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On the discovery of the gluon

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Abstract. Quantum chromodynamics, the theory of the strong interaction, is a field theory of quarks and gluons. When it was formulated, the existence of its basic ingredients was still unproven and controversial. While for the quarks the case had been settled by 1975, it remained open for the gluons until in 1979 experiments at the electron-positron collider PETRA at DESY in Hamburg led to a breakthrough. Peculiar final configurations of hadrons produced in the electron-positron annihilation process at high energies, so-called planar events and three-jet events, were discovered. In a close cooperation between experiment and theory they were unambiguously identified as signatures of the radiation of hard gluons by quarks ("hard gluon bremsstrahlung"), providing the first clear and direct observational evidence for the existence of the gluon and confirming crucial predictions of quantum chromodynamics.

1 Introduction

Quantum chromodynamics (QCD), the theory of the strong interaction, was formulated in the early seventies of the past century as a non-Abelian gauge field theory of *quarks* that interact by the exchange of *gluons* [1–4]. Today QCD is part of the standard model of particle physics and is one of the pillars on which our understanding of nature rests. At the time when it was first proposed though, neither the quarks nor the gluons were established particles. The community of particle physicists was far from sharing a consensus about the existence of either of them.

The first hints of quarks being possible constituents of the proton and the neutron had come from the systematics and the spectroscopy of hadrons which in 1964 led Murray Gell-Mann and George Zweig independently to the quark hypothesis [5–7]. *Hadrons* was the generic name given to the strongly interacting particles, an abundance of which were discovered in the 1950s and 1960s. The observations suggested that the *baryons*, fermionic hadrons like the proton and neutron, consisted of three quarks while the *mesons*, their bosonic counterparts, were bound states of a quark and an antiquark. Initial problems with the statistics of the quarks were resolved by introduction of an additional degree of freedom, *color* [8].

A new page was opened in 1968 by measurements of high energy, deep inelastic electron-nucleon scattering at the Stanford Linear Accelerator Center, SLAC [9–12].

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The nucleon structure functions that describe the scattering process were found to be approximately *scale invariant* [13,14]. This could be interpreted as an indication for the existence of virtually free, electrically charged, pointlike (or almost pointlike) constituents in the nucleon [15–17]. Soon, experiments scattering neutrinos and antineutrinos on nucleons provided further, complementary insight [18,19]. The constituent's momentum distribution inside the nucleon was revealed, and the angular dependence of the scattering showed the spin of the constituents to be $\frac{1}{2}$. Comparing electron scattering with neutrino scattering — *i.e.* the electromagnetic interactions of the constituents with their weak couplings — the average squared electric charges of the constituents could be determined. Putting everything together it became evident that the constituents, or *partons* as they were called by Feynman, fitted the warrant for quarks [15].

It remained however mysterious that even by the most ingenious searches the quarks themselves were not observed. Consequently it was widely thought that nature was perhaps fooling physicists by behaving just *as if* quarks existed, the quarks being merely a mathematical construct mirroring an underlying symmetry.

We now jump to the year 1975 when our narrative begins. By then, the quarks as true dynamical constituents of the hadrons were no longer in serious doubt. The approximate "scaling" in deep inelastic lepton-nucleon scattering had been verified with increasing precision in subsequent experiments [20–22]. Even more, the large cross section for electron-positron annihilation into hadrons [23], and eventually the emerging charm spectroscopy [24], had convinced the last sceptics. Asymptotic freedom [3,4] had made it plausible that quarks were permanently confined and unobservable as free particles. The nearest approach to observing a free quark would be to observe the "jet" into which an energetic quark fragments — a shower of hadrons developing close to the momentum direction of the quark with strongly limited momenta transverse to that direction.

Jets as a possible signature of quarks had been discussed as early as 1969 by Bjorken, Cabibbo, Drell and colleagues [25–28]. For many years the existence of jets had remained doubtful however, because the available energies and transverse momenta in collision experiments were not large enough to clearly identify the emerging hadrons as fragmentation products of single quarks. Eventually this was achieved in 1975 in a groundbreaking analysis of the data recorded at the electron-positron collider SPEAR at SLAC [29,30]. The process observed was $e^+e^- \rightarrow q\bar{q} \rightarrow jet + jet$ at an energy in the center-of-mass system of 7.4 GeV. The jets were not directly "visible" to the unaided eye (*i.e.* as narrow bundles of particles in the detector) but using the *sphericity tensor*[1] to analyse the final state of hadrons and checking the angular distribution of the jet axis with respect to the incident beam yielded convincing evidence for the existence of the quark jets.

By contrast, the evidence for *gluons*[2] had remained circumstantial. The gluons of QCD are massless, flavorless, neutral vector particles. They do not scatter leptons directly as quarks do. Being colored, the gluons interact among each other and with the quarks; they are permanently confined like the quarks, hence they cannot be detected as free particles. A first indication of the existence of gluons in the nucleon had come from the data on lepton nucleon scattering: the *momentum sum rule* of the nucleon structure functions [32–35] was not saturated by the quarks and antiquarks in the nucleon, suggesting that about half of a fast nucleon's momentum must be carried by

[1] The sphericity tensor is the inertia tensor of classical mechanics with coordinate vectors replaced by momentum vectors and was suggested by Bjorken and Brodsky [28] as a measure of the shape of a multiparticle state in momentum space, and thereby of its "jettiness".

[2] The term "gluon" was introduced by Gell-Mann originally to designate a hypothetical neutral vector field coupled strongly to the baryon current, without reference to color [31].

flavorless parton constituents, presumably gluons [19]. A more distinct signal would come from the emission of collinear gluons by the quarks in the nucleon and by the splitting of gluons into collinear quark-antiquark pairs [36–40]. This should lead to a characteristic pattern of *scaling violations* in lepton nucleon scattering [41–43]. However, these scaling violations are of logarithmic nature and were not easily separated from other, stronger scale-violating effects; a compelling experimental verification required precise measurements over a large kinematic range, which became only gradually available in the course of the years[3]. By 1978 scaling violations compatible with QCD were consistently observed in deep inelastic neutrino scattering [45–48]. Also lepton pair production in hadronic collisions began to show first, albeit still weak, indications [49].

What was lacking though was a clear and significant effect that definitely and undeniably was due to gluons. Thus there was the outstanding challenge to either find the gluon, or to disprove QCD. The crucial step was taken in 1979 by experiments at the electron-positron collider PETRA of DESY[4]; these will be the topic of the present article. An earlier record of the experimental developments can be found in references [50–52] while a theorist's personal account of early theoretical work has been given recently in reference [53].

2 Setting the stage

With PETRA a wide area for the investigation of electron-positron interactions was opened. The collider was originally designed for 15 GeV beam energy and later upgraded to 23 GeV. The design plans for PETRA had been made in 1974 already before the discovery of the charm quark. One wanted an e^+e^- collider exceeding the energies reached with the existing machines, SPEAR at SLAC and DORIS at DESY, by as much as possible. The ring of 2.3 km circumference was the largest that could be accommodated on the DESY site. Thanks to the dedicated efforts of DESY director Herwig Schopper, the strong support by the DESY scientific council under Wolfgang Paul and Volker Soergel and the excitement following the discovery of charm, authorization and financing was obtained in 1975 and construction was vigorously pushed. The DESY accelerator group, led by the outstanding Gustav-Adolf Voss and with some help by universities, got the whole big project completed in less than 3 years, well before the anticipated target date and even below budget [54]. After a short commissioning phase PETRA was ready for the experiments to begin in October 1978, almost two years ahead of the competitive project PEP at SLAC.

It is amusing to note that in the 1974 proposal for building PETRA [55] which, of course, included a discussion of the physics opportunities offered by such a collider, the word *gluon* did not appear at all. Even the quarks received only passing mention, *viz. if* they existed, the rates for hadron production would remain relatively large at the higher energies. There still was a concern of running the risk of not being taken seriously, if one argued for a new machine based on such unproven concepts. Two years later when construction of PETRA had begun, an international meeting on "Physics and Experiments at PETRA" was held in Frascati [56]. From the 630 pages of presentations the gluon was still notoriously absent. Only as a "weird option" it was mentioned that a jet might split into two [57]. As it stood at the time, the experimental

[3] The experiments on lepton-nucleon scattering were carried on over many decades to today, culminating in the recent results from the electron-proton collider HERA showing precise distribution functions of the gluons in the proton [44].

[4] DESY, the "Deutsches Elektronen-Synchrotron DESY", is the German center for particle physics and synchrotron radiation research in Hamburg.

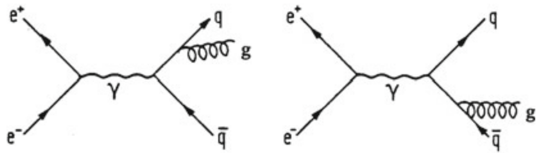

Fig. 1. Feynman diagrams for hard gluon bremsstrahlung $e^+e^- \rightarrow q\bar{q}g$.

proof for jets from quarks was somewhat involved, relying on a sophisticated analysis, and not everybody was convinced they really existed.

In this situation hardly anybody appeared to think seriously of *gluon jets* until, in the same year 1976, a seminal paper by John Ellis, Mary K. Gaillard and Graham Ross was published [58]. The authors suggested the emission of hard gluon bremsstrahlung by quarks in analogy with the radiation of electromagnetic bremsstrahlung by electrically charged particles (Fig. 1). An emitted hard gluon would subsequently generate a jet similar to a quark jet. "*Motivated by the approximate validity of the naive parton model and by asymptotic freedom, we suggest that hard gluon bremsstrahlung may be the dominant source of hadrons with large momenta transverse to the main jet axis. This process should give rise to three-jet final states*". Cross sections, momentum and angular distributions were predicted in leading order of perturbative QCD. The title of the paper could actually be read as an imperative: "*Search for Gluons in e^+e^- Annihilation*"! While the issue was not uncontroversial among theorists, the paper pointed the direction for experiment. Another basic paper was reference [59] by Sterman and Weinberg who in 1977 introduced the proper procedure to define and measure jets in QCD.

3 Preparations

The PETRA collider had four interaction regions in which the electrons and positrons met and detectors could be installed. Four collaborations had formed, each consisting of between 60 and 90 physicists from different institutions and countries:

- **CELLO**: DESY, Karlsruhe, MPI München, Orsay, Paris, Saclay;
- **JADE**: DESY, Hamburg, Heidelberg, Lancaster, Manchester, Rutherford Lab., Tokyo;
- **MARK-J**: Aachen, DESY, MIT Cambridge Mass., NIKHEF Amsterdam;
- **TASSO**: Aachen, Bonn, DESY, Hamburg, Imperial College London, Oxford, Rutherford Lab., Weizmann Institute, Wisconsin.

They all had worked very hard to get their detectors ready for taking data as soon as PETRA would start running. Unfortunately, CELLO was faced with a delay of the cryogenics for its superconducting magnet. In its place the well-proven detector of PLUTO, one of the collaborations that had performed experiments at the lower energy e^+e^- collider DORIS at DESY, was installed in the fourth interaction region of PETRA, to be replaced by CELLO at a later time (Fig. 2):

- **PLUTO**: Aachen, Bergen, DESY, Hamburg, Maryland, Siegen, Wuppertal.

It should be added here that some time before the PETRA experiments began, the PLUTO detector had taken data at DORIS on the so-called "upsilon" Υ(1S) bottomium resonance, the lowest-energy S-wave bound state of a b quark and a $\bar{b}$ antiquark. The total energy in the center of mass system (*cms*) of the colliding electrons and positrons had been chosen to precisely match the mass of this unstable $b\bar{b}$ bound state, so that the Υ(1S) was abundantly created. It subsequently decays

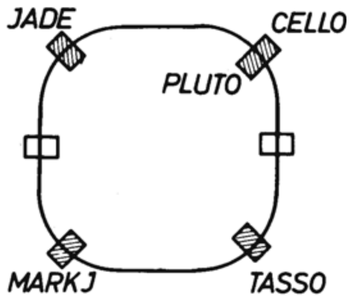

Fig. 2. The five detectors at the PETRA collider.

by mutual annihilation of the b and the $\bar{b}$ into lighter hadrons. While the analysis of the measurements of these decays was still ongoing, in August 1978 the PLUTO collaboration had demonstrated that the event shapes for $e^+e^- \to \Upsilon(1S) \to$ *hadrons* differed significantly from those in the nearby e^+e^- off-resonance continuum: On resonance the shapes were less cigar-like and more spherical [60]. This was intriguing as a hint towards a possible three-gluon decay mechanism of the $\Upsilon(1S)$ as expected in QCD [61–63], quite analogous to triplet positronium decay into three photons; the gluons would subsequently fragment into hadrons.

A few months later the evidence was already much augmented [64] and pursuing this further, by summer of 1979 the PLUTO experimenters showed with a multitude of plots for both charged and neutral particles that a two-jet decay of the $\Upsilon(1S)$ could be excluded while a three-gluon decay model, based on the decay distribution predicted from QCD convoluted with hadronization, was in perfect agreement with the data (Fig. 3) [65, 66]. The jet structure of the final hadron states was studied in terms of *thrust* [67, 68] and its extension *triplicity* [69]. Supporting evidence came from another experiment at DORIS [70]. Assuming the decay to proceed indeed *via* gluons, the data even vindicated the *vector* (spin 1) nature of the gluon [71] and proved the gluon to carry *color charge* [72].

However, the mass of the $\Upsilon(1S)$ is too low for its decay to produce three clearly distinct jets in the final state. The average particle momentum is only 0.4 GeV/c and thus not much larger than the average transverse momenta in a typical jet. The evidence for the existence of gluon jets provided by the analyses of the Υ decay was therefore quite indirect. Direct evidence had by then, in summer 1979, been obtained at PETRA. Nevertheless, the measurements at DORIS of the $\Upsilon(1S)$ decay provided beautiful, independent support for QCD and the existence of gluons and added greatly to the consistency of the overall picture.

Meanwhile at PETRA, by October/November 1978 the detectors were all set for taking data. Although initially the beam energy in the collider was only about half of the design value, the expectations on the part of the experimenters were high. With PETRA they were given a tool that was unique and opened access to a vast region of physics to be explored. Excitement rose when on November 18 the first e^+e^- annihilation event with hadron production was registered by PLUTO. One of the keenest hopes was to find *toponium*, the bound state of a *top* and an anti-*top* quark; its mass was at the time almost generally thought to be in the 20 to 40 GeV region[5]. One could also hope to discover new heavy leptons; it was not known yet

[5] A definite indication for the *top* quark mass to be very much higher than originally expected, came only in 1987 with the discovery of $B^0-\bar{B}^0$ mixing by the ARGUS experiment at DORIS [73].

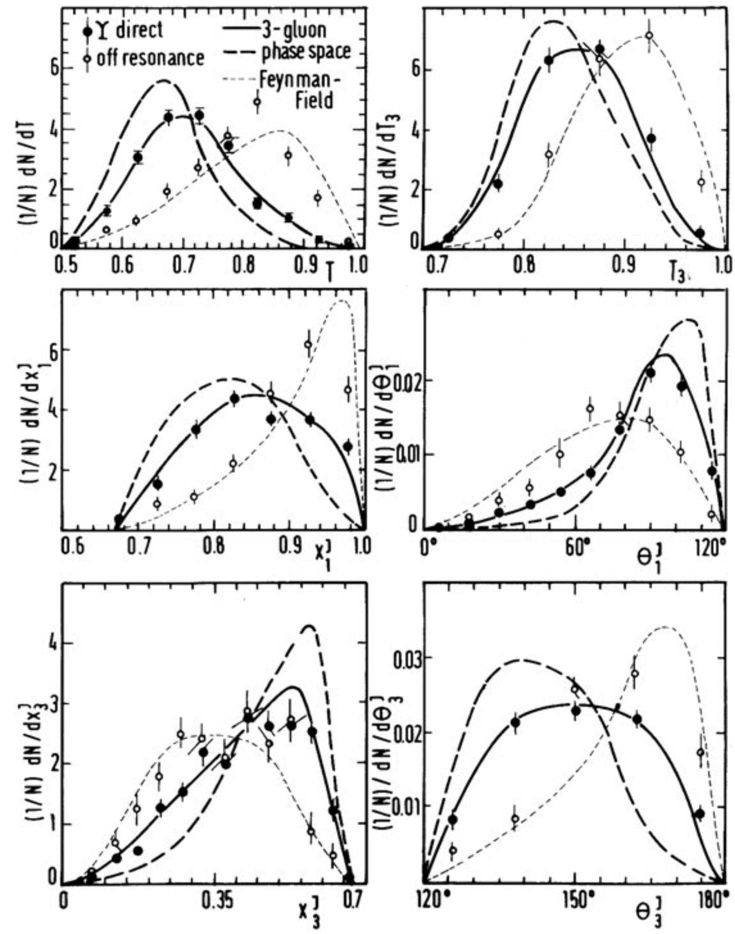

Fig. 3. Experimental data and analysis by PLUTO of the $\Upsilon(1S)$ decay into hadrons, as presented in June 1979 [65]. Shown are, both *on* and *off* the $\Upsilon(1S)$ resonance, the distributions of thrust T, triplicity T_3 (a generalization of thrust to three axes), smallest and largest reconstructed "gluon fractional energies" (x_1^J, x_3^J) and smallest and largest reconstructed "angles between gluons" (θ_1^J, θ_3^J), compared with Monte Carlo calculations based on different models. It is striking how well the three-gluon calculation describes the data for the direct Υ decay, and the two-jet simulation ("Feynman-Field" jets) the off-resonance data.

that there are only three standard generations. To explore electroweak interference effects was also in the foreground of most everybody's thinking.

While there was general agreement about the importance of the above topics, it seems that in the minds of many of the experimenters the question of the existence of the gluon was less of a top priority item. The TASSO collaboration, led by Günter Wolf of DESY, certainly was prepared. Their central tracking detector built under the guidance of Bjørn Wiik was working and a powerful method to recognize and analyze three-jet events was already at hand. Wide angle gluon bremsstrahlung $e^+e^- \to q\bar{q}g$ (Fig. 1) should, after fragmentation of the quarks and gluons into jets, lead to final multihadron configurations that are well spread out in the plane spanned by the momentum vectors of the three partons while showing strongly limited momentum components transverse to that plane (Fig. 4). This approximate planarity of the array of momentum vectors of the hadrons is simply a consequence of momentum conser-

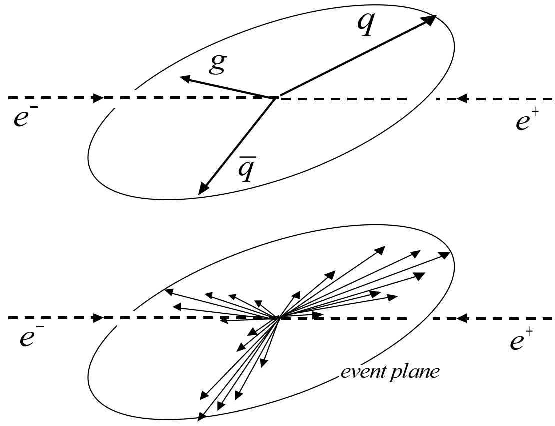

Fig. 4. The momentum vectors of the three elementary "partons" quark, antiquark and gluon, produced by annihilation of an electron positron pair, span a plane (upper figure). Consequently, the three jets generated by the hadronization of the partons are forming an (approximately) "planar event" (lower figure).

vation and the limited transverse momenta within a jet. By creatively extending the application of the *sphericity tensor* that had proven useful in the discovery of quark jets, Sau Lan Wu and Georg Zobernig of the Wisconsin group in the TASSO collaboration had designed and implemented an efficient method to recognize, present and investigate such "planar" events and three-jet configurations [74]. Wu figured that once the invariant mass of each *pair* of jets in a three-jet event was at least about 7.4 GeV, the total energy at which the $q\bar{q}$ two-jet states had first been identified at SPEAR, a three-jet state would be identified by the method. This led to the estimate that three-jet events could be detected once PETRA reached an energy of $\gtrsim$ 22 GeV in the e^+e^- center-of-mass system (*cms*) [51,52].

4 Discovery of three-jet events and hard gluon radiation

While initially operating at reduced energy, by April 1979 PETRA succeeded in accelerating the beams to an energy of 13.7 GeV, yielding 27.4 GeV in the e^+e^- *cms*. The detectors of MARK-J, PLUTO and TASSO were recording data while JADE had suffered the bad luck of having been damaged by beam loss in the machine; it was repaired in a crash effort and started data taking by late June. Meanwhile the three other detectors had each registered a few dozens of events in which hadrons were produced at the high energy. The tracks appeared collimated, suggestive of a two-jet origin; indeed for the first time jets were visible by "naked eye", see Figure 5 for an example. No trace of toponium or of a new lepton was detected. But the Wu-Zobernig analysis of the TASSO data began to turn up events that differed markedly from the dominant two-jet class by their "planar" nature [75]. Along with other results from TASSO [76,77] they were presented in June 1979 at international conferences in Bergen and Geneva [78,79]. A few of the events showed a distinct three-jet pattern (Figs. 6, 7).

Had the first signs of hard gluon bremsstrahlung been uncovered? Even though the final proof had to come from a quantitative analysis in terms of QCD, the evidence was striking and suggestive and this appeared to be the only possible explanation. Hadron production by e^+e^- annihilation was bound to proceed, in lowest order, by

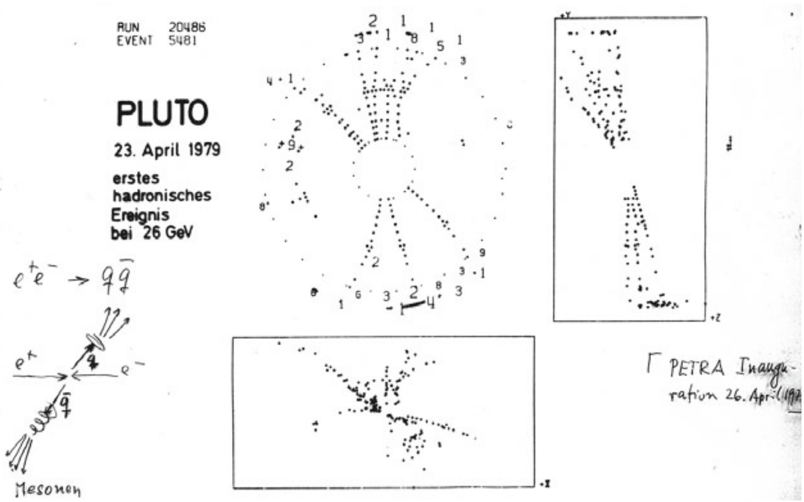

Fig. 5. One of the first events of the type $e^+e^- \to$ *hadrons* observed at high energy at PETRA, as shown in this computer printout from the PLUTO detector. Particle tracks were recorded in a cylindrical multiwire tracking chamber of 112 cm diameter, coaxial with the incident e^+e^- beams. The tracks are displayed in different projections. A clear two-jet structure is seen, characteristic of a final state that has evolved from an energetic back-to-back quark-antiquark pair.

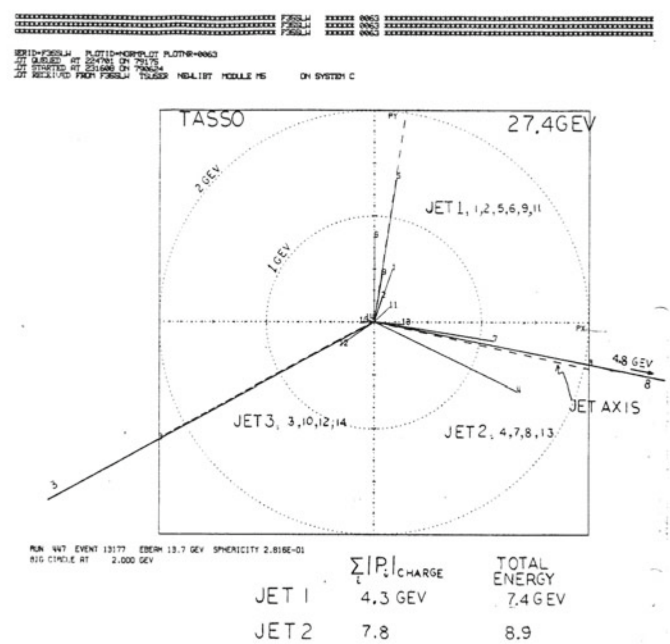

Fig. 6. The computer printout of the first three-jet event found in June 1979 [75, 78]. It shows the momentum vectors of the charged hadrons projected onto the event plane. Note that the event has three separate jets, and does not at all look like a back-to-back two-jet event with one narrow jet and a second, somehow broadened, jet.

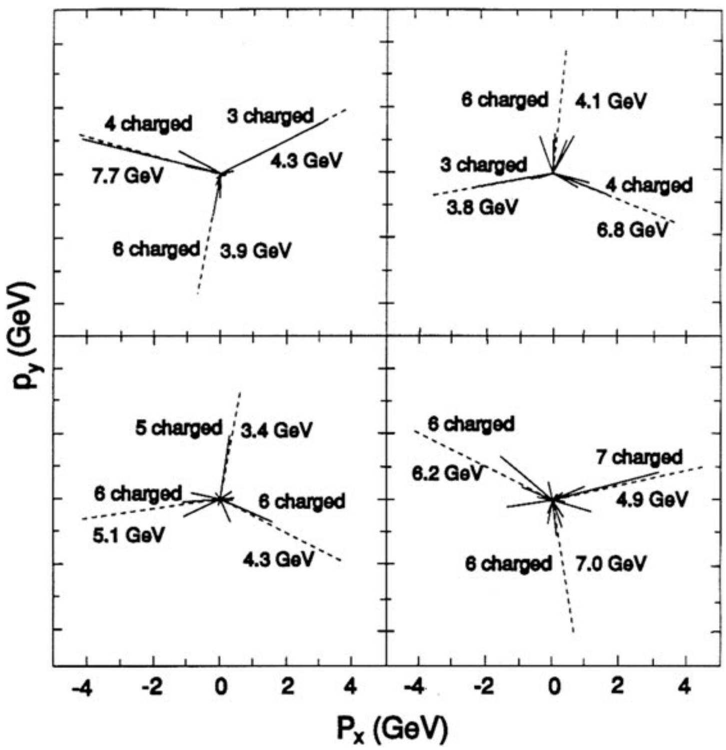

Fig. 7. Four three-jet events recorded in the TASSO detector at an e^+e^- *cms* energy of $W = 27.4$ GeV, as shown at the Geneva EPS Conference in June 1979 [79]. Plotted are the momentum vectors of the charged particles projected onto the event plane, and the directions of the fitted jet axes (dotted lines). These events had very large transverse momenta in the event plane, so they were among those with $\langle p_T^2 \rangle_{IN}$ values far out in the tail of the $\langle p_T^2 \rangle_{IN}$ distribution of Figure 10 for which the expectation of gluonless background was substantially less than 1 event. Therefore, these events not only showed three jets but were also statistically quite significant.

first generating a pair of $q\bar{q}$; since these are fermions, the third jet had necessarily to come from a boson. Could it have been faked by the decay of a single meson? This was excluded because the properties (*e.g.* the hadron multiplicity) of the three jets were looking very much alike, none of them resembled a meson; moreover, no mechanism was known that could produce a "hard" meson, *i.e.* a meson with a large momentum transfer relative to the emitting quark or antiquark, at a rate as large as observed for the production of the three-jet events. The only viable conclusion was therefore that the three-jet states signaled the production of an elementary boson coupling strongly to quarks — almost the definition of a gluon!

Of course such a far-reaching inference had to be substantiated by quantitative analysis. Two major problems had to be addressed:

- How to unravel reliably the perturbative QCD signatures in spite of the strong nonperturbative (*i.e.*, hadronization) effects that had totally dominated all the measured hadronic distributions until then. More simply, how could one exclude that the apparent third jet was faked by a statistical fluctuation of the dominant process $e^+e^- \to q\bar{q} \to jet + jet$.
- How to distinguish gluon bremsstrahlung from the production and decay of heavy quarks, which also could cause the jets to appear broader and more spread out.

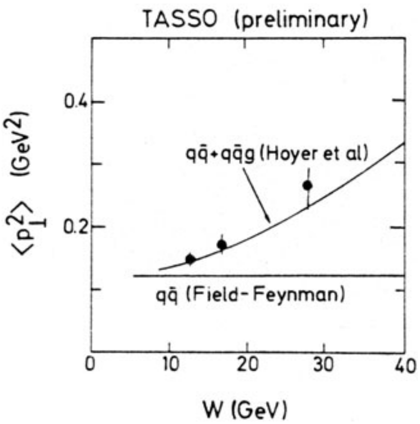

Fig. 8. Mean squared transverse momentum of the charged hadrons with respect to the jet (thrust) axis, as a function of the total e^+e^- *cms* energy W. The predictions for quark pair production *without* ("Field-Feynman") and *with* gluon bremsstrahlung (QCD, Hoyer *et al.* [87]) are also shown. From [79].

These problems had already caught the attention of experimentalists and theorists at CERN, DESY, Hamburg, Aachen and elsewhere. Following the original proposition of gluon bremsstrahlung by Ellis *et al.* [58], a number of authors had produced further papers on hadron production by e^+e^- annihilation [80–83], including Ellis himself as well as Gustav Kramer and his Hamburg group by whom more publications were to follow [84–86]. Just at the right time for the experiments the work by Hoyer, Osland, Sander, Walsh and Zerwas appeared [87]. These authors had convoluted quark and gluon production distributions calculated from first order QCD with the fragmentation functions introduced by Field and Feynman [88]. They presented detailed Monte Carlo predictions of transverse momentum distributions and other observables for $e^+e^- \rightarrow hadrons$ with the inclusion of hadronization following Field and Feynman; the hadronization of a gluon was assumed to be similar to that of a flavor-averaged quark. This work developed into a basic tool for the interpretation of the experimental data. This is also true for the related work by Ali and colleagues [89–92].

The TASSO data of June 1979 [79][6] showed, throughout the entire kinematic region, good agreement with the predictions from the Field-Feynman jet model extended according to QCD while being inconsistent with two-jet production *without* gluon radiation [87–93]. Examples are:

- Broadening of the jets with rising energy: For each hadronic event, a single jet axis was fitted to the final state hadron momenta. The mean squared momentum $\langle p_T^2 \rangle$ transverse to this jet axis would, in a model of quark-antiquark jet production without gluon radiation, remain essentially independent of the primary energy. By contrast, the data recorded at PETRA at *cms* energies of 13, 17 and 27.4 GeV showed a strong rise of $\langle p_T^2 \rangle$ with energy (Fig. 8). This agreed quantitatively with the QCD prediction [87], where the rise is due to jet broadening by gluon radiation. Moreover, this rise was observed to come exclusively from *one* of the

[6] For the integrity of the measurements a dependable calibration of the tracking chamber was crucial; the data accumulated by this time in the TASSO detector were just sufficient to accomplish this. The reason for the plots from a conference report [79], shown in Figures 8–10, to be marked "preliminary" is that they were obtained by a subgroup of TASSO physicists and had, at the time, not yet been formally authorized by the whole collaboration.

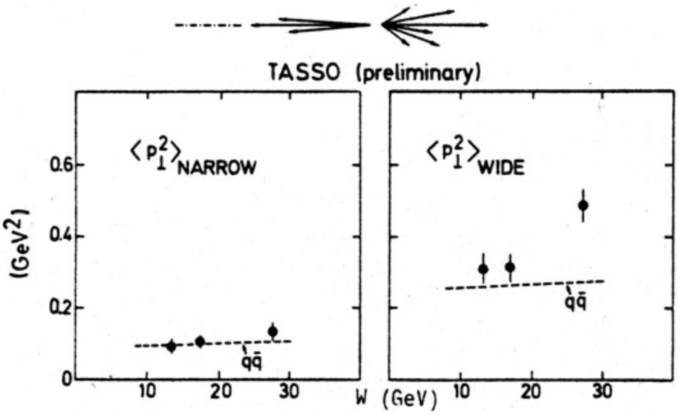

Fig. 9. Mean squared transverse momentum of the narrow and the wide jet, as a function of the total e^+e^- *cms* energy W. A part of the difference between $\langle p_T^2 \rangle_{\text{NARROW}}$ and $\langle p_T^2 \rangle_{\text{WIDE}}$ is due to selection bias; this is shown by the curves labeled $q\bar{q}$, obtained from a two-jet Monte Carlo calculation. Non-trivial one-sided jet broadening, as expected in first order QCD, is observed at the highest PETRA energy. No plausible explanation for such a behavior in terms of some peculiarity of the hadronization process in a $e^+e^- \to q\bar{q} \to jet + jet$ model was found. From [79].

two jets (Fig. 9). This is expected from QCD according to which the emission of *one* hard gluon strongly dominates over the emission of two.

- Appearance of planar events inconsistent with quark-antiquark generation without gluons: Events with a broad jet showed a tendency to form the "planar" configurations expected from hard gluon bremsstrahlung as noted above. The probability for these planar events to occur was found to be much too large to be faked by statistical fluctuations of $q\bar{q}$ final states including the decays of heavy quarks. This was demonstrated in the following way: for each event the *event plane* (Fig. 4) was determined as the plane normal to which the sum of the squared momentum components of the charged hadrons was smallest. At the *cms* energy of $W = 27.4$ GeV the average squared transverse momenta of the charged hadrons *normal to* the event plane, $\langle p_T^2 \rangle_{OUT}$, remained strongly limited while those *in* the plane, $\langle p_T^2 \rangle_{IN}$, showed a tail towards large values (Fig. 10). This could not be accounted for by statistical fluctuations or selection bias. In fact, the discrepancy of the $\langle p_T^2 \rangle_{IN}$ distribution with the expectation for jet production *without* hard gluons (calculated by Monte Carlo simulation) was very significant: 11 events with $\langle p_T^2 \rangle_{IN} > 0.3$ GeV^2 observed while only < 1 was predicted — ruling out the gluonless case with high confidence[7].

[7] For this estimate it was assumed that in the quark hadronization process, the characteristic average momentum transverse to the jet axis did not change drastically with energy. The value used was 300 MeV/c, which fitted the distributions measured at PETRA for *cms* energies below 20 GeV. Even if this average was blown up to 450 MeV/c for a *cms* energy of 27.4 GeV, the $q\bar{q}$ model could not fit the data: it then predicted 1.25 events with $\langle p_T^2 \rangle_{IN} > 0.5$ GeV^2 while 5 events were observed in this region, giving a confidence level $< 1\%$ for the $q\bar{q}$ model and in addition deteriorating the agreement with the $\langle p_T^2 \rangle_{OUT}$ distribution. The effects of the decays of heavy c and b quarks were included in the Monte Carlo calculations [93] (while searches at PETRA for still heavier flavors had not turned up anything [76, 77, 94, 95]). Thus one can safely conclude that the observation of planar events in the TASSO detector, as reported in June 1979, was significant even under extreme assumptions for the hadronization process.

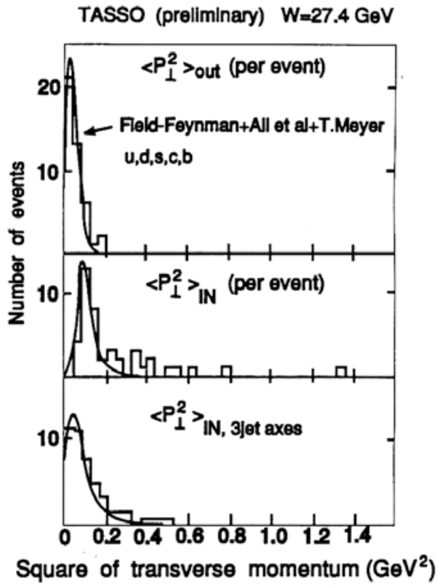

Fig. 10. Distribution of the average squared momentum component *out* of the event plane (top) and *in* the event plane (center), for e^+e^- annihilation events at a *cms* energy of $W = 27.4$ GeV (averaging over charged particles only). The curves are for $q\bar{q}$ jets without hard gluon bremsstrahlung [88,93]. These distributions give evidence that broadening (compared to $q\bar{q}$ jets) occurs *in a plane.* The bottom figure shows $\langle p_T^2 \rangle$ per jet when *three* jet axes were fitted, again compared with the $q\bar{q}$ jet model. From [79].

This made it also obvious that the four three-jet events of Figure 7 which were among those having $\langle p_T^2 \rangle_{IN}$ values located far out in the tail of the $\langle p_T^2 \rangle_{IN}$ distribution, were almost free from background of gluonless $q\bar{q}$ events and were therefore statistically quite significant[8].

With these and more findings, by June 1979 TASSO had presented consistent and statistically significant evidence for planar events and three-jet configurations. The only viable interpretation was in terms of the radiation of a field quantum of the strong interaction. The only known theory of the strong interaction was QCD. However, the strong coupling constant α_S was badly known at the time, so quantitative comparisons of the observed three-jet rates with the expectation from QCD could only have limited significance. Nevertheless, a first such comparison was made in the TASSO presentation, just to verify that the observed rate was of the right order of magnitude [79]. Selecting events with angles between the three fitted jet axes of at least 40° yielded a sample of 5 while a rough estimate[9] from QCD gave 9 events with

[8] Could this have been a spurious conclusion, due to insuffiencies of the early Monte Carlo models? In a 1995 study, current models were used for a re-analysis of the TASSO data [96]. Jets were defined by the JADE jet algorithm [97,98]. For the kinematic region of the four three-jet events of Figure 7, the updated QCD calculation predicted 2.7 events, the gluonless $q\bar{q}$ model only 0.34. Obviously the evidence of the 1979 presentation was perfectly sound.

[9] Here QCD was used on the parton level, *i.e.* the uncertainties in the directions of the jet axes fitted to the observed events were disregarded. For the value of the strong coupling constant α_S to which the three-jet rate is directly proportional in leading order, only rough estimates were available at the time: deep inelastic lepton nucleon scattering suggested a QCD scale parameter Λ of ~ 0.5 GeV which for PETRA energies led to the expectation $\alpha_S \sim 0.2$.

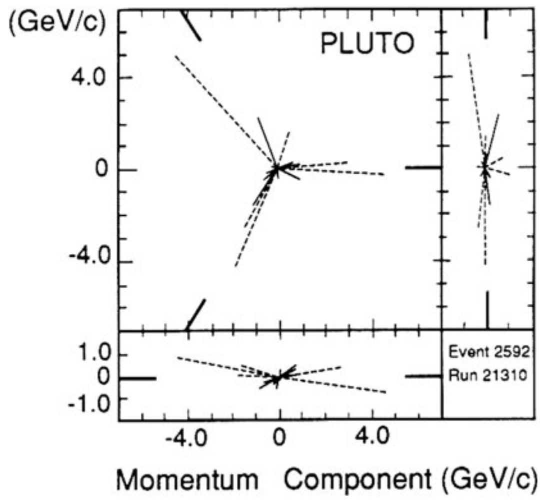

Fig. 11. An early three-jet event observed by PLUTO, viewed from three directions (*perpendicular* to resp. *in* the event plane). From [102].

an assumed value of the strong coupling constant $\alpha_S = 0.20$. With $\alpha_S = 0.15$ as known today, a better estimate would have been 7 events.

Thus credible first evidence for hard gluon bremsstrahlung had been obtained. What remained was to accumulate more data and to make the case airtight by further checks with higher statistics.

5 Follow-up: more data, more experiments, more analysis

The reports on the planar and three-jet events observed in the TASSO detector [99] stimulated much activity by the other three collaborations taking data at PETRA. Since these events were of striking appearance and occurred with an appreciable rate — depending on the cuts applied, of order 10% of all events in which hadrons were produced belonged to the planar/three-jet class at the highest PETRA energies — it took the experimenters of JADE, MARK-J and PLUTO just a few weeks to confirm the production of such a type of events with different variants of the analysis. Also, PETRA was now reliably delivering data at *cms* energies ranging up to 31.6 GeV.

Two months after the first presentations of the TASSO findings, in late August 1979 all four collaborations showed their evidence for gluon radiation at the biannual "International Symposium on Lepton and Photon Interactions at High Energies" held at Fermilab (FNAL) [100–103]. JADE and PLUTO were using track detectors with magnetic fields like TASSO and also measured neutral secondaries. For the jet analysis, the PLUTO experimenters used a method already proven in their analysis of the Υ, based on a generalization of *thrust* [69], while JADE used the *sphericity tensor* method. MARK-J presented an analysis of the *energy flow* of the secondaries around the jet (= thrust) axis. Individual particle momenta were not reconstructed; rather, the energy deposited by charged and neutral particles in a calorimeter was determined.

A three-jet event observed by PLUTO is shown in Figure 11. MARK-J used oblateness as a measure of planarity and found good agreement with a QCD calculation while the $q\bar{q}$ jet model could be ruled out (Fig. 12). TASSO confirmed the earlier findings with a much increased event sample: as an example, Figure 13 shows an update

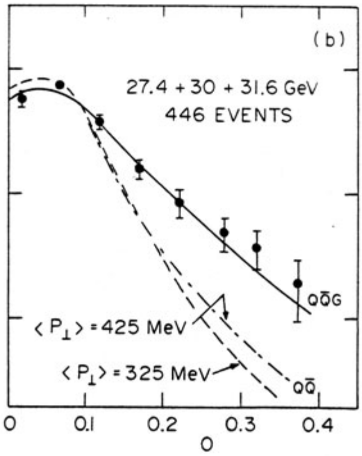

Fig. 12. The oblateness distribution measured by MARK-J, compared with a gluonless jet model with two different assumptions on the mean transverse momentum of the jets (broken lines) and with a QCD model involving gluon bremsstrahlung (solid line). From [101].

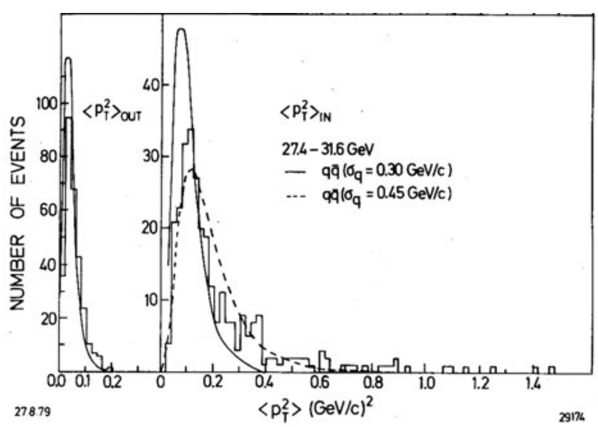

Fig. 13. Distribution of the average squared momentum component for charged secondaries *out* of the event plane (left) and *in* the event plane (right), measured by TASSO for e^+e^- annihilation events at *cms* energies of $W = 27.4$–31.6 GeV. The curves are for $q\bar{q}$ jets without hard gluon bremsstrahlung [88,93], using two different assumptions on the mean transverse momentum in the jets. From references [103,105].

of the distribution of hadron transverse momenta *in* and *normal to* the event plane. Also, the agreement of the rate of production of three-jet events with the expectation from QCD was verified again.

The numbers of events observed were by now large enough for TASSO to perform a model-independent check on the three-jet states [103]: a sample of planar events was selected and analyzed for a three-jet structure with the Wu-Zobernig method [74]. All the events gave a good fit to the three-jet hypothesis while a two-jet interpretation failed with a confidence level of $< 10^{-5}$. The transverse momentum of each hadron was determined relative to the axis of the jet to which it was assigned. In this way a mean transverse momentum of about 300 MeV/c with respect to each of the jet axes was found. In other words, in high energy planar events the particles were shown to be

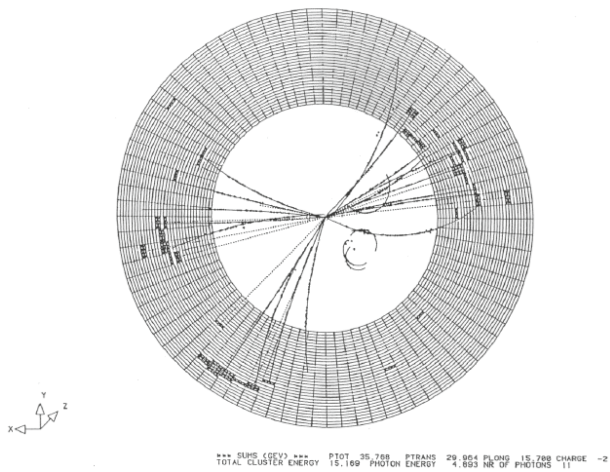

Fig. 14. A three-jet event registered in the JADE detector at PETRA at a total e^+e^- *cms* energy of $W = 31$ GeV. The view is along the beam axis into the interior of the detector, shown in perspective; the larger circle represents the nearby edge, the smaller circle the opposite distant edge of the cylindrical tracking region. The tracking region has a diameter of 1.6 m and a length of 2.4 m. It is surrounded by a calorimeter for electromagnetic showers, whose inner surface is segmented as indicated. Those segments in which energy has been deposited by photons or electrons, are marked in black.

just as collimated around three axes as particles are collimated around one common jet axis at lower energies.

The summary speaker at the conference, theoretical physicist Haim Harari of the Weizmann Institute, formulated what was probably generally agreed [104]: *"It has been clear for some time that the most direct way of "discovering" the gluon would be to observe "gluon jets"... Have we really seen three-jet events in* e^+e^- *collisions? If we did, does that confirm the existence of the gluon? Our answer to both questions is a cautious, qualified yes... several important checks and tests are yet to be performed. We believe, however, that five years from now, when we look back, we will all agree that the gluon was discovered in the summer of 1979."* Quite appropriately, the cover of the conference proceedings is showing a three-jet event.

Submission of the results for publication in refereed[10] journals followed shortly [105–108].

The event samples on which the four papers were based, were of similar size since the four experiments had been running simultaneously. Accordingly the results had about equal statistical precision.

Of course, as Harari had noted, the story of the gluon was far from being complete. With data from PETRA accumulating, increasingly large samples of events with very pronounced three-jet patterns were registered; a beautiful example from the JADE detector is shown in Figure 14. More precise and more profound investigations became possible. This spurred much activity both by experimentalists and theoreticians.

Arguably the most crucial task was to verify the *vector* (spin 1) nature of the hard gluons emitted in the bremsstrahlung process. The first relevant results were presented by the TASSO collaboration [110], using angular correlations between the three jets as proposed by Ellis and Karliner [82]. Almost simultaneously evidence came from PLUTO [111], followed by the other PETRA collaborations using different methods.

[10] One of the papers [106] appears to have been published without having been refereed [109], see Appendix.

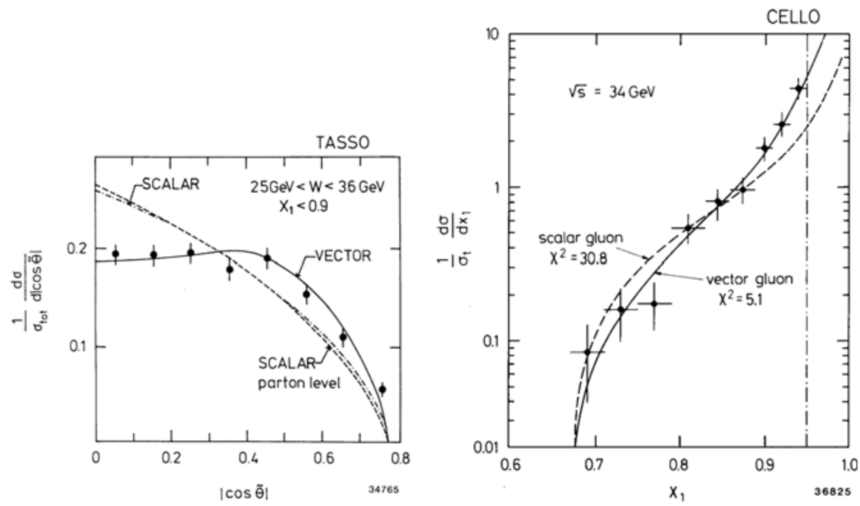

Fig. 15. Results from TASSO [50] and CELLO [112] confirming the vector nature of the gluon. Shown at left is the distribution of the Ellis-Karliner angle [82], a measure of angular correlations between the jets, and at right the jet fractional momentum distribution [58].

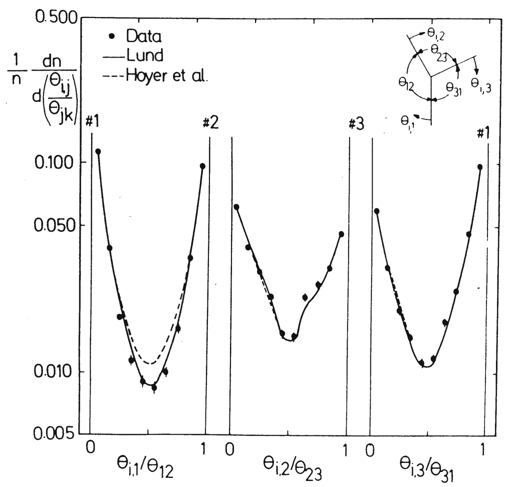

Fig. 16. Angular distribution of particle flow relative to the jet axes of three-jet events, interpreted as indication for color string fragmentation ("Lund" model [114, 115]). Data from the JADE experiment [113].

Figure 15 shows TASSO [50] and CELLO [112] data from a later stage obtained with larger event samples and partly at higher PETRA energies, giving definite evidence for the gluon to have spin 1.

Because of its inherent influence on all comparisons between the observations and QCD predictions, the fragmentation mechanism of the quarks and gluons received careful attention both by experimentalists and theorists. Since perturbative QCD is not applicable, this implied model building. The pioneering Field-Feynman proposition [88] was amended in different ways and intriguing subtleties were brought into evidence [113] which may be interpreted as a signature of color string fragmenta-

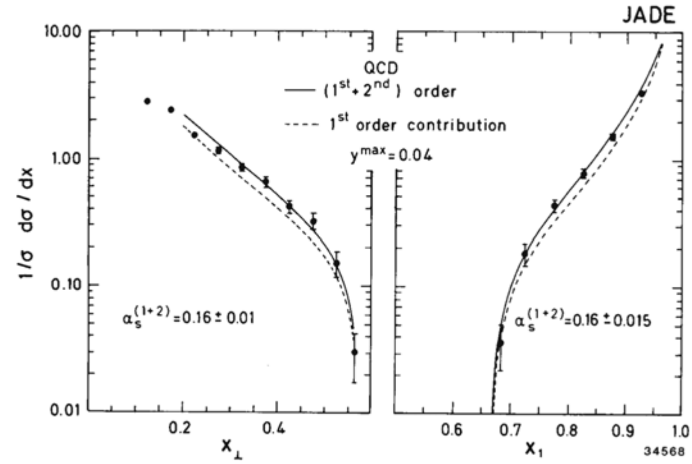

Fig. 17. Jet fractional energy distributions from JADE [119], compared with a second order QCD calculation by Fabricius *et al.* [120].

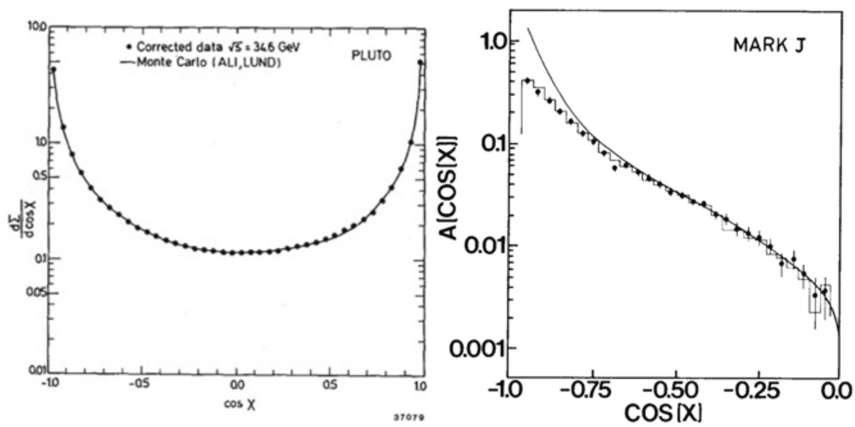

Fig. 18. Energy-energy correlation function from PLUTO [121] (left), and the asymmetry distribution of the energy-energy correlation from MARK-J [122] (right), showing excellent agreement with second order QCD calculations [123–125]. The right hand figure shows also a comparison of the QCD prediction *with* (histogram) and *without* (curve) hadronization effects, demonstrating insensitivity to hadronization over a wide kinematic range.

tion [114, 115] (Fig. 16); similar hadron redistributions between jets can be caused by interference effects within the quark-gluon cascades [116, 117].

It was also important to check that the perturbative QCD calculations of hard gluon bremsstrahlung to first order $o(\alpha_S)$ were not compromised by higher order contributions, and to compare $o(\alpha_S^2)$ predictions with the data. Various groups of theorists performed calculations of gluon bremsstrahlung to $o(\alpha_S^2)$ (for reviews see [86, 118]). An example of a comparison with data from JADE [119] is shown in Figure 17. The agreement is impressive.

As the rate of hard gluon emission is directly determined by the strong coupling constant α_S, from the measurements of this rate α_S could be determined. This was done first by the JADE collaboration [108]. It required a good understanding and control of the hadronization effects. Studies showed that the sensitivity to model assumptions could be kept small by using suitable observables. Two more examples

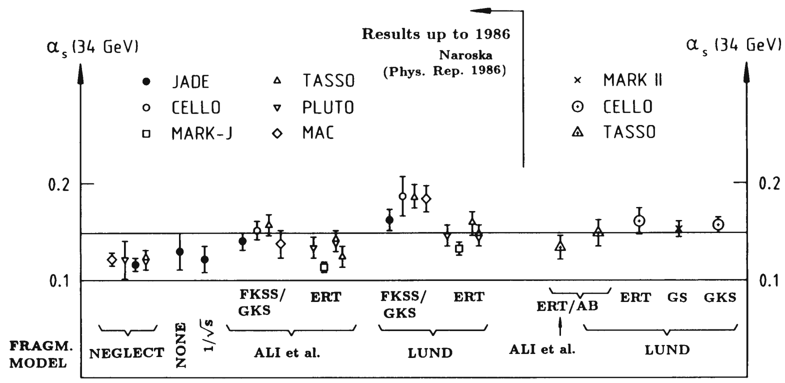

Fig. 19. A summary of values of the quark-gluon coupling constant α_S, determined from data obtained in experiments at PETRA and PEP between 1980 and 1987. Various different second order QCD calculations and jet hadronization models were used. The earlier results show a large scatter as they were affected by limited knowledge of hadronization and approximations in the QCD calculations. The later data, shown by the 5 rightmost points, were based on improved calculations and are in agreement with today's accepted value of $\alpha_S = 0.15$. From reference [137].

for excellent agreement between second order QCD calculations and data are shown in Figure 18.

For a while even after the discovery of the three-jet events, QCD was still considered by some to be only a "candidate theory" of the strong interaction and alternative theories were investigated further. However on confrontation with the data from PETRA and elsewhere, one by one they fell into obsolescence and QCD became the sole survivor. So within a few years any doubts that the gluons really existed with properties and interactions as implied by QCD, had effectively dissolved. Nevertheless the investigations were being pursued at PETRA with increasing statistics and sophistication. Additional impetus was coming from the experiments at PETRA's "competitor" PEP, an e^+e^- collider at the Stanford Linear Accelerator Center SLAC. *Four*-jet events were identified [126, 127] and evidence for differences between the fragmentation of quarks and gluons was observed [128–130]. Extensive reviews of the results are available [50, 131–138]. Figure 19 shows a summary of determinations of the quark-gluon coupling constant α_S leading to an increasingly consistent picture, reflecting the overall convergence of the different experimental results and the different QCD calculations and hadronization models. Eventually JADE even demonstrated the running of α_S as a function of energy, as expected in QCD [139].

In 1986 the PETRA machine was converted into an injector for the HERA electron-proton collider and the PETRA experiments were terminated. QCD studies were taken up at the higher energy e^+e^- collider TRISTAN in Japan and, most significantly, from 1989 at the Large Electron-Positron collider LEP at CERN and the SLC collider at SLAC. Now it was possible to follow the running of the quark-gluon coupling constant over a wide energy range. The accuracy with which α_S was determined became extraordinary; see [140] for a recent summary. Studies of differences between quark jets and gluon jets confirmed the higher color charge of gluons compared to quarks [141]. Another outstanding achievement was the confirmation, by analyzing energy distributions and angular correlations in $e^+e^- \to 4\ jets$ [142], of the self-coupling of the gluons — a cornerstone of the non-Abelian character of QCD and at the root of asymptotic freedom (see Ref. [141] for a summary of experimental results). With this, the crucial properties of the QCD gluon had finally been verified

— although one challenge is remaining to this day: the definite experimental proof that gluons are able to form quarkless hadronic states ("glueballs").

6 Summary and conclusions

In 1975 the PETRA project was launched at DESY: the construction of an electron-positron colliding beam accelerator that was the first of its kind to reach e^+e^- center-of-mass energies in the 30 GeV range. It greatly extended the frontier of particle physics and opened unique opportunities for testing the emerging standard model.

The experiments at PETRA began in the fall of 1978. Analyzing the multihadron states generated by the annihilation of electrons and positrons, the TASSO collaboration discovered planar and three-jet configurations among these final states. The first evidence was presented in June 1979 and shown to fit the expectations from QCD for hard gluon radiation while disagreeing with gluonless $q\bar{q}$ pair creation. Within two months this was confirmed and augmented by more data and by the results of the MARK-J, PLUTO and JADE collaborations also working at PETRA. The signature of jets generated by hard gluon bremsstrahlung was convincingly established, providing direct and compelling evidence for the gluon and verifying a crucial prediction of QCD. The observations at DORIS of the decay of the ground state of bottomium fitted beautifully into the picture. It took only a few more months to also verify the spin 1 nature of the hard gluons. Investigations of the strength of the quark-gluon interaction, of the properties of gluon jets and of the gluon self-coupling followed. The PETRA experiments, now also including CELLO, were complemented by similar experiments at the PEP collider of SLAC. The cooperation between theorists and experimentalists resulted in a convincing demonstration of the consistency of the experimental findings with QCD.

Looking back, it is perhaps not too pretentious to view the discovery of the three-jet events as the experimental breakthrough for QCD. In the words of John Ellis [53] *"... the gluon finally joined the Pantheon of established particles as the first gauge boson to be discovered after the photon."*

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Appendix: A comment on priority

A claim for priority to the "Discovery of Three-Jet Events"[11] by the MARK-J collaboration requires a comment. Right after the presentation of the results from the four PETRA experiments at the Lepton-Photon Symposium in August 1979 (see p. 17), the TASSO paper [105] was the first to be submitted for publication, followed a few days later by the paper of MARK-J [106] which however appeared in print first; for some amusing circumstances connected with this see reference [109]. The TASSO presentations of June 1979 [76–79] (a written account being already at hand) were ignored in the MARK-J publication.

Subsequently the claim was stated more precisely as MARK-J to have obtained "*the first statistically relevant observation of the three-jet pattern*" (*e.g.* [143–147]). It

[11] The quote is from the title of the MARK-J publication of September 1979 [106].

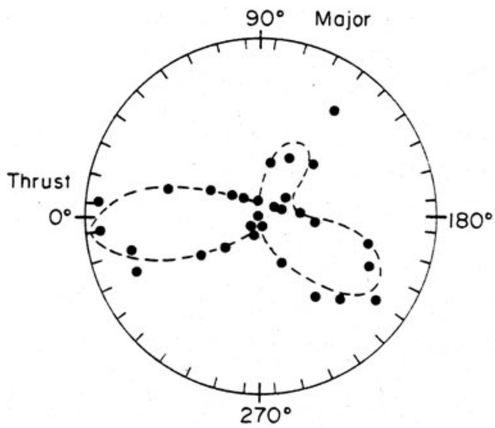

Fig. 20. Energy flow pattern in the event plane, summed over a selection of events that are candidates for three-jet events. The energy value is proportional to the radial distance. Measurements by MARK-J at *cms* energies of 27.4–31.6 GeV [106]. The dashed curve shows the distribution calculated from a $q\bar{q}g$ model.

does not appear that many outside of the MARK-J collaboration found this convincing (for example see [148]). Already the initial observation of three-jet states reported in June 1979 by members of the TASSO collaboration [78, 79] was quite significant, as discussed in Section 4. As TASSO's publication a few weeks later [105] was based on a much enlarged data sample, its significance was correspondingly increased. Of similar statistical weight was the evidence presented in the publications by PLUTO and JADE that followed shortly [107, 108].

The size of the data sample used in MARK-J's "Discovery" publication [106] was comparable to those of the other PETRA collaborations. The paper gave evidence for an excess of oblate (planar) events at the highest PETRA energies, as was shown in Figure 12. In order to prove the existence of three separate jets, a sample of events with low thrust and high oblateness, for which the gluon emission effect is expected to be relatively large, was selected for detailed examination. After aligning the jet axes, the summed energy flow projected onto the event plane produced an impressive three-lobed "antenna pattern" (Fig. 20). The lobes were identified as "jets" in the paper. This was somewhat misleading: the angles between the jets in three-jet events are continuously distributed, therefore summing up the angular energy flows of different events does not show the true jet shapes. Monte Carlo simulation of phase space-like events was said to produce a similar three-lobed pattern (not shown in the paper) and so would two-jet events, as pointed out by the authors in a later paper [149].

A statistically significant incompatibility ($\chi^2 = 222$ for $n_D = 70$) between the measured data and a phase space distribution was asserted while an $e^+e^- \rightarrow q\bar{q}g$ model was found to be compatible with the data ($\chi^2 = 67$ for $n_D = 70$). This presumably was the basis for the claim of the "first statistically relevant observation". However, the sketchy information given left relevant questions unanswered. Were the model predictions normalized to the energy flow of the totality of the events, or to the flow of the events in the selected three-jet sample? How large were the statistical errors of the data shown in Figure 20, and how many events were contained in the selection? Information on the QCD model (fragmentation functions used, mean transverse momentum in jets, treatment of heavy quark decays, value of α_S assumed (or fitted?)) and a fit with a gluonless $q\bar{q}$ jet model were likewise lacking.

Therefore it is not obvious how to appraise the significance of the model comparisons quoted above. A *direct* evidence for three-jet structure on an event-by-event basis was not provided. It is left to everybody's judgement how convincing a proof for three-jet events the "Discovery" paper actually was offering. Fully credible results using the energy flow method were only presented in later publications.

References

1. H. Fritzsch, M. Gell-Mann, Current Algebra: Quarks and what else?, *Proc. 16th Int. Conf. on High Energy Physics* (Chicago-Batavia, 1972), Vol. 2, p. 135
2. H. Fritzsch, M. Gell-Mann, H. Leutwyler, Advantages of the Color Octet Gluon Picture, Phys. Lett. B **47**, 365 (1973)
3. H.D. Politzer, Reliable Perturbative Results for Strong Interactions?, Phys. Rev. Lett. **30**, 1346 (1973)
4. D.J. Gross, F. Wilczek, Ultraviolet Behavior of Non-Abelian Gauge Theories, Phys. Rev. Lett. **30**, 1343 (1973)
5. M. Gell-Mann, A Schematic Model of Baryons and Mesons, Phys. Lett. **8**, (1964) 214
6. G. Zweig, An SU(3) Model for Strong Interaction Symmetry and its Breaking, CERN Reports No. 8152/TH.401 and 8419/TH.412 (1964), *unpublished*
7. R.P. Feynman, M. Gell-Mann, G. Zweig, Group U(6)⊗U(6) Generated by Current Components, Phys. Rev. Lett. **13**, 678 (1964)
8. M.H. Han, Y. Nambu, 3-triplet model with SU(3) symmetry, Phys. Rev. **139**, 1006B (1965)
9. W.K.H. Panofsky, Low q^2 Electrodynamics, Elastic and Inelastic Electron (and Muon) Scattering, *Proc. 14th Int. Conf. on High Energy Physics* (Vienna, 28 Aug - 5 Sept 1968), p. 23
10. R.E. Taylor, Inelastic Electron-Proton Scattering in the Deep Continuum Region, Invited talk, *Proc. 4th Int. Symp. on Electron Photon Interactions at High Energies* (Liverpool, 1969), p. 251
11. E.D. Bloom *et al.*, High-Energy Inelastic $e-p$ Scattering at 6° and 10°, Phys. Rev. Lett. **23**, 930 (1969)
12. M. Breidenbach *et al.*, Observed Behavior of Highly Inelastic Electron-Proton Scattering, Phys. Rev. Lett. **23**, 935 (1969)
13. J.D. Bjorken, Asymptotic Sum Rules at Infinite Momentum, Phys. Rev. **179**, 1547 (1969)
14. J.D. Bjorken, E.A. Paschos, Inelastic Electron-Proton and γ-Proton Scattering and the Structure of the Nucleon, Phys. Rev. **185**, 1975 (1969)
15. R.P. Feynman, *Photon-Hadron Interactions* (Benjamin, Reading, Mass., 1972)
16. R.P. Feynman, Very High-Energy Collisions of Hadrons, Phys. Rev. Lett. **23**, 1415 (1969)
17. R.P. Feynman, The Behavior of Hadron Collisions at Extreme Energies, *High Energy Collisions* (New York, Gordon and Breach, 1969), p. 237
18. G. Myatt, D.H. Perkins, Further Observations on Scaling in Neutrino Interactions, Phys. Lett. B **34**, 542 (1971)
19. D.H. Perkins, Neutrino Interactions, Review paper, *Proc. 16th Int. Conf. on High Energy Physics* (Chicago-Batavia, 1972), Vol. 4, p. 189
20. J.I. Friedman, H.W. Kendall, Deep Inelastic Electron Scattering, Ann. Rev. Nucl. Sci. **22**, 203 (1972)
21. G. Miller *et al.*, Inelastic Electron-Proton Scattering at Large Momentum Transfers and the Inelastic Structure Functions of the Proton, Phys. Rev. D **5**, 528 (1972)
22. T. Eichten *et al.*, Measurement of the Neutrino-Nucleon and Antineutrino-Nucleon Total Cross Sections, Phys. Lett. B **46**, 274 (1973)
23. B. Richter, $e^+e^- \rightarrow$ HADRONS, Plenary session report, *Proc. XVII Int. Conf. on High Energy Physics, London, 1 - 10 July 1974* (Science Research Council, Rutherford Lab., 1974), pp. IV-37

24. G.S. Abrams, Properties of the New Particles $\psi(3095)$ and $\psi'(3684)$, *Proc. 1975 Int. Symp on Lepton and Photon Interactions at High Energies* (Stanford U., Aug. 21 - 27, 1975), p. 25; G.J. Feldman, New Particle Searches and Discoveries at SPEAR, *ibid.*, p. 39; A.D. Liberman, $\psi(3095)$ and $\psi(3684)$ Results from the HEPL Experiment at SPEAR, *ibid.*, p. 55; B.H. Wiik, Recent Results from DORIS, *ibid.*, p. 69; J. Heintze, DORIS Results from the DESY Heidelberg Collaboration, *ibid.*, p. 97; SPEAR-DORIS Discussion, *ibid.*, p. 109
25. S.D. Drell, D.J. Levy, T.-M. Yan, Theory of Deep-Inelastic Lepton-Nucleon Scattering and Lepton-Pair Annihilation Processes I, Phys. Rev. **187**, 2159 (1969)
26. S.D. Drell, D.J. Levy, T.-M. Yan, Theory of Deep-Inelastic Lepton-Nucleon Scattering and Lepton-Pair Annihilation Processes III, Phys. Rev. D **1**, 1617 (1970)
27. N. Cabibbo, G. Parisi, M. Testa, Hadron Production in e^+e^- Collisions, Lett. Nuovo Cim. **4**, 35 (1970)
28. J.D. Bjorken, S.J. Brodsky, Statistical Model for Electron-Positron Annihilation into Hadrons, Phys. Rev. D **1**, 1416 (1970)
29. G. Hanson *et al.*, Evidence for Jet Structure in Hadron Production by e^+e^- Annihilation, Phys. Rev. Lett. **35**, 1609 (1975)
30. R.F. Schwitters *et al.*, Azimuthal Asymmetry in Inclusive Hadron Production by e^+e^- Annihilation, Phys. Rev. Lett. **35**, 1320 (1975)
31. M. Gell-Mann, Symmetries of Baryons and Mesons, Phys. Rev. **125**, 1067 (1962)
32. C.H. Llewellyn Smith, Current-Algebra Sum Rules Suggested by the Parton Model, Nucl. Phys. B **17**, 277 (1970)
33. C.H. Llewellyn Smith, Inelastic Lepton Scattering in Gluon Models, Phys. Rev. D **4**, 2392 (1971)
34. J. Kuti, V.F. Weisskopf, Inelastic Lepton-Nucleon Scattering and Lepton Pair Production in the Relativistic Quark-Parton Model, Phys. Rev. D **4**, 3418 (1971)
35. R.P. Feynman, *Photon-Hadron Interactions* (Benjamin, Reading, Mass., 1972), p. 152
36. D.J. Gross, F. Wilczek, Asymptotically Free Gauge Theories I, Phys. Rev. D **8**, 3633 (1973)
37. D.J. Gross, F. Wilczek, Asymptotically Free Gauge Theories II, Phys. Rev. D **9**, 980 (1974)
38. H. Georgi, H.D. Politzer, Electroproduction Scaling in an Asymptotically Free Theory of Strong Interactions, Phys. Rev. D **9**, 416 (1973)
39. J.B. Kogut, L. Susskind, Scale-Invariant Parton Model, Phys. Rev. D **9**, 697 (1974)
40. J.B. Kogut, L. Susskind, Parton Models and Asymptotic Freedom, Phys. Rev. D **9**, 3391 (1974)
41. Y. Watanabe *et al.*, Test of Scale Invariance in Ratios of Muon Scattering Cross Sections at 150 and 56 GeV, Phys. Rev. Lett. **35**, 898 (1975)
42. C. Chang *et al.*, Observed Deviations from Scale Invariance in High Energy Muon Scattering, Phys. Rev. Lett. **35**, 901 (1975)
43. W.B. Atwood *et al.*, Inelastic Electron Scattering from Hydrogen at 50° and 60°, Phys. Lett. B **64**, 479 (1976)
44. H1 and ZEUS Collaborations, Combined Measurement and QCD Analysis of the Inclusive $e^{\pm}p$ Scattering Cross Sections at HERA, Journal of High Energy Physics, DOI: 10.1007/JHEP01(2010)109
45. P.C. Bosetti *et al.*, Analysis of Nucleon Structure Functions in CERN Bubble Chamber Neutrino Experiments, Nucl. Phys. B **142**, 1 (1978)
46. J.G.H. De Groot *et al.*, Comparison of Moments from the Valence Structure Function with QCD Predictions, Phys. Lett. B **82**, 292 (1979)
47. J.G.H. De Groot *et al.*, QCD Analysis of Charged-Current Structure Functions, Phys. Lett. B **82**, 456 (1979)
48. J.G.H. De Groot *et al.*, Inclusive Interactions of High-Energy Neutrinos and Antineutrinos in Iron, Z. Phys. C **1**, 143 (1979)
49. J.K. Yoh *et al.*, Study of Scaling in Hadronic Production of Dimuons, Phys. Rev. Lett. **41**, 684 (1978)
50. Sau Lan Wu, e^+e^- Physics at PETRA – The first five years, Phys. Rep. **107**, 59 (1984)

51. P. Söding, B. Wiik, G. Wolf, Sau Lan Wu, The First Evidence for Three-Jet Events in e^+e^- Collisions at PETRA – First Direct Observation of the Gluon (presented by S.L. Wu), *Proc. Int. Europhysics Conf. on High Energy Physics (EPS HEP 95)* (Brussels, 1995), p. 3
52. Sau Lan Wu, Hadron Jets and the Discovery of the Gluon, *The Rise of the Standard Model: Particle Physics in the 1960s and 1970s* edited by L. Hoddeson, L. Brown, M. Riordan and M. Dresden (Cambridge Univ. Press, 1997), p. 600
53. J. Ellis, Those were the days: discovering the gluon, CERN Courier **49** Nr. 6 (July/August 2009) p. 15; see also reference [147]
54. E. Lohrmann, P. Söding, *Von schnellen Teilchen und hellem Licht: 50 Jahre Deutsches Elektronen-Synchrotron DESY* (WILEY-VCH Weinheim 2009)
55. PETRA – Ein Vorschlag zur Erweiterung der Speicherringanlagen bei DESY zu hohen Energien (DESY, Hamburg, Nov. 1974), *unpublished*
56. Discussion Meeting on PETRA Experiments, organized by DESY and INFN (Frascati, March 1 - 5, 1976), *unpublished*
57. T.F. Walsh, Hadron Production in e^+e^- Annihilation at High Energies, *ibid.* p. B1, referring to A.M. Polyakov. See also A.M. Polyakov, Ultraviolet and Infrared Interactions of the Quantized Field, *Proc. 1975 Int. Symp on Lepton and Photon Interactions at High Energies* (Stanford U., Aug. 27 - 27, 1975), p. 855
58. J. Ellis, M.K. Gaillard, G.G. Ross, Search for Gluons in e^+e^- Annihilation, Nucl. Phys. B **111**, 253 (1976)
59. G. Sterman, S. Weinberg, Jets from Quantum Chromodynamics, Phys. Rev. Lett. **39**, 1436 (1977)
60. Ch. Berger *et al.* (PLUTO Coll.), A Study of Jets in Electron Positron Annihilation into Hadrons in the Energy Range 3.1 to 9.5 GeV, Phys. Lett. B **78**, 176 (1978)
61. T. Appelquist, H.D. Politzer, Heavy Quarks and e^+e^- Annihilation, Phys. Rev. Lett. **34**, 43 (1975)
62. T. Appelquist, H.D. Politzer, Heavy Quarks and Long-Lived Hadrons, Phys. Rev. D **12**, 1404 (1975)
63. K. Koller, T.F. Walsh, Three Gluon Jets as a Test of QCD, Phys. Lett. B **72**, 227 (1977)
64. Ch. Berger *et al.* (PLUTO Coll.), Jet Analysis of the $\Upsilon(9.46)$ Decay into Charged Hadrons, Phys. Lett. B **82**, 449 (1979)
65. PLUTO Coll., Experimental Search for Υ Decay into 3 Gluons (presented by S. Brandt), *Proc. Int. Conf. on High Energy Physics* (European Physical Society, Geneva, 27 June - 4 July 1979), Vol. 1, p. 338
66. PLUTO Coll., Measurement of the Properties of the Υ Family from e^+e^- Annihilation (presented by H. Meyer), *Proc. 9th Int. Symposium on Lepton and Photon Interactions at High Energies* (Fermi National Accelerator Lab. FNAL, Batavia, Ill. August 1979), p. 214
67. S. Brandt *et al.*, The Principal Axis of Jets – An Attempt to Analyse High-Energy Collisions as Two-Body Processes, Phys. Lett. **12**, 57 (1964)
68. E. Fahri, Quantum Chromodynamics Test for Jets, Phys. Rev. Lett. **39**, 1587 (1977)
69. S. Brandt, H.D. Dahmen, Axes and Scalar Measures of Two-Jet and Three-Jet Events, Z. Phys. C **1**, 61 (1979)
70. F.H. Heimlich *et al.* (DESY-Hamburg-Heidelberg-MPI München Coll.), Hadronic Jets from e^+e^- Annihilations in the Υ- and Υ'-Region, Phys. Lett. B **86**, 399 (1979)
71. K. Koller, H. Krasemann, Excluding Scalar Gluons, Phys. Lett. B **88**, 119 (1979)
72. T.F. Walsh, P. Zerwas, $\Upsilon(9.46)$ Decays Do Test QCD, Phys. Lett. B **93**, 53 (1980)
73. H. Albrecht *et al.* (ARGUS Coll.), Observation of $B^0\bar{B}^0$ Mixing, Phys. Lett. B **192**, 245 (1987)
74. S.L. Wu, G. Zobernig, A Method of Three-Jet Analysis in e^+e^- Annihilation, Z. Phys. C **2**, 107 (1979)
75. S.L. Wu, G. Zobernig, A three-jet candidate, TASSO Note No. 84 (June 26, 1979)
76. G. Wolf, High Energy Trends in e^+e^- Physics, Invited talk, *Proc. Int. Conf. on High Energy Physics* (European Physical Society, Geneva, 27 June - 4 July 1979), Vol. 1, p. 220

77. TASSO Coll., The Hadronic Final State in e^+e^- Annihilation at c.m. Energies of 13, 17 and 27.4 GeV (presented by R. Cashmore), *Proc. Int. Conf. on High Energy Physics* (European Physical Society, Geneva, 27 June - 4 July 1979), p. 330
78. B. Wiik, First Results from PETRA, *Proc. Int. Conf. on Neutrinos, Weak Interactions and Cosmology*, edited by A. Haatuft, C. Jarlskog (Bergen, 18 - 22 June 1979), Vol. 1, p. 113
79. P. Söding, Jet Analysis; Invited talk, *Proc. Int. Conf. on High Energy Physics* (European Physical Society, Geneva, 27 June - 4 July 1979), Vol. 1, p. 271
80. T.A. DeGrand, Y.G. Ng, S.H.H. Tye, Jet Structure in e^+e^- Annihilation as a Test of Quantum Chromodynamics and the Quark-Confining String, Phys. Rev. D **16**, 3251 (1977)
81. A. De Rujula, J. Ellis, E.G. Floratos, M.K. Gaillard, QCD Predictions for Hadronic Final States in e^+e^- Annihilation, Nucl. Phys. B **138**, 387 (1978)
82. J. Ellis, I. Karliner, Measuring the Spin of the Gluon in e^+e^- Annihilation, Nucl. Phys. B **148**, 141 (1979)
83. G. Kramer, G. Schierholz, J. Willrodt, QCD Precictions for Jets in e^+e^- Annihilation: Angular Correlations and Asymmetries, Phys. Lett. B **79**, 249 (1978)
84. G. Kramer, G. Schierholz, Transverse Momentum and Angular Distributions of Hadrons in e^+e^- Jets from QCD, Phys. Lett. B **82**, 108 (1979)
85. G. Kramer, G. Schierholz, J. Willrodt, Cross Sections and Angular Distributions of Three-Jet Final States in e^+e^- Annihilation for Heavy Quarks, Z. Phys. C **4**, 149 (1980)
86. G. Kramer, Theory of Jets in Electron-Positron Annihilation, Springer Tracts Mod. Phys. **102**, (1984)
87. P. Hoyer, P. Osland, H.G. Sander, T.F. Walsh, P.M. Zerwas, Quantum Chromodynamics and Jets in e^+e^-, Nucl. Phys. B **161**, 349 (1979)
88. R. Field, R.P. Feynman, A Parametrization of the Properties of Quark Jets, Nucl. Phys. B **136**, 1 (1978)
89. A. Ali, J.G. Körner, G. Kramer, J. Willrodt, Jet-Like Distributions from the Weak Decay of Heavy Quarks, Z. Phys. C **1**, 203 (1979)
90. A. Ali *et al.*, Indications of $b\bar{b}$ Production and Decay at PETRA, Phys. Lett. B **83**, 375 (1979)
91. A. Ali *et al.*, A QCD Analysis of the High Energy e^+e^- Data from PETRA, Phys. Lett. B **93**, 155 (1980)
92. A. Ali *et al.*, Heavy Quarks in e^+e^- Annihilation, Nucl. Phys. B **168**, 409 (1980)
93. T. Meyer (Wisconsin group in TASSO) had added the signatures of heavy quark decays to the Monte Carlo program of references [87,88]
94. MARK-J Coll., A Measurement of $e^+e^- \to$ hadrons at $\sqrt{s} = 27.4$ GeV (presented by J.G. Branson), *Proc. Int. Conf. on High Energy Phys.* (European Physical Society, Geneva, 27 June - 4 July 1979), Vol. 1, p. 325
95. PLUTO Coll., Results from PLUTO at PETRA (presented by V. Blobel), *Proc. Int. Conf. on High Energy Phys.* (European Physical Society, Geneva, 27 June - 4 July 1979), p. 43
96. D. Lüke, P. Mättig, P.M. Zerwas, *Gluon jets at PETRA*, internal note (1995)
97. W. Bartel *et al.* (JADE Coll.), Differential Three-Jet Cross Section in e^+e^- Annihilation and Comparison with Second-Order Predictions of QCD, Phys. Lett. B **119**, 239 (1982)
98. W. Bartel *et al.* (JADE Coll.), Experimental Studies on Multijet Production in e^+e^- Annihilation at PETRA Energies, Z. Phys. C **33**, 23 (1986)
99. An update of the TASSO work was shown by P. Schmüser, presentation in the open session of the DESY Physics Research Committee, July 31, 1979
100. JADE Coll., First Results from JADE (presented by S. Orito), *Proc. 9th Int. Symposium on Lepton and Photon Interactions at High Energies* (Fermi National Accelerator Lab. FNAL, Batavia, Ill, August 1979), p. 52
101. MARK-J Coll., The First Year of MARK-J at PETRA (presented by H. Newman), *Proc. 9th Int. Symposium on Lepton and Photon Interactions at High Energies* (Fermi National Accelerator Lab. FNAL, Batavia, Ill, August 1979), p. 3

102. PLUTO Coll., Results from the PLUTO Experiment on e^+e^- Reactions at High Energies (presented by Ch. Berger), *Proc. 9th Int. Symposium on Lepton and Photon Interactions at High Energies* (Fermi National Accelerator Lab. FNAL, Batavia, Ill, August 1979), p. 19
103. TASSO Coll., TASSO Results on e^+e^- Annihilation between 13 and 31.6 GeV and Evidence for Three-Jet Events (presented by G. Wolf), *Proc. 9th Int. Symposium on Lepton and Photon Interactions at High Energies* (Fermi National Accelerator Lab. FNAL, Batavia, Ill, August 1979), p. 343
104. H. Harari, Theoretical Interpretation of e^+e^- Results, *Proc. 9th Int. Symposium on Lepton and Photon Interactions at High Energies* (Fermi National Accelerator Lab. FNAL, Batavia, Ill, August 1979), p. 198
105. R. Brandelik *et al.* (TASSO Coll.), Evidence for Planar Events in e^+e^- Annihilation at High Energies, Phys. Lett. B **86**, 243 (1979)
106. D.P. Barber *et al.* (MARK-J Coll.), Discovery of Three-Jet Events and a Test of Quantum Chromodynamics at PETRA, Phys. Rev. Lett. **43**, 830 (1979)
107. Ch. Berger *et al.* (PLUTO Coll.), Evidence for Gluon Bremsstrahlung in e^+e^- Annihilations at High Energies, Phys. Lett. B **86**, 418 (1979)
108. W. Bartel *et al.* (JADE Coll.), Observation of Planar Three-Jet Events in e^+e^- Annihilation and Evidence for Gluon Bremsstrahlung, Phys. Lett. B **91**, 142 (1980)
109. Michael Riordan, *The Hunting of the Quark* (Simon & Schuster, New York 1987), p. 351 ff
110. R. Brandelik *et al.* (TASSO Coll.), Evidence for a Spin-1 Gluon in Three-Jet Events, Phys. Lett. B **97**, 453 (1980)
111. Ch. Berger *et al.* (PLUTO Coll.), A Study of Multi-Jet Events in e^+e^- Annihilation, Phys. Lett. B **97**, 459 (1980)
112. H.J. Behrend *et al.* (CELLO Coll.), Topology of Hadronic e^+e^- Annihilation Events at 22 and 34 GeV CM Energy, Phys. Lett. B **110**, 329 (1982)
113. W. Bartel *et al.* (JADE Coll.), Experimental Study of Jets in Electron-Positron Annihilation, Phys. Lett. B **101**, 129 (1981)
114. B. Andersson, G. Gustafson, T. Sjöstrand, A Three-Dimensional Model for Quark and Gluon Jets, Z. Phys. C **6**, 235 (1980)
115. B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand, Parton Fragmentation and String Dynamics, Phys. Rep. **97**, 31 (1983)
116. G. Marchesini, B.R. Webber, Simulation of QCD Jets Including Soft Gluon Interference, Nucl. Phys. B **238**, 1 (1984)
117. B.R. Webber, A QCD Model for Jet Fragmentation Including Soft Gluon Interference, Nucl. Phys. B **238**, 492 (1984)
118. A. Ali, F. Barreiro, Jets in e^+e^- Annihilation and QCD, *High Energy Electron-Positron Physics*, edited by A. Ali, P. Söding (World Scientific, Singapore, 1988), p. 612
119. W. Bartel *et al.* (JADE Coll.), Differential Three-Jet Cross Section in e^+e^- Annihilation and Comparison with Second-Order Predictions of QCD and Abelian Vector Theory, Phys. Lett. B **119**, 239 (1982)
120. K. Fabricius, I. Schmitt, G. Schierholz, G. Kramer, Order α_S^2 Correction to Jet Cross Sections in e^+e^- Annihilation, Phys. Lett. B **97**, 431 (1981)
121. Ch. Berger *et al.* (PLUTO Coll.), A Study of Energy-Energy Correlations in e^+e^- Annihilations at $\sqrt{s} = 34.6$ GeV, Z. Phys. C **28**, 365 (1985)
122. B. Adeva *et al.* (MARK-J Coll.), Model-Independent Second-Order Determination of the Strong Coupling Constant α_S, Phys. Rev. Lett. **50**, 2051 (1983)
123. A. Ali, E. Pietarinen, G. Kramer, J. Willrodt, A QCD Analysis of the High Energy e^+e^- Data from PETRA, Phys. Lett. B **93**, 155 (1980)
124. R.K. Ellis, D.A. Ross, A.E. Terrano, Calculation of Event-Shape Parameters in e^+e^- Annihilation, Phys. Rev. Lett. **45**, 1226 (1980)
125. A. Ali, F. Barreiro, An $O(\alpha_S)^2$ Calculation of Energy-Energy Correlation in e^+e^- Annihilation and Comparison with Experimental Data, Phys. Lett. B **118**, 155 (1982)
126. W. Bartel *et al.* (JADE Coll.), Observation of Four-Jet Structures in e^+e^--Annihilation at $\sqrt{s} = 33$ GeV, Phys. Lett. B **115**, 338 (1982)

127. W. Bartel *et al.*, Experimental Studies on Multijet Production in e^+e^- Annihilation at PETRA Energies, Z. Phys. C **33**, 23 (1986)
128. W. Bartel *et al.* (JADE Coll), Experimental Evidence for Differences in $\langle p_T \rangle$ between Quark Jets and Gluon Jets, Phys. Lett. B **123**, 460 (1983)
129. M. Althoff *et al.* (TASSO Coll.), A Study of 3-Jet Events in e^+e^- Annihilation into Hadrons at 34.6 GeV c.m. Energy, Z. Phys. C **29**, 29 (1985)
130. A. Petersen *et al.* (SLAC-LBL-Berkeley-Harvard Coll.), Inclusive Charged-Particle Distribution in Nearly Threefold-Symmetric Three-Jet Events at $E_{c.m.} = 29$ GeV, Phys. Rev. Lett. **55**, 1954 (1985)
131. B.H. Wiik, New e^+e^- Physics; *XX Int. Conf. on High Energy Physics–1980*, American Institute of Physics Conference Proceedings **68**, 1379 (1981)
132. J. Ellis, Gluons, Comm. Nucl. Part. Phys. **9**, 153 (1981)
133. P. Söding, G. Wolf, Experimental Evidence on QCD, Ann. Rev. Nucl. Part. Sci. **31**, 231 (1981)
134. P. Söding, Evidence on the Gluon; *Particles and Fields 1981: Testing the Standard Model*, American Institute of Physics Conference Proceedings **81**, 107 (1982)
135. L. Criegee, G. Knies, e^+e^- Physics with the PLUTO detector, Phys. Rep. **83**, 192 (1982)
136. B. Naroska, e^+e^- Physics with the JADE detector at PETRA, Phys. Rep. **148**, 67 (1987)
137. Sau Lan Wu, e^+e^- Interactions at High Energies, *Proc. 1987 Int. Symposium on Lepton and Photon Interactions at High Energies* (Hamburg, 1987), pp. 39–137
138. A. Ali, P. Söding (Eds.), *High Energy Electron-Positron Physics* (World Scientific, Singapore, 1988)
139. S. Bethke *et al.* (JADE Coll.), Experimental Investigation of the Energy Dependence of the Strong Coupling Strength, Phys. Lett. B **213**, 235 (1988)
140. S. Bethke, The 2009 World Average of α_S, Eur. Phys. J. C **64**, 689 (2009)
141. S. Bethke, QCD Studies at LEP, Phys. Rep. **403-404**, 203 (2004)
142. M. Bengtsson, P.M. Zerwas, Four-Jet Events in e^+e^- Annihilation: Testing the Three-Gluon Vertex, Phys. Lett. B **208**, 306 (1988)
143. The MARK J Coll., Physics with High Energy Electron-Positron Colliding Beams with the MARK J Detector, Phys. Rep. **63**, 337 (1980)
144. P. Duinker, D. Luckey, In Search of Gluons, Comm. Nucl. Part. Phys. **9**, 123 (1981)
145. The MARK J Coll. (B. Adeva *et al.*), A Summary of Experimental Results from MARK J: High Energy e^+e^- Collisions at PETRA, Phys. Rep. **109**, 131 (1984)
146. J.G. Branson, Gluon Jets, *Int. Conf. on the History of Original Ideas and Basic Discoveries in Particle Physics*, Erice, July 1994, Gluon Jets, UCSD/PTH 9509 (1995)
147. Letters to the Editor, CERN Courier **49** Nr. 8, October 2009, p. 29, http://cerncourier.com/cws/article/cern/40428/2
148. European Physical Society, Press Release, Geneva, June 27, 1995
149. D.P. Barber *et al.* (MARK-J Coll.), Test of Quantum Chromodynamics and a Direct Measurement of the Strong Coupling Constant α_S at $\sqrt{s} = 30$ GeV, Phys. Lett. B **89**, 139 (1979)