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SUMMARY TALK*

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It is a special pleasure to return once more to this beautiful city of Bonn and to join together for this brief week with colleagues from the world over, temporarily insulating ourselves from the funding problems, the political strains and the nuclear dangers of the transitory world of man, and refreshing ourselves in the mutual search for an understanding of that one and only enduring Nature that governs us all.

I. Introduction

Eight years ago I started my summary talk[1] to the 1973 edition of this series of biannual symposia with the map shown in figure 1. Who could then

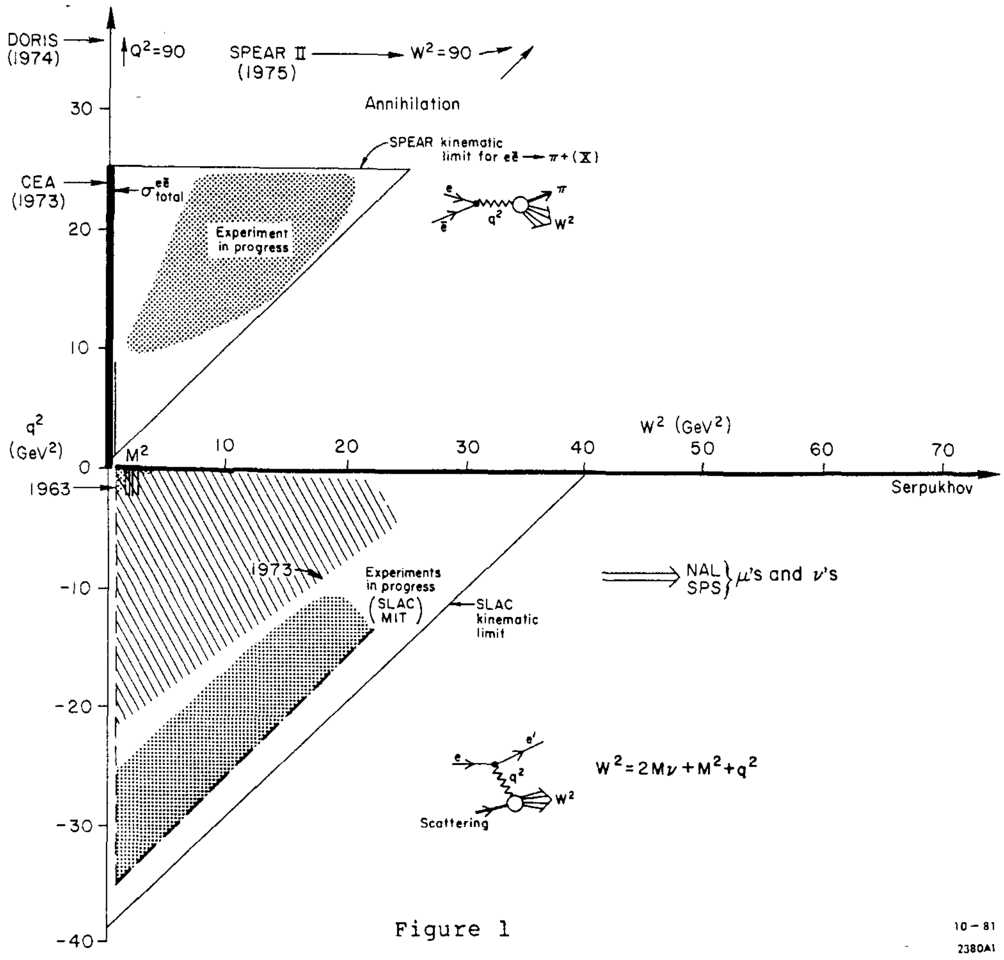

Figure 1

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* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

(Invited talk presented at the 1981 International Symposium on Lepton and Photon Interactions at High Energies, Bonn, Germany, August 24-29, 1981.)

anticipate that in the year ahead, as the frontiers moved forward, we would start discovering new worlds--of charm, of third generation structures--the heavy τ lepton; and that in only a few years our progress toward achieving the dream of unification would be made with further confirmation of the Glashow-Salam-Weinberg ideas; that a theoretical edifice for a strong interaction dynamics QCD would be constructed of gauge principles and would be extensively probed including in particular the properties and dynamics of gluons; and that the phase map would change its scale so extensively as shown in figs. 2 and 3, and in fig. 4 on a logarithmic scale which is the one believed to be significant (except for new thresholds).

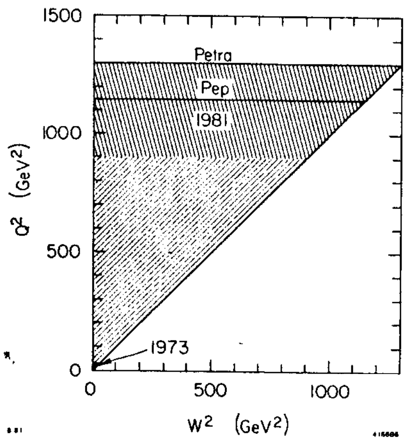

Figure 2

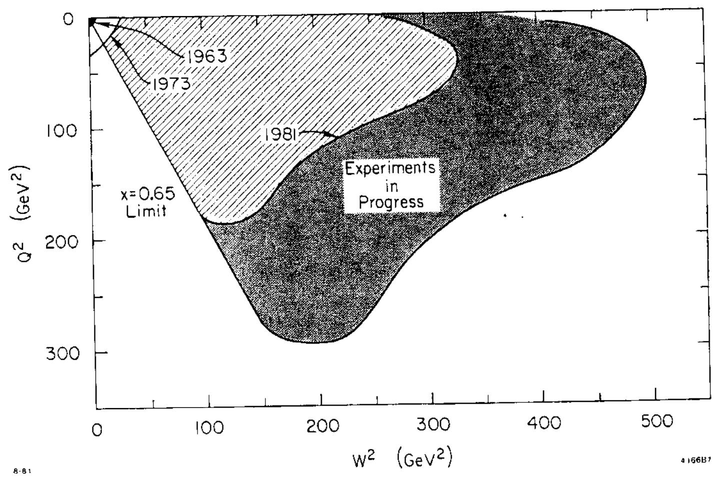

Figure 3

The phase space has also become multidimensional as we study details of jets and of scaling behavior. We now ask: what new scales are there ahead--the top quark, new generations beyond the third, the grand unification scales, the W and Z^0 masses, spontaneous and/or dynamical symmetry breaking scales (i.e., elementary Higgs and pseudo-Goldstones); preons?

No spectacular new discoveries were reported at this meeting. Our zoo is empty, but very impressive progress has occurred during the past year and has been reported here: evidence in accord with general QCD behavior has accumulated. QCD is becoming a quantitative science, but we still have a long way to go before we know accurate values of α_s and how it "runs". Upsilonium and charmonium spectra and transition rates, and B and D meson decays have been reported. A new charmonium state has been observed which may in fact be the η_c', the first excited singlet state. Further evidence on gluons and their vector nature was presented and the possible existence of gluonium, or glueball states and maybe also of crypto-exotics has been described. The τ lifetime has been measured, the limits of QED have been extended and possible candidates for axions have been reported. I have an impressive menu to summarize. Where to begin is a problem. When I summarized the conference here just eight years ago, it marked the end of an evolutionary period. A year later came the great November Revolution of the J/ψ, charm, and the τ lepton. So I predict another revolution, or phase change, by Christmas

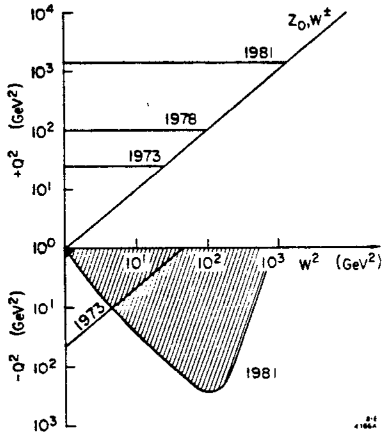

Figure 4

1982. Perhaps that is why I was once again asked to summarize this Conference; I proved to be so successful a harbinger in 1973! And by a second revolution I don't just mean already predicted Z's and W's, but evidence anew that Nature's imagination is richer than ours as we cross new frontiers of the unknown.[2]

The central topic of this Conference is the status of QCD. How decisive is the current experimental basis of QCD? I refer here to tests of behavior beyond the simple, or naive, parton model, for which it provides a justification in zeroth order, and thus we must come to grips with dynamics. This is very difficult since we are dealing with a theory that must explain color confinement and therefore, in general perturbative calculations in terms of quarks and gluons are inadequate. The most fundamental test of QCD would be its ability to explain confinement and to predict the hadron mass spectrum. Confinement has been strongly suggested by the lattice gauge calculations[3] of K. Wilson, M. Creutz and others for a world with no flavor, but the observed hadronic mass spectrum has proved to be beyond the calculational power of theoreticians so far. Our present choice then is to identify those observable process~~es~~ amenable to a perturbative calculation or to identify those relations between physical processes insensitive to strong dynamics and to test them decisively using the operator product expansion method to separate out the short distance, or "hard", behavior that is known on the basis of the asymptotic freedom character of QCD from the nonperturbative or "soft" interaction parts.

II. Electron-Positron Annihilation: Total Cross Section

The total e^+e^- annihilation cross section to hadrons, $\sigma(e\bar{e} \to \text{hadrons})$, is the goldplated process for QCD because as fig. 5 illustrates this process at high energies probes only the commutator of the electromagnetic currents at the tip of the light cone. Hence distances comparable to the dimensions of hadrons, where the physical behavior is sensitive to the nonperturbative phenomenon of confinement, do not enter. Only the short distance behavior of the theory affects the results--and as a result of the asymptotic freedom, or weak coupling, behavior at short distances, we can apply perturbative QCD (PQCD).[4] This is a process with no mass singularities and can be calculated by a presumably safe expansion in powers of the strong coupling constant $\alpha_s(E^2)$ which decreases logarithmically for large energy E and is $\lesssim 1/3$ for $E > 5$ GeV. It is not a series in $\alpha_s(E^2)[\ell n\ E/m]^n$ which could, and usually does, exponentiate into large corrections[5,6] (i.e., phase changes, anomalous dimensions, etc.).

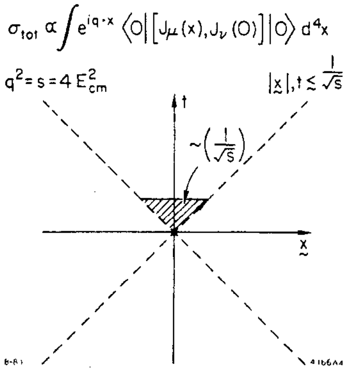

Figure 5

In the parton model the ratio R of $\sigma(e\bar{e} \to \text{hadrons})$ to the pointlike process $\sigma(e\bar{e} \to \mu\bar{\mu})$ simply measures the sum over flavors and colors of the squares of the quark charges. Corrections to this have been calculated through order α_s^2 in QCD:

$$R = \sum_i Q_i^2 \left[1 + \frac{\alpha_s}{\pi} + C_2\left(\frac{\alpha_s}{\pi}\right)^2\right] + 0\left[\left(\frac{\alpha_s}{\pi}\right)^3\right] \tag{1}$$

At 30 GeV collision energy the first term gives an increase of roughly 5% above the sum of squares of charges. The coefficient C_2 is known from several independent and mutually consistent calculations; its numerical value depends on the specified renormalization procedure,[5] but in any event is less than 1%. I have four comments to make:

1. In terms of testing QCD, and in terms of looking for evidence of possible new particles, it is impossible to overemphasize the importance of measuring R to an accuracy of about 2%. QCD has no easy or even credible "nonperturbative" escapes from a discrepancy for this one process which is entirely governed by the short distance structure of the theory. The precise value of the QCD coupling constant depends on the scale parameter Λ. To second order,

$$\begin{aligned}
\alpha_s(s) &= \alpha_s^0(s)\left[1 - \frac{\beta_1}{4\pi\beta_0}\,\alpha_s^0(s)\,\ln\ln\frac{s}{\Lambda^2}\right] \quad (S \equiv E^2)\\
\alpha_s^0(s) &= \frac{4\pi}{\beta_0\,\ln\left(\frac{s}{\Lambda^2}\right)}\\
\beta_0 &= 11 - \frac{2}{3}\,n_f\\
\beta_1 &= 102 - \frac{38}{3}\,n_f\\
n_f &= \text{number of flavors}
\end{aligned} \tag{2}$$

In the subtraction scheme of Bardeen[7] et al., the higher order perturbative strong radiative corrections are found to be small for both e^+e^- annihilation and deep inelastic scattering. If the latter process is used to fix the value of Λ very loosely between $\Lambda \sim$ (100-500) MeV, R, in (1), is determined by first order QCD to better than ± 1% at $S = 1000\ \text{GeV}^2$; i.e., R = 3.84 and 3.90 for Λ = 100 MeV and Λ = 500 MeV, respectively.

As difficult as it may be to determine R to ≈ 2% accuracy, point-to-point, at perhaps 200 MeV intervals over a very broad energy range, that information would be very valuable. Depending on Λ, the size of the α_s/π correction in (1) will differ in absolute value by 1-2% and will "run" in value by ~2% in the energy range 12-60 GeV.

2. The theoretical analysis of R, including QED radiative corrections and the smoothing out of finite mass thresholds, has been performed by Barnett and collaborators[8] so that the theory is in shape to meet such an experimental test.

3. One needs to know R to better than 5% if there is to be hope in detecting integrally charged scalars (elementary Higgs or pseudo-Goldstone bosons in a hypercolor theory) which would contribute (asymptotically)

$$\Delta R = 1/4\ Q_H^2 \quad \text{or roughly} \quad \frac{1/4}{11/3} \cong 7\%$$

above the upsilon threshold. Do any such objects exist? Some theories conjecture[9] that they may at masses of less than 10 GeV. A color singlet "quark" of charge 1/3 would contribute ~ 3%; or an additional color triplet of charge 1/3 would add 9% to R.

4. In making and interpreting fits to R we are assuming that the electromagnetic part of the process, i.e., the e^+e^- annihilation via the electromagnetic currents, is well understood. This assumption can be made with confidence in the energy regime available for experimental study at PETRA and PEP because the measured electromagnetic cross sections are in complete agreement with the calculated cross section for

$$e^-e^+ \rightarrow \begin{array}{l} \mu^-\mu^+ \\ e^+e^- \\ \gamma\gamma \end{array}$$

Measurements[10] have extended the limits on QED modifications to the point that $\Lambda_{QED} \gtrsim 150$ GeV or, in terms of lepton size[11] $r_e \lesssim 10^{-16}$ cm. QED remains at least for the present our standard confident probe. Indeed we are now at the point that study of the angular distributions in Bhabha scattering, of the value of R, and of the front-back charge asymmetry in $e^-e^+ \rightarrow \mu^+\mu^-$ production provides interesting limits on the weak-electromagnetic interference parameters in the standard model. For example, if all four PETRA experiments on $e^-e^+ \rightarrow \mu^+\mu^-$ are combined statistically, as shown in Table I from Branson's talk,[12] one finds a 3-standard deviation result for the front-back asymmetry with a value centered on the parameters of the "standard model" of weak-electromagnetic interference. Much more decisive data are still needed on this.

Table I Front-Back Asymmetry in $e\bar{e} \to \mu\bar{\mu}$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\,[F_1(1+\cos^2\theta) + F_2 \cos\theta] + \text{QED radiative corrections}$$

$$F_1 = 1 + 8\,s\,g\,g_V^2\,\frac{M_z^2}{S-M_z^2} + -----$$

$$F_2 = 16\,s\,g\,g_A^2\,\frac{M_z^2}{S-M_z^2} + -----$$

$$g = 4.49 \times 10^{-5}\ \text{GeV}^{-2}$$

$$A_{\mu\mu} = 7 \times 10^{-4}\,s\,g_A^2\,\frac{M_z^2}{S-M_z^2}\,\frac{\cos\theta}{1+\cos^2\theta}$$

	PEP	PETRA				
$A_{\mu\mu}$(%)	Mark II	Jade	Mark J	Pluto	Tasso	Average
Observed	-4 ± 3.5	-11 ± 4	-3 ± 4	+7 ± 10	-11.3 ± 5	-7.7 ± 2.4
Expected (Standard Model)	-4	-7.8	-7.1	-5.8	-8.7	-7.8

Parameters of the "Standard Model" deduced from PETRA average
(95% confidence level)

$$.31 < |g_A| < .63$$

$$\sin^2\theta_w \cong .25 \pm .1$$

To conclude this section I repeat, a measurement of R to an accuracy of a few percent would be of inestimable importance. Theoretically R has the following important features:

- it is sensitive only to the short distance structure of the theory
- one can calculate the corrections in powers of $\alpha_s(s)$
- experimentally the highest values of s are available for this process and therefore the corrections in 1/s are small; already we have achieved s > 1000 GeV^2
- the absolute normalization of R is known, not just its functional variation over a limited kinematical range; note that at present energies 5/11, or more than 40%, of the contribution to R comes from the "new matter," i.e., c and b quarks
- values of α_s and of Λ can be determined free of any model dependence.[5]

Although we continually refer to QCD as a reference standard for analyzing the strong processes because of its royal pedigree as a local gauge theory, remain alert to the fact that its experimental roots are still far from quantitative. It is also true that a disagreement between R_{th} and R_{expt} would not necessarily be grounds to discard QCD, but might be evidence that we don't understand fully either the weak currents or the particle content of the theory in the relevant energy regime--due to Higgs bosons, pseudo-Goldstone bosons in a hypercolor theory, or precursors of higher generations. In fact there is already some impatience at finding the sixth or "top" quark, although a very broad range of mass predictions for it can be made, almost without theoretical input, as illustrated in Table II.

Table II
Guesses for the Mass of the "Top" Quark

1)	$\frac{m_t}{m_c} = \frac{m_\tau}{m_\mu}$	23 GeV
2)	$\frac{m_t}{m_b} = \frac{(2/3)^2}{(-1/3)^2}$	19 GeV
3)	$\frac{m_t}{m_b} = \frac{m_c}{m_s} = \frac{1.35\text{ GeV}}{150\text{ MeV}}$	43 GeV
4)	$\ln m \sim$ smooth function of (N,Q)	27 GeV

These numbers are calculated using the "on shell"current quark masses and are not renormalized by radiative corrections which may be significant. Estimate (2) is due to R. M. Barnett; estimate (4) is due to J. D. Bjorken.

III. Deep Inelastic Scattering

The operator product expansion techniques as well as improved perturbation theory have permitted detailed analyses for many physically interesting and practically useful quantities beyond processes dominated by the light cone.[5,6] Any time a hadron mass scale enters a problem there is a nonperturbative element because the confinement scale also enters, as in the study of deep inelastic scattering illustrated in fig. 6. In the study of this process it is necessary to separate, i.e., to factorize, the analysis into its hard parts and its soft parts.[13] The hard part of the process is that part dominated by the light cone and calculable perturbatively as a consequence of asymptotic freedom. The soft part is affected by the hadronization processes--and is not perturbatively calculable. However we can make progress if the dependence on the hard kinematical quantity, i.e., Q^2 for inelastic scattering or p_T^2 for jet structure, can be isolated and treated perturbatively in QCD, while the soft part remains a multiplier, or better yet is related between different physical processes. In deep inelastic scattering the moments of the structure functions--i.e., weighted integrals over x from 0 to 1 are strictly given by the operator product expansion. The difficulty is, as illustrated in figure 3, that data are not available over the entire range of x. The structure functions themselves, $F(Q^2,x)$, are sensitive to QCD behavior away from the light cone by distances comparable to the confinement length, $\sim 1/M_{\text{hadron}}$, as illustrated in figure 6. However we can use theoretically known properties of $F(Q^2,x)$ to analytically continue it starting from a very precise parametrization at any one value of Q^2. In practice, this continuation requires that we have precise data over a range of values. Similar continuations can be made in the analyses of jets although as yet no proof of the analytic structure has been given.

Intuitively, we expect scale breaking of $F(Q^2,x)$ in QCD because of gluon radiation. This was first described intuitively by Kogut and Süsskind and given a formal basis in the evolution equations of Altarelli and Parisi.[5] As illustrated in figure 7 the structure function is expected to grow at lower x values and to shrink for larger x > 1/2 as Q^2 increases.

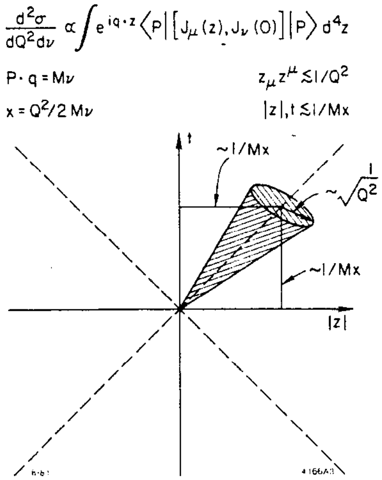

Figure 6

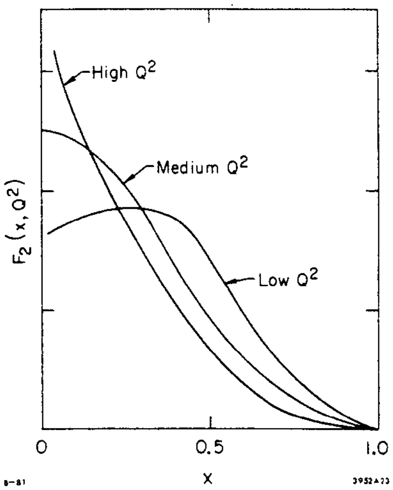

Figure 7

This can be understood in terms of the increasing resolving power of the probing current with increasing Q^2. What appears as a quark on a larger scale is probed as a system of the quark with a cloud of gluons and $q\bar{q}$ pairs into which it cascades on smaller spatial scales. Hence the fractional momentum carried by an individual quark being probed will appear smaller at high Q^2. Consequently, the structure function will shrink toward smaller values as Q^2 grows. The rise (fall) of structure functions for small (large) x is logarithmic with Q^2 due to the logarithmic dependence of α_s itself. Thus, although the basic shape of the structure functions is not predicted, or calculable, from QCD, its Q^2 variation is. This in principle can be used to determine Λ and to relate different processes. It also can be used to determine the spin of the gluon--because the amplitude and angular structure for a quark to split up into a gluon and a quark of lower momentum, and for a gluon to create quark or gluon pairs, is sensitive to gluon spin. This in turn affects the shape of the scale breaking as a function of Q^2 as well as the relation with other processes.

If this program fails to give consistent results for Λ and the structure functions when different processes are compared, the blame can of course always be attributed to imprecise data for analytic continuation, i.e., to the fact that the range of Q^2 values experimentally available is too limited. Also higher twist effects can lead to larger corrections as x approaches 1, as both Buras[5] and Mueller[6] described in their lectures. These higher twist terms arise from graphs in which the struck quark subsequently interacts with other quarks and gluons (partons). They involve bound-state contributions and diquark correlation corrections and cannot be calculated perturbatively, but require introducing specific models or bound-state wave functions.

In the study of deep inelastic scattering, or lepto-production, the operator product expansion of QCD provides a framework for systematically studying higher twist effects. However the hadronic matrix elements that enter can be computed only on the basis of specific models of the hadron wave functions. These have been studied now[5] extensively in a Fock space wave function formalism by Brodsky, Lepage, and collaborators. A systematic analysis of the twist-4 contributions has recently been constructed by Jaffe and Soldate in the operator product expansion language, with matrix elements being evaluated on the basis of the MIT Bag model.

With all these caveats in mind I summarize the status of inelastic lepton scattering (muon, neutrino, and electron) as presented to this conference[14] in Table III.

TABLE III Deep Inelastic Scattering Summary

- Observed scale breaking is consistent with a scale parameter

$$\Lambda_{\overline{MS}} \sim 100\text{-}200 \text{ MeV}$$

- The muon and neutrino data agree within errors but there remains a 10% normalization difference with the lower energy SLAC/MIT data for electron scattering. This may be related to higher twist effects.
- The gluon distribution is, as expected, softer than the quark distribution and varies as $\sim (1 - x)^{5-6}$.
- Higher twist terms are more important at large x, being enhanced by $[1/(1-x)]^p \, (M^2/Q^2)$.
- The ratio, "R", of the longitudinal to transverse cross sections is small and positive but its variation with x or Q^2 is only poorly known. "R" is proportional to α_s in QCD.
- There is no evidence for intrinsic charm at the 1% level (for $x > 0.5$)
- Observed patterns of jet broadening and energy flow in the final states give rough measurements of α_s, or $\Lambda_{\overline{MS}}$.
- The ratio of the "down" to "up" parton distributions decreases for $x \gtrsim 0.5$ and shows a slow, if any, Q^2 variation as expected in QCD.

IV. Final States in e^+e^- Annihilation

The study of specific final states in e^+e^- annihilation, including both single particles and jets, is a burgeoning industry. Many masurements have been reported at this Conference[10] up to the maximum energy of $\approx$ 36.6 GeV. The physics output has been extensive and interesting, if not sensational. I review here five results that I found of particular interest:

1. Multiplicity of charged particles
2. The energy fraction in neutrals
3. The question of scaling in the inclusive spectra
4. Baryon production in final states
5. Jet characteristics as signals of QCD.

1. The mean multiplicity of charged secondaries has increased to a value of $\langle n \rangle_{\text{charged}} \approx 13 \pm 1$ at maximum PETRA energies. The energy dependence of $\langle n \rangle_{\text{charged}}$ is consistent with a logarithmic growth all the way from 2 to 36 GeV. However, as remarked by Felst,[10] it is also consistent with a power growth $\propto s^{1/4}$ as predicted by Fermi in 1951 on the basis of a statistical model for hadron collisions.

2. The energy fraction carried off by gamma rays and also the energy fraction carried away by all neutral particles, including K^0's and Λ's, have been measured at PETRA. They are roughly constant from 10 up to 35 GeV and equal, approximately, 25% and 35%, respectively. This means that the fraction carried off by neutrinos is $\lesssim$10%, consistent with predictions of fractionally charged quark models.

3. The inclusive spectrum for charged particles, $s(d\sigma/dx)$, with $x \equiv p/p_{\text{beam}}$, has been measured up to 36.6 GeV at PETRA. For $0.2 < x < 0.8$ it is observed to scale, within 30% experimental uncertainties, in accord with the parton model, as reported by Felst[10] in his talk. PEP results differ from this in that the same Mark II detector has compared its high energy spectra up to 29 GeV at PEP with SPEAR running at 5 GeV, and has also checked its 5 GeV data with Mark I. As reported by Hollebeek,[10] it finds a substantial deviation from scaling. I have no theoretical prediction with which to compare the magnitude of the scaling violation, but its trend with x is as intuitively to be expected. At high energy the spectra at small $x \lesssim 0.1$ increase due to gluon emission, which softens the x dependence in he same way as found in the scaling corrections to the structure functions in inelastic scattering. There are also data on the inclusive spectra for individual species. New results were reported for the neutral kaon spectrum $(K_s + K_L)$ which was measured to comprise 20% of all charged secondaries, independent of x. The p_T distribution of the K's is also similar with that of nonstrange secondaries.

4. Baryon pairs are produced copiously. In particular, like sign pairs (pp and $\bar{p}\bar{p}$) were observed at PEP in 41 out of 110 baryon pair events, indicating that four or more baryons were produced 37% of the time. The baryons are observed only in a narrow momentum interval, 1/2 to 2 GeV, and do not constitute leading hadrons in their respective jets. However, it is evident that diquark production must be a very important mechanism in forming the final jets as illustrated in fig. 8.

5. Turning to jets, there is now a vast wealth of evidence obtained by very different analyses which support the general features predicted by QCD, in particular the J = 1 gluon contribution and running coupling constant. The PETRA groups in their presentation, as reported by Braunschweig,[10] used Monte Carlo event generators and QCD production mechanisms for quark pairs and gluons to compare with the data. Several models of the hadronization process were used (in particular, the Lund and Field/Feynman models) in order to reconstruct the event topologies. Detailed studies of the event structures in terms of p_T distributions, thrust, sphericity or triplicity axes were made and, overall, a very good fit to first order QCD was achieved for a great variety of data. "2-jet"

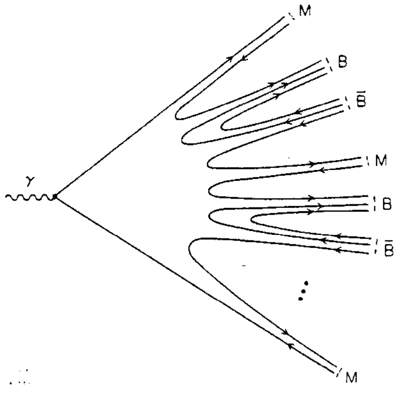

Figure 8

models all failed--including those defining hadronization with long p_T tails. They could fit oblateness but not the energy flow in the jets. The observed broadening and angular distribution among 3-jet events supports a $j = 1$ gluon interpretation.

No clear differences were established between gluon and quark jets, either at PETRA or by Mark II comparing PEP and SPEAR data, but much greater precision is needed to tie this point down quantitatively. The second order QCD corrections to the thrust distribution of jets were reported to be large and highly model dependent by Braunschweig.[10] This result suggests how difficult it will be to attempt to determine α_s from analyses of jets.

An alternative approach to the analysis of e^+e^- jets is to measure the energy flow into calorimeters. One can study the energy moments in a given jet or the energy-energy correlation between two jets. Such studies provide less detail about the final states. Their interpretation relies on approximate theoretical analyses to leading log approximation. On the other hand, the advantage of such an approach is that one can directly describe the observations without recourse to a Monte Carlo model of the soft hadronization process. This makes it easier for me, in this summary, to describe what is being learned. I shall also rely on the energy moment analysis for persuasive evidence that α_s actually runs.

Consider first the energy flow into a set of calorimeters which cover a jet in $e\bar{e}$ annihilation. As one varies the cone angle δ, i.e., the half opening angle of the individual calorimeters, the moment functions

$$C_n(\delta) \equiv \frac{\sum_{i=1}^{N} E_i^n}{(E_{jet})^n} \qquad (3)$$

also vary. In eq. (3) N denotes the number of calorimeters covering the jet and n the moment. Theoretical predictions of the δ dependence have been calculated[15] for different moments using collinear kinematics and the leading log approximation.

The calculation follows steps in the cascade

$$\begin{aligned} q &\rightarrow q(x) + g(1-x) \\ g &\rightarrow q(x) + \bar{q}(1-x) \\ &\rightarrow g(x) + g(1-x) \end{aligned}$$

with successive decays strongly ordered in mass and perturbatively calculated for high mass states. When finally the "parton" reaches a hadronic mass the perturbative treatment fails but the calculation also stops since all products from that point on enter the same calorimeter as long as angle δ is large enough.

As δ increases to the point that one calorimeter, $N = 1$, covers the jet the moments $C_n(\delta) \rightarrow 1$ since all the energy is deposited in one calorimeter. For smaller δ, $C_n(\delta)$ will decrease. In particular, due to geometry alone, the second moment $C_2(\delta)$, for example, would vary with the number of calorimeters as

$$C_2(\delta) \propto N \cdot \frac{1}{N^2} \propto \frac{1}{N} \propto \delta^2$$

where the last relation follows from the fact that $N\delta^2$ = constant in covering a jet with a fixed total solid angle. A deviation from this quadratic dependence of $C_2(\delta)$ would reflect additional physical dependence of the cascade process on δ. The point is that larger values of δ correspond to larger values of p_T and hence to smaller values of a running coupling constant α_s as a function of p_T or δ. As shown in Hollebeek's[10] talk, such a dependence was, in fact, found by Mark II at PEP indicating that indeed the coupling constant does run. It has the right qualitative behavior and $\alpha_s \sim .15-.16$ at 30 GeV although I am not at all sure at this time how accurate a scale parameter Λ can be deduced from such an analysis.

A study of the asymmetry in the energy correlation function between two jets is also sensitive to perturbative QCD behavior and allows a value of α_s to be inferred independent of details of the fragmentation process. In this approach one measures where the energy goes[16]--i.e.,

$$\frac{1}{\sigma_0}\frac{d\Sigma}{d(\cos\chi)}\Delta\chi \equiv \frac{2}{\sin\chi}\frac{1}{N}\sum_N \frac{(\sum_i E_i)(\sum_j E_j)}{S}$$

where the $\sum_i E_i$ and $\sum_j E_j$ are the sums over particle energies incident at angles (θ_i,ϕ_i) and (θ_j,ϕ_j), respectively, with χ the angle between the directions of the two energy depositions; the sums extend over all measurements N. By considering two well separated jets--i.e., for $45^\circ \lesssim \chi \lesssim 135^\circ$ it is hoped that sensible and qualitatively reliable results can be obtained on the basis of perturbative QCD calculations for the emission of the initial hard quark pair plus gluon. There are no infrared problems in this region. The nonperturbative contributions to the hadronization process should be symmetric around $\chi = \pi/2$, with gluon radiation required to produce any asymmetry. Therefore, the asymmetry

$$A(x) \equiv \frac{1}{\sigma_0}\left[\frac{d\Sigma(\pi-\chi)}{d\cos\chi} - \frac{d\Sigma(\chi)}{d\cos\chi}\right]$$

is proportional to α_s in lowest order, corresponding to creation of a gluon jet, and independent of the soft hadronization. The observed asymmetry as reported by Hollebeek is consistent with the perturbative QCD result for $\alpha_s \sim 0.15$ but higher order corrections are not all under control and therefore I can give no estimate on the numerical accuracy of this result.

To summarize this section, all observed properties in the annihilation of e^+e^- to hadrons can be explained naturally by QCD with spin 1 gluons. No other mechanism is known that can explain all the data. However, when we try to make quantitative conclusions, it is not possible to escape the fact that every process other than the total $e\bar{e}$ annihilation cross section, or R, involves some nonperturbative ingredients. In order to illustrate the element of faith involved in invoking a model, or in extrapolating, as to how the quarks and gluons at short distances "hadronize" into observed states at large distances let us consider a toy world containing only massive quarks, M, much heavier than the confinement scale, Λ, which is the intrinsic scale of pure QCD and characterizes the mass of glueballs in QCD. This toy world is very different from our world with light quarks, $m < \Lambda$, in which perturbative QCD leads to each finite order of calculation and to leading order in $m^2/Q^2 << 1$ at high energies, to final states formed by soft hadronization processes as illustrated in fig. 8. However, in a toy world with only heavy quarks, $M >> \Lambda$, these soft processes are excluded and the formation of a final state of glueballs of mass Λ, plus a heavy "onium" state, is suppressed order by order in perturbation theory by $\propto M^2/Q^2 << 1$ at high energy. Indeed, production of hadrons at high energies in such a toy world would proceed primarily through the nonperturbative mechanism of string formation as illustrated in fig. 9. Such a nonperturbative contribution will always be present in a world with both light and heavy quarks, as recently emphasized by Gupta and Quinn,[13] building on earlier ideas of Bjorken. Its contribution cannot be controlled in a $1/Q^2 \to 0$ limit. Furthermore, the actual numerical size of such a contribution to a leading order process can be estimated only if nonperturbative effects can be theoretically bounded. This observation in no way diminishes the need for making detailed experimental studies of physical processes that require us to go beyond operator product expansions at short distances in order to compare data and theory. What we learn from them will shed important new information on QCD behavior beyond our present limited tests, but numerical and quantitative conclusions will in general be sensitive to nonperturbative effects and to corrections still to be analyzed beyond the leading log approximations.

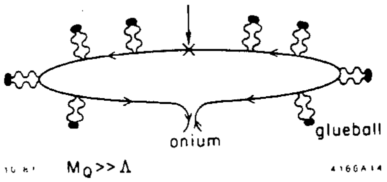

Figure 9

In all discussions of QCD there is great interest in the running behavior of α_s and its dependence on the scale parameter Λ. The fact that α_s runs is not a fundamental new feature of QCD. It is the sign of the running to asymptotic freedom that differs from quantum electrodynamics (QED). In testing QED one seldom introduces explicitly the notion of a running fine structure constant because α has always been normalized on the electron mass shell for scattering in a uniform external field with $q_\mu \to 0$. Higher order radiative corrections have then been computed in terms of α, to the desired or needed order of precision, although at present the measured hydrogen and muonium hyperfine structure and the electron and muon g - 2 values are demanding yet one more order in precision[17] from theorists. However, as long ago as 1950 the running coupling constant was described in the pioneering work on the renormalization group by Gell-Mann and Low and by Petermann. An example of this is the difference in muon and electron g - 2 values, which in fourth order is $\sim 2.2(\alpha/\pi)^2$. This difference is simply an expression of the difference between the fine structure constant when renormalized by the vacuum polarization insertion for $(q^2)^{1/2} \approx$ the muon mass scale[18] relative to its value for $(q^2)^{1/2} \approx 0$, i.e., on the electron mass scale.

V. The New Spectroscopy

The new spectroscopy of particle physics has studied seven exotic new systems, largely unheard of when we last met in Bonn, and all discovered since then: B, D, and F mesons, charmonium, upsilonium, gluonium, and crypto-exotics (or 4-quark states). Many exciting and important new results about these systems have been reported to this Conference. They remind us of the importance of special purpose detectors and of precision studies at facilities that are not at the highest energy frontiers.

The discovery[19] at SPEAR of the η_c' which is believed to be the first radially excited singlet state of charmonium, adds an eighth state to our knowledge of the rich spectrum of bound states of the charmed quark and antiquark $(c\bar{c})$. In analyzing the bound states of massive quarks it is reasonable to rely on a static potential model for qualitative results when the quarks move slowly and the characteristic periods are long enough so that the gluon fields can be averaged into a static potential, including spin-orbit and spin-spin terms, relative to the instantaneous quark positions.

For charmonium, with $\langle v^2/c^2\rangle_{J/\psi} \approx 0.25$ and $\alpha_s(M_{J/\psi}) \sim 0.3$, the potential model shouldn't be too bad, and the QCD radiative corrections shouldn't be too large. For states formed of more massive quarks such as upsilonium, the $(b\bar{b})$ system, the predictions of a potential model should be more quantitative since $\langle v^2/c^2\rangle_{T} \approx 0.1$ and $\alpha_s(M_T) \sim 0.23$. For toponium, if it is ever discovered, at mass $\gtrsim 40$ GeV, the system will even be more coulombic and static in character and truly quantitative studies may be possible.[20] In this connection, and to emphasize how rapid has been our progress in so short a time, I show in fig. 10 the positronium spectrum. Only three transitions have been measured, but with what precision they are known, both theoretically and experimentally![17]

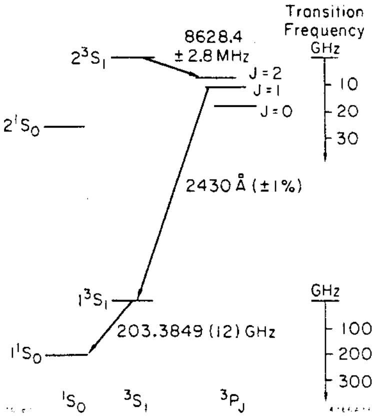

Figure 10

The η_c' fits naturally into the spectrum of charmonium as the n = 2 $^1S_0$ state although the assignment is not yet definite in the absence of data on its exclusive decay channels. Its mass splitting[19,21] below the ψ' is

$$M_{\psi'} - M_{\eta_c'} = 92 \pm 5 \text{ MeV}$$

which is ~ 15% larger than theoretical calculations, including radiative corrections, of 80 ± 10 MeV. In particular, there is a simple expression for hyperfine splitting ratios in terms of the leptonic decay widths, via the squares of the wave functions at the origin:

$$\frac{\Delta M(\psi'-\eta_c')}{\Delta M(J/\psi-\eta_c)} = \frac{|\Psi_{2s}(0)|^2}{|\Psi_{1s}(0)|^2} = \frac{M^2_{\psi'}\,\Gamma_{e\bar{e}}(\psi')}{M^2_{J/\psi}\Gamma_{e\bar{e}}(J/\psi)} \qquad (4)$$

The ratio observed for the mass splittings on the left hand side of (4) is 0.80 and for the decay widths on the right hand side is 0.62; it would be 0.44 if the decays were calculated in terms of quark masses common to both the J/ψ and ψ' states instead of in terms of the ψ' to J/ψ mass ratios. This indicates the importance of including binding corrections, which are ~ 40% in this case. The values of the leptonic decay widths themselves are decreased by a factor $\{1 - (16/3)[\alpha_s(m_{J/\psi})/\pi]\} \sim 1/2$ by first order QCD radiative corrections. A number of different parametrizations in terms of theoretical potentials all agree with one another in giving satisfactory qualitative fits.[21]

From the above discussion one concludes that accurate quantitative fits to charmonium spectra are not possible. The study of the electric dipole transition rates from the ψ' to the n = 2 $^3P_{2,1,0}$ triplet gives ratios of decay rates in close accord with theory--i.e., $[1/(2J+1)K^3]\ \Gamma(\psi' \to \chi_J+\gamma)$ should be independent of J, but absolute rates are roughly a factor of two too low, again presumably due to large radiative corrections.

The radiative decays of the J/ψ itself are of interest for the study of even charge conjugation states, including gluonium or glueballs if they exist. To leading order in $\alpha_s(m_{J/\psi}) \sim 0.3$, the J/ψ decays to hadrons via a three-gluon state, one gluon being forbidden by color and two gluons by charge conjugation. The radiative decay via one gamma and two gluons is expected to occur $(36/5)(\alpha/\alpha_s)(2/3)^2 \sim 10\%$ of the time and is thus a copious source of C = + states. In this way the Crystal Ball Collaboration at SPEAR[19] reported the discovery of a 0^{-+} state at 1440 MeV decaying to a $\delta^0\pi^0$ and called the i(1440). Evidence against its interpretation as the E(1420), the 1^{++} partner of the A_1 and D(1285), seems compelling, but whether the i(1440) is a gluonium (or a glueball), or a radial excitation, or a $q\bar{q}q\bar{q}$ cryptoexotic remains to be settled. Another very interesting new state whose quantum numbers and quark configuration remain to be confirmed in the $\theta(1640)$. It is suggested that its width of 220^{+100}_{-70} MeV is too narrow for a 2^{++} MIT bag state of $q\bar{q}q\bar{q}$ and that it is more likely a glueball. The QCD sum rule analysis of Voloshin and collaborators at ITEP in Moscow, as reported in Shifman's talk,[20] favors a 2^{++} glueball configuration.

The spectroscopy of upsilonium has yet to emerge from a sample as large as 10^6 or so decays as done for charmonium and so is not yet at the same level of precision and detail as achieved for the charmonium atom. However, this system is more amenable to quantitative analysis, being even less relativistic, and already has taught us very valuable new information.[21,22] First of all, the success of the simple potential model is entirely consistent with a flavor independent interaction, in accord with QCD. Also the absence of evidence of a string state between the n = 3 and n = 4 excited $^3S_1$ levels of T" and T"' supports a very simple static potential picture of the bound state. The upsilonium radii are sufficiently small so that a multipole analysis of the hadronic decays via gluon emission can be made. In particular, the retardation factor is

$$kR \sim (300 \text{ MeV})\ (0.2 \text{ fermi}) \sim 0.3 < 1 \ .$$

Thus in analyzing soft pion radiation in the hadronic transitions

$$\begin{aligned} T'' &\to T' + \pi\pi \\ &\to T + \pi\pi \\ T' &\to T + \pi\pi \end{aligned}$$

one can approximately factorize the process as illustrated in fig. 11 and make a multipole expansion of the gluon radiation. Following the procedure developed by Gottfried, Yan, and collaborators at Cornell[23] the heavy quarks are treated nonrelativistically and their gluon matrix elements are given in electric dipole approximation by

$$ME \propto \vec{r} \cdot \vec{E} \qquad (5)$$

where $\vec{E}$ is the color electric field. The subsequent soft pion emission is then given by PCAC. Predictions from this multipole analysis are sensitive to the radius of the excited and ground states and in good agreement with the observations. Were the gluon radiation not characterized in a local gauge invariant theory by the radiated field strengths but expressed only in terms of potential amplitudes (as for J = 0 gluons, for example) the radii would be absent from (5) and transition ratios off by an order of magnitude.

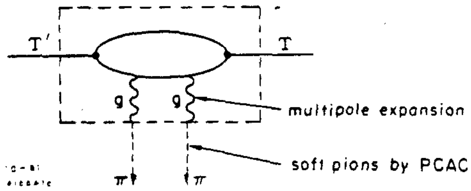

Figure 11

The upsilonium system is also a very good factory of gluonium states. For energies off the peak the final state looks predominantly like the formation of two jets. On the T peak an analysis of the thrust indicates three jets are formed, corresponding to three gluon decay of a C = -1 state. The angular distribution of the 3-jet axes indicates a gluon spin of J = 1. However, at the T mass we are still dealing with relatively soft gluons so that predictions of perturbative QCD are not accurate. In fact, perturbative QCD predicts a 3-gluon distribution that is symmetrical and relatively flat in gluon momenta; whereas, what is observed is two fast and one soft gluon. As reported to the Conference,[22] the angular distribution of the fastest gluon relative to the beam axis is predicted to be $1 + .39\cos^2\theta$ for a gluon spin J = 1; whereas, for a J = 0 gluon the distribution would be $1 - \cos^2\theta$. After fragmentation of the gluon jet, the constant .39 is calculated to change to $.20 \pm .03$ for the fragments and this is in good agreement with the observations at CESR of .35 ± .11. Similarly, the distribution of the normal to the 3-gluon plane relative to the beam axis indicates unit spin for the gluon.

Two theoretically important parameters in the Υ decay are the partial width to lepton pairs and the ratio of widths for Υ decay to 3 gluons relative to the decay width to muon pairs. The observed decay width to lepton pairs at CESR and DORIS agrees very well with predictions of static potential models for upsilonium as well as with comparable width predicted by the ITEP group based on the QCD calculations using the gluon condensate as described by Shifmann.[20]

The calculation of the 3-gluon decay width has been carried through in a very important and impressive calculation by Lepage and MacKenzie[24]

$$\frac{\Gamma_{3g}}{\Gamma_{\mu\bar{\mu}}} = \frac{10(\pi^2 - 9)}{81\ \pi\ e_b^2}\ \frac{\alpha_s^3}{\alpha^2}\ \left[1 + (9.1 \pm 0.5)\ \frac{\alpha_s(M_\Upsilon)}{\pi}\ \right] \qquad (6)$$

The very large numerical size of the radiative correction in (6) indicates that this process cannot yet be used for quantitive determination of the coupling constant or scale parameter of QCD. Nevertheless, the approximate value of α_s is in good agreement with indications from the various jet analyses presented to this Conference and discussed earlier. I emphasize these results to make the point that when and if heavier onia states (toponium, etc.) are discovered and we move further into the realm in which perturbative QCD can be applied with some quantitative confidence, we will have further gold-plated tests of QCD in addition to the total annihilation cross section.

The third excited state of upsilonium Υ (4s) is a factory of B mesons. Thus we can anticipate accumulating quantitative results on the various decay modes of the B during the coming year or two. These can be expected to be as valuable for understanding the decay mechanisms of the B as have been the very beautiful quantitative studies of K meson decay in the past, and as are the D and F meson decays of the present. In particular, we already know that many K mesons are observed in the semileptonic decays of the B. This indicates a predominant decay chain of the bottom quark to the charmed to the strange quark as is to be expected naively from the Kobayashi-Maskawa model with a small Cabibbo angle. Also the search for flavor changing neutral currents in B decays of the type

$$B \rightarrow \ell\ \bar{\ell}\ X$$

and other exotica have come up negative.[22] This result puts stringent limits on models without a charge 2/3 "top" quark.

One of the emerging threats to the "standard model" last year seemed to be the very large ratio of lifetimes for the D^+ and D^0 decays. A ratio of 10 as indicated by the initial round of experiments seemed larger than could be accomodated in the standard model. In particular, a spectator model which treats the light quark in the D system as being uninvolved in the decay or in final state interactions leads to the prediction

$$\tau(D^+) = \tau(D^0)$$

This threat to the standard model has now largely evaporated in the light of further experimental and theoretical results reported to this Conference. Indeed theory and experiment have established a detente with a "compromise" ratio

$$\frac{\tau(D^+)}{\tau(D^0)} \approx 3 \pm 1 \quad .$$

On one hand, the experiments, in particular photoproduction studies of charmed mesons, have brought this ratio of lifetimes down by a factor of roughly three.[25] At the same time, extensive calculations summarized by Fritzsch[26] indicate that, by turning the "spectator" light quark into an "active participant" on the basis of QCD and its gluons, one can also account for a factor of 3 in the ratio.

Many beautiful results on photoproduction were reported[27] about which I have no comments to add except to say that more and more the light meson spectroscopy advances as a quantative science. New results in the scattering of neutrino and antineutrinos have come up with no surprises or dilemmas for our understanding of weak neutral and charged currents. The τ lepton now has a lifetime reported from Mark II at PEP of $\tau_\tau = (4.9 \pm 1.8) \times 10^{-13}$ sec which is in satisfactory accord with the prediction based upon τ-μ universality: $\tau_\tau = (2.8 \pm 0.2) \times 10^{-13}$ sec.

We heard that two-gamma physics in the electron-positron scattering process in now experimentally under study[29] at the storage rings and that theory has a lot to say about this process,[30] illustrated in fig. 12. In particular, the two gamma decay widths of the even charge conjugation resonances can now be measured accurately. This includes the 2^{++} resonances and the 0^{-+} resonances. The production of 2 ρ^0 mesons reveals an enhancement in the 4π decay channel in the near threshold. The structure of jets in the inclusive cross section has a tail falling as $1/P_T^4$ which indicates the presence of a point coupling to the electromagnetic current in addition to the softer vector meson dominance parts. Further, there are now initial studies under way of photon structure function via the processes shown in figure 13. Finally, we heard a report of the axion search by Professor Faissner and collaborators,[31] but the final interpretation of this remains for the future. Theoretically, the axion predictions are very flexible and in the structure of grand unified theories[1] one can accommodate at present without any difficulty either their observation or nonobservation.

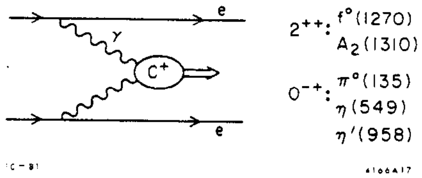

Figure 12

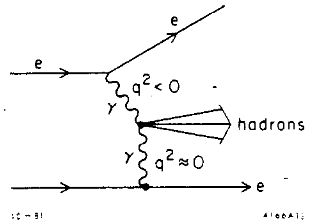

Figure 13

VI. Summary

To sum it all up then, I would say that:

1. QCD has made its mark and is here to stay with its J = 1 gluons.

2. A quantitative determination of the strong coupling constant α_s, and scale parameter, Λ, remains for the future. The reliable processes from the theoretical point of view for determining their values will be R or the study of the 3-gluon decays of heavy onia still to be discovered.

3. Very deep questions such as the scale of grand unification and the hierarchy problem, viz. why is the weak interaction lifetime of the neutron so many orders of magnitude shorter than the proton decay lifetime, or why is the grand unification scale so much larger than the weak vector boson mass, remain beyond our understanding.

4. All theories, as so eloquently described in Professor Okun's beautiful talk,[9] lead us to expect to observe evidence of scalars in the ee annihilation process, whether they arise from dynamical or spontaneous symmetry breaking. Please find them!

ACKNOWLEDGEMENTS

Very valuable conversations with many colleagues -- in particular R. M. Barnett, M. Chanowitz, S. Gupta and A. Mueller, helped me in preparing my talk. The exceptionally high quality of the reports made to the Bonn Conference were of enormous value to me. To the speakers and organizers of this wonderful conference I give my deepest thanks.

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2. See P. Langacker. Perhaps the proton lifetime may be the next surprise. (Here and henceforth I refer to the relevant talks to be published along with this in the Conference Proceedings. They contain extensive references to the original research papers.)
3. Talk of P. Hasenfratz.
4. This is rigorous for space-like momenta, $Q^2 < 0$, in evaluating the vacuum expectation value. Problems of continuing to time-like $Q^2 > 0$ and smearing the data to average effects of nearby thresholds are discussed in R. M. Barnett, M. Dine and L. McLerran, Phys. Rev. D22, 582 (1980).
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7. In the modified minimal subtraction scheme ($\overline{\mathrm{MS}}$) of Bardeen et al., [Bardeen, Buras, Duke and Muta, Phys. Rev. D18, 3998 (1980)]

$$C_2 = 1.98 - 0.115\, n_f$$

$$n_f \equiv \text{number of flavors} \quad .$$

   In this scheme α_s is renormalized by subtracting the (1/N-4) poles from dimensionally regularized integrals together with the factor $1/2\ (\gamma_E - 4\pi)$, where $\gamma_E = .577 \ldots$ is the Euler γ function, which is introduced as an artifact of the dimensional regularization scheme. The collision energy $s = 4E^2$ is the regularization mass scale of this scheme.
8. See Reference 4.
9. Talk of L. B. Okun.
10. Talks of R. Hollebeek, A. M. Litke, R. Felst, W. Braunschweig, D. Fournier, J. Bürger and A. Silverman.
11. Talk of M. Peskin. A comparable limit is set on the size of composite leptons by their precisely measured gyromagnetic anomalies, (g-2).
12. Talk of J. G. Branson. Note that above 30 GeV, R is therefore sensitive to weak interaction effects as well as QCD and the particle content.
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28. Talk of G. Barbiellini.
29. Talk of R. Wedemeyer.
30. Talk of W. Bardeen.
31. Talk of H. Faissner.