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.

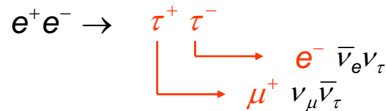
We have found 64 events of the form $e^+e^- \rightarrow e^\pm + \mu^\pm + \geq 2$ undetected particles (1) for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle

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-

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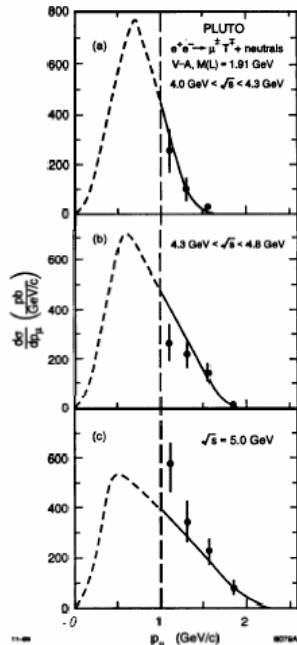
Explanation:



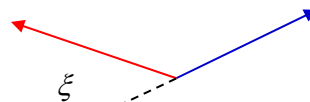
A lot of Discussions in 1975:

Are these events really decays of a new 3rd generation heavy lepton ?

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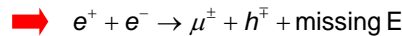
1) Large acollinearity confirms tau hypothesis



2) Anomalous "single muon events" predicted:

Expectation: $BR(\tau \rightarrow e(\mu)\nu\bar{\nu}) \approx 20\%$

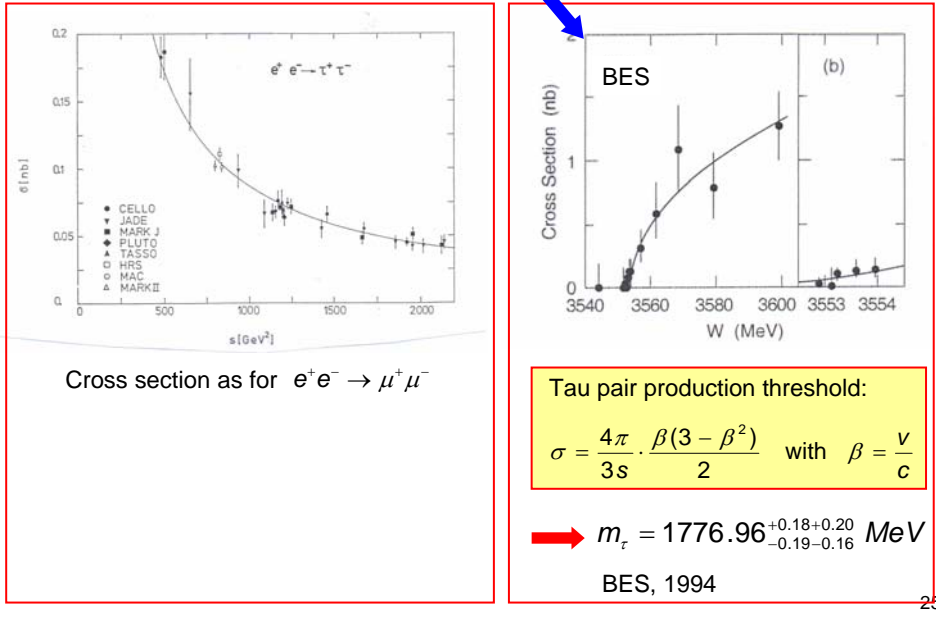
$BR(\tau \rightarrow h + \nu) \approx 60\%$



PLUTO (DESY, 1976) confirms the anomalous "single muon events". Muon spectrum consistent with 3-body tau decay.

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Tau lepton: A “sequential” heavy lepton

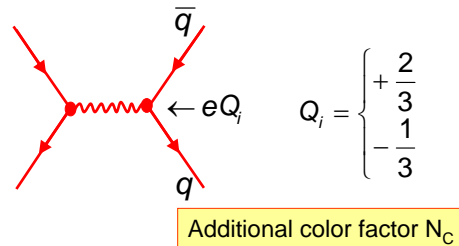


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4.6 $e^+e^- \rightarrow \text{hadrons}$

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

Quarks have fractional charges and carry “color” as additional quantum number.



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

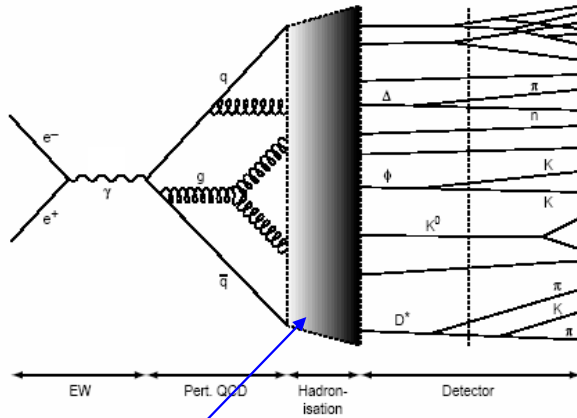
Sum over kinematically possible quark flavors:
 $4m_q^2 < s$

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

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From Quarks to Jets



Described successfully by different phenomenological fragmentation models realized as Monte Carlo programs: **PHYTIA, HERWIG**

~ 20 particles at 90 GeV

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Quark jets and angular distribution

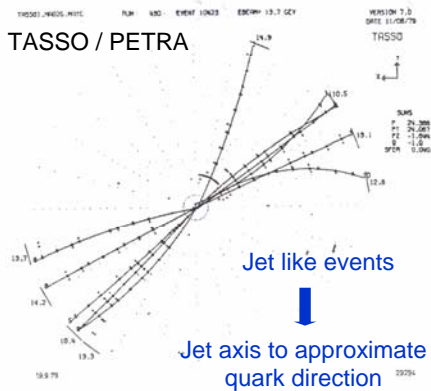


Fig.2 A typical multihadron event at 27.4 GeV recorded in the central detector. The inner 4 layers belong to the proportional chamber, the following 9 are zero degree layers of the drift chamber. The solid bars at the periphery mark time-of-flight counters.

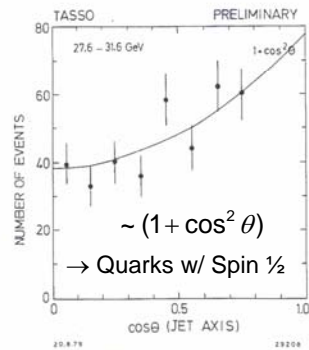
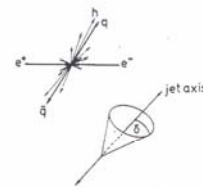


Fig.7 Angular distribution of the jet axis with respect to the beam.

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