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USING e^+e^- CROSS-SECTIONS TO TEST QCD AND TO SEARCH FOR NEW PARTICLES*

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ABSTRACT

A careful analysis is presented of the most recent data for $R(e^+e^- \to \text{hadrons})$ using improved theoretical techniques. Recent calculations of higher-order corrections are discussed. It shown why R is potentially one of the best tests of QCD. For $\sqrt{s}$ near 7 GeV, the data lie about 16% above the theory; the experimental uncertainty is ±10% (dominated by systematics). While this discrepancy may well be due to experimental problems, we also consider the possibility that there is a threshold for new particles (at $\sqrt{s} \approx 6$ GeV) such as new quarks, Higgs bosons, heavy leptons, quixes and massive gluons.

Many process have been investigated as tests of QCD. For e^+e^- physics there has been considerable discussion concerning the use of jet phenomena as such a tool. At the same time it should be remembered that the total cross-section for e^+e^- annihilation to hadrons is also an excellent means of testing QCD. This cross-section is usually normalized to the muonic cross-section:

$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \quad . \tag{1}$$

The magnitude of R is one of the best tests of QCD, because: (a) it is conceptually simple, (b) the magnitude of R at any single value of Q^2 is predicted by QCD (unlike deep-inelastic scattering), (c) Q^2 can (as a result of (b)) be chosen large in order to minimize non-perturbative effects such as higher-twist contributions, and (d) the α_s^2 term in R has been calculated[1] and is small ($\lesssim 1\%$ of the total R for $\sqrt{s} > 4$ GeV).

Neglecting masses, the perturbation expansion for R is

$$R = \sum_i 3Q_i^2 \left[1 + \sum_{n=1}^{\infty} C_n \left(\frac{\alpha_s}{\pi}\right)^n \right] \quad . \tag{2}$$

The calculation of the second-order term is very important since it provides some indication of how rapidly the perturbation series converges and since Λ is not well-defined without going to second-order. The calculation is most easily performed[2] by calculating the divergent part of the photon's vacuum polarization tensor. This is related to R through standard renormalization group and unitarity arguments. The calculation of C_2 has now been done by three groups using different methods, but with identical results. Dine and

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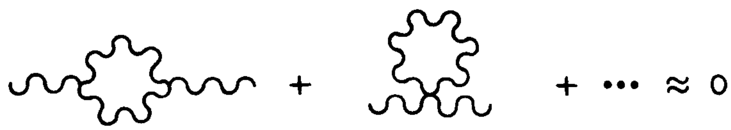
Sapirstein[1] performed much of the calculation numerically with self-energy insertion diagram, treated analytically. Chetyrkin, Kataev and Tkachev[1] performed the calculation analytically in coordinate space while Celmaster and Gonsalves[1] used momentum space. The results depend, of course, on the renormalization procedure ($N_f \equiv$ number of flavors):

$C_2 = 7.36 - 0.44\ N_f$ in MS $\equiv$ minimal subtraction scheme

$C_2 = 1.99 - 0.12\ N_f$ in $\overline{\mathrm{MS}}$ scheme (Bardeen et al.[3])

$C_2 = -2.19 + 0.16\ N_f$ momentum space scheme.[4]

The MS scheme appears to be an inappropriate scheme to use. In calculations of other processes, the MS scheme also gives larger corrections. Here the $\overline{\mathrm{MS}}$ and momentum space schemes are smaller because



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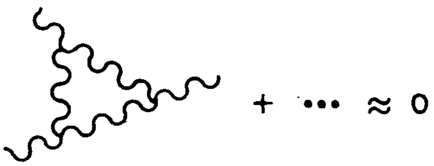
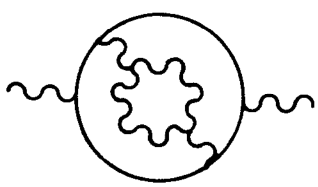


at a symmetric point with $q^2 = q_0^2 \equiv$ typical momentum. Therefore



(etc.) is small for the $\overline{\mathrm{MS}}$ and momentum space schemes. We may then conclude from the magnitude of C_2 in these two schemes that perturbution theory for R is reliable.

In work[5] I have done with Michael Dine and Larry McLerran we concentrated on the data above the charm resonance region with $5.5 \le \sqrt{s} \le 7.5$ GeV (where only the Mark I experiment has published significant data[6]), see Fig. 1.

To test QCD, we should smooth[7] the data and theory using an appropriate procedure. The smoothing assump-

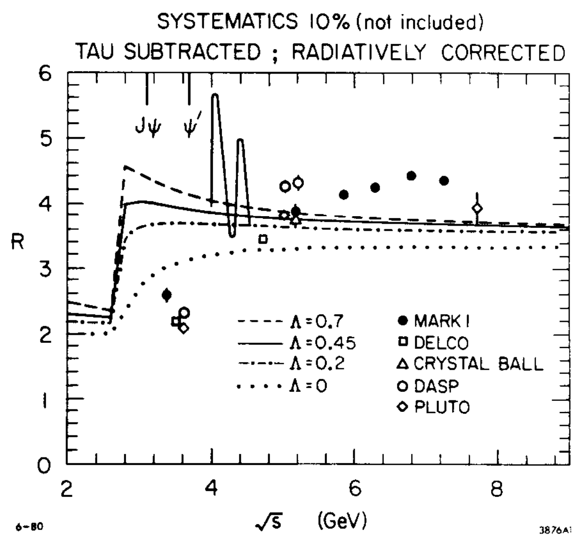


Fig. 1. Data for R from the SLAC-LBL COLLABORATION (Ref. 6) and from other collaborations (references in Ref. 5). The resonance region is shown schematically. The contributions of the τ have been subtracted, and radiative corrections have been applied. Only statistical errors are shown. The locations of J/ψ and ψ' have been indicated, since they are included in smoothing. The curves are the QCD predictions for R (Λ = 0 is the parton model).

tion is almost equivalent to the assumption of local duality. Dine, McLerran and I developed a general procedure[5] using

$$\bar{R}(s) = \int_{4m_\pi^2}^{\infty} ds'\ W(s,s',\Delta)\, R(s') \tag{3}$$

where W is a weight function such as

$$W \propto \exp\left[-\tfrac{1}{2}(s-s')^2/\Delta^2\right] \quad . \tag{4}$$

Figure 2 shows smoothed theory and data.

There is a discrepancy between theory and experiment of about 16%; systematic errors are reported to be 10%. From this discrepancy we can draw one of three conclusions:

(1) The experiment is inaccurate; the 10% systematic error is actually 16%. This is the most probable conclusion.
(2) QCD is wrong.
(3) There is a threshold for new particles.

The discussion[5] of what types of particles may have missed up to now is relevant not only at SPEAR but also at DORIS, CESR, PETRA and PEP.

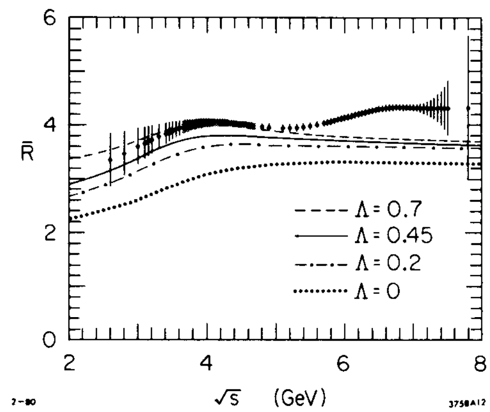


Fig. 2. The results of smoothing the theoretical and experimental values of R with $\Delta = 5$ GeV^2. All data were from Ref. 6. The error bars are statistical only. The curves are QCD. $\Lambda = 0$ indicates the parton model.

Is it possible that a quark of charge = −1/3 and mass ≈ 3 GeV has been missed? It would give an excellent fit to Mark I data[6] for R and cannot be ruled out by PETRA data. But the expected $Q\bar{Q}$ resonances have not been observed. Mark I data[8] give $\Gamma_{ee}(Q\bar{Q}) \lesssim 0.15$ keV (90% confidence) for $4.5 < \sqrt{s} < 7.5$ GeV, but we expect $\Gamma_{ee}(Q\bar{Q}) \approx$ 1 keV. Could the $Q\bar{Q}$ resonances be hidden by making them wide? They would have to be 100 MeV wide. Particles such as quix resonances are probably only about 3 MeV wide. Unless a mechanism to make $Q\bar{Q}$ resonances wide can be found, new quarks are ruled out.

The production of charged Higgs bosons cannot explain the data because their threshold has $\Delta R \propto (\text{velocity})^3$ unlike fermions which have $\Delta R \propto$ velocity. As a result R rises very slowly (asymptotically $\Delta R = 0.25$).

Ordinary charged heavy leptons, though consistent with Mark I data for R, are ruled out by examination of $e\mu$, $eX^\pm$,... events at SPEAR and PETRA. However, consider

$$L^+ \to N_L^o + (e\nu),\ (\mu\nu) \text{ or } (ud)$$

where mass $(N_L^o) \approx 2$ GeV and N_L^o is relatively stable, or

$$L^+ \to \tau^+ \nu\nu$$

where this is the dominant decay. Then experimental cuts made at PETRA to eliminate backgrounds would also eliminate these events. At SPEAR these events would be counted, usually as 2-prong events (slow electrons and muons cannot be distinguished from hadrons).[9] It is possible (but not at all certain) the apparent rise in R is due mostly to a rise in the 2-prong cross-section, see Fig. 3.

Finally is it possible that the "rise" in R is not a threshold but is a 2 GeV wide resonance? This might correspond to an extra U(1) gluon separate from the usual massless gluons. With only one free parameter (besides mass), one can get ΔR, Γ_{hadron} and Γ_{ee} correct. However if this massive gluon couples to c and b, then $\Gamma(\psi)$ and $\Gamma(\Upsilon)$ are 100-1000 times too large. If it couples only to u and d quarks, it is probably impossible to make a natural and consistent model without strangeness-changing-neutral-currents, etc.

In conclusion, R is potentially one of the best tests of QCD. (There are also sum rule tests [10] of R not discussed here.) But currently R is 16% higher than theory for $\sqrt{s} = 6 - 7.5$ GeV although this is likely to be due to systematic error. The apparent rise may come from 2-prong events. Clearly more accurate (3-5% accuracy) experiments are needed, and already there are new data under analysis. It should be noted that some types of new particles may have eluded detection at present storage rings.

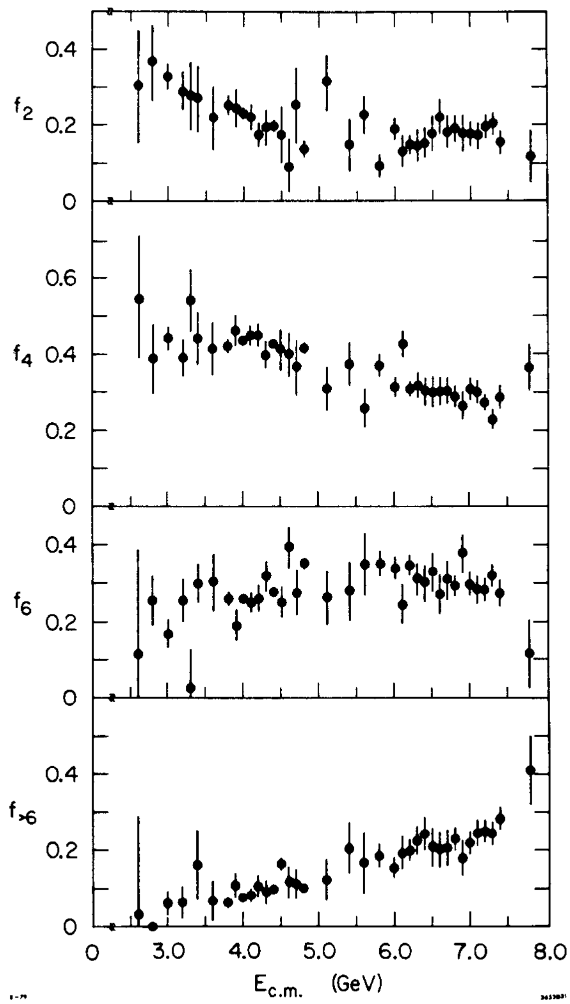


Fig. 3. The ratio of R for events with a given number of charged prongs to the total R. Data are from Ref. 6.

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REFERENCES

1. M. Dine and J. Sapirstein, Phys. Rev. Lett. 43, 668 (1979); K. G. Chetyrkin, A. L. Kataev and F. V. Tkachev, Phys. Lett. 85B, 277 (1979); W. Celmaster and R. J. Gonsalves, Phys. Rev. Lett. 44, 560 (1980).
2. T. Appelquist and H. Georgi, Phys. Rev. D8, 4000 (1973); A. Zee, Phys. Rev. D8, 4038 (1973).
3. W. A. Bardeen et al., Phys. Rev. D18, 3998 (1978).
4. W. Celmaster and R. J. Gonsalves, Phys. Rev. Lett. 44, 560 (1980).
5. R. M. Barnett, M. Dine and L. McLerran, Phys. Rev. D22, 594 (1980) (an analysis of the new heavy lepton hypothesis using earlier data appears in M. Biyajima and O. Terazawa, Prog. Theor. Phys. 60, 1240 (1978)).
6. J. Siegrist, Report No. SLAC-225 (1979) (Ph.D. Thesis).
7. E. C. Poggio, H. R. Quinn and S. Weinberg, Phys. Rev. D13, 1958 (1976); R. Shankar, Phys. Rev. D15, 755 (1978); R. G. Moorhouse, M. R. Pennington and G. G. Ross, Nucl. Phys. B124, 285 (1977); and Ref. 5.
8. Private communication with G. Feldman.
9. Similar arguments would also apply to fractionally-charged heavy leptons ("freptons"). In that case we could imagine a 2/3-charged lepton which decays quickly into a 2 GeV, -1/3-charged lepton. See Ref. 5.
10. T. Hagiwara and A. I. Sanda, Rockefeller Report No. COO-2232B-165 (1978); K. G. Chetyrkin, N. V. Krasnikov and A. N. Tavkhelidze, Phys. Lett. 76B, 83 (1978).