1995 EPS HEPP PRIZE - SPECIAL EPS PRIZE

Gluon Discovery Honoured

The 1995 EPS High Energy and Particle Physics (HEPP) Prize has been awarded to **Paul Söding**, *DESY-Institute of High-Energy Physics, Zeuthen*, **Björn Wiik** and **Günther Wolf**, *Deutsches Elektronen-Synchrotron (DESY), Hamburg*, and **Sau Lan Wu**, *University of Wisconsin, Madison, WI, USA*, for the first evidence for three-jet events in e^+e^- collisions at DESY's PETRA collider while working with the TASSO Collaboration.

A Special EPS Prize has been awarded by the EPS Executive Committee to the **JADE**, **MARK-J**, **PLUTO**, and **TASSO Collaborations**, *Deutsches Elektronen-Synchrotron (DESY), Hamburg*, each responsible for one of the four detectors initially installed at DESY's PETRA collider whose results independently confirmed the gluon's existence.

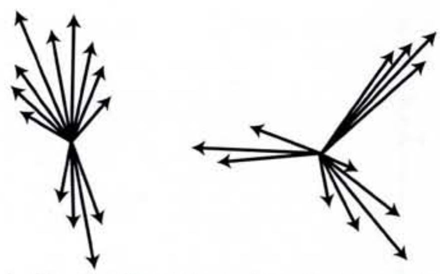

Fig. 1 - Illustrations showing the narrow bundles (jets) of particles with unusual topologies produced in the fragmentation of a quark-antiquark pair and a gluon. Left: jet broadening; right: three-jet event.

The strong interaction, the most powerful force we know, binds together the quarks from which protons, neutrons and all other fundamental particles are made. It is so strong that it is impossible to produce a single, unbounded quark or antiquark (the quarks and antiquarks are "glued"). Field theory tells us that all forces are transmitted by carrier particles, called gauge bosons, such as the photon for the electromagnetic force and the massless gluon for the strong force. Whereas photons can travel throughout the whole of space, gluons are only able to move within a region 10^{-15} m in radius — the typical size of protons and neutrons, the building blocks of Nature.

The 1995 HEPP Prize was awarded by the EPS HEPP Division to four individuals working with TASSO Collaboration at DESY, Hamburg for "the first evidence of three-jet events at PETRA". This contribution stimulated an enormous analytical effort by all four PETRA Collaborations that led to the confirmation of the gluon's existence in several independent ways. The Special Prize awarded by the Executive Committee of EPS to the four Collaborations acknowledges this major contribution.

Jets Identified

It was a US group from the Stanford Linear Accelerator Center and the Lawrence Berkeley Laboratory which first showed that for e^+e^- annihilation in the 3-7.4 GeV energy range, the final-state hadrons (particles with the strong interaction) emitted in collisions organize themselves into two preferred directions, *i.e.*, into two bundles of particles called jets (Fig. 1). This phenomena could be seen as a decrease of sphericity S with increasing energy as the jet structure became more pronounced [*Phys. Rev. Lett.* **35** (1975) 1609], where sphericity, defined as $S = (3/2) \min \Sigma p_T^2 / \Sigma p^2$, is essentially the sum of the transverse momenta p_T of particles measured relative to an event axis which is varied in order to minimize S.

The PLUTO Collaboration at DESY's DORIS accelerator subsequently extended this analysis to 9.5 GeV. Fragmentation models describing how the primary partons (quarks) transformed into jets of hadrons were now available, and the Collaboration showed that jet axes defined by either charged or neutral particles were the same. As a function of the scattering angle θ, the jets followed a $(1 + \cos^2\theta)$ distribution associated with the spin-1/2 of the quarks.

PETRA

PETRA is the name of the 2.3 km storage ring at DESY which, under the leadership G.A. Voss, started to operate at 13 GeV in the centre-of-mass in November 1978, increasing in energy to 27 GeV in the spring of 1979. Four experiments were installed in the initial phase: JADE, PLUTO, MARK-J, and TASSO. German government approval for constructing PETRA was obtained while H. Schopper was Chairman of the DESY Directorate.

Search Underway

The deep-inelastic scattering experiments at SLAC in the late-1960s (recognized by the 1990 Nobel Prize in Physics) and the identification of partons with quarks together with subsequent neutrino scattering experiments led one to expect that the structure-function integral describing the momentum distribution of the quarks should equal unity, *i.e.*,

$$(18/5) \int F_2^{eN}(x)\, dx = \int F_2^{\nu N}(x)\, dx \approx 1,$$

since the total fractional momentum summed over all constituents is unity (F_2^{eN} and $F_2^{\nu N}$ are the structure factors for electron-nucleon and neutrino-nucleon scattering, respectively). But it turned out that the contribution from lepton scattering *via* the leptons' electric and weak charges only accounted for one-half of the observed momentum. So it was known that quarks did not carry all of the momentum of the proton in which they were imprisoned, and the existence of another type of constituent besides the quarks, namely gluons, was postulated. J.G.H. de Groot *et al.* [*Phys. Lett. B* **82** (1979) 292 and 456] then demonstrated excellent agreement between data on high-energy neutrino interactions and QCD predictions for the structure functions F_2 and F_3 based on the gluon hypothesis (see Fig. 2).

The search for gluons, the proposed mediators of the strong interaction, was begun in 1979 by PLUTO using data from DESY's DORIS collider taken around the ypsilon resonances, where the predicted three-gluon decay of the spin-1 bound states of b-bbar should be different from the quark-antiquark final state of the continuum. However, the final state here had a collision energy of only 10 GeV to share among the final-state particles, so the jets of hadrons were not easily visible.

Theory Gave Some Guidance

Gluons are required in any field theory for the strong interaction, and quantum chromodynamics (QCD) predicts gluon emission by one of the quarks (bremsstrahlung) analogous to photon emission by electrons in the field theory of quantum electrodynamics. It was therefore well-known before PETRA experiments that QCD predicted an increase of gluon bremsstrahlung at high energy [see, *e.g.*, J. Ellis *et al.*, *Nucl. Phys. B* **111** (1976) 253; A. De Rujula *et al.*, *ibid* **138** (1978) 387]. Ellis *et al.* in fact proposed that gluons should manifest themselves as jets, and that planar events and even three-jet topologies (illustrated in Fig. 1) should be observable at the higher energies which would be available. However, the formation of three-jet events was regarded as very speculative at the time. It was not understood how gluons would fragment, a first assumption being that gluons would reveal themselves by generating jets of particles not very different from those for quarks.

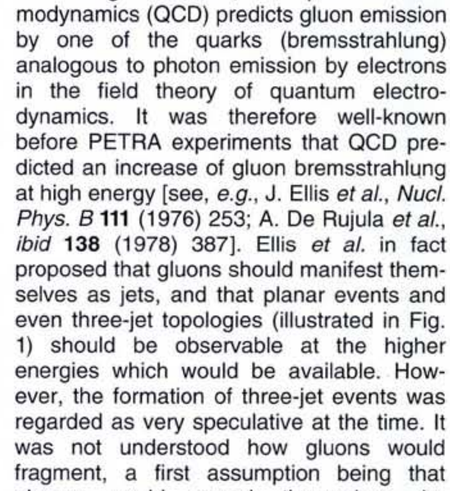

Fig. 2 - The total fractional momentum of all nucleon constituents as a function of the momentum transfer squared for neutrino scattering as obtained from QCD fits to the structure functions F_2 and F_3. It can be seen that the gluons carry more than 50% of the momentum.

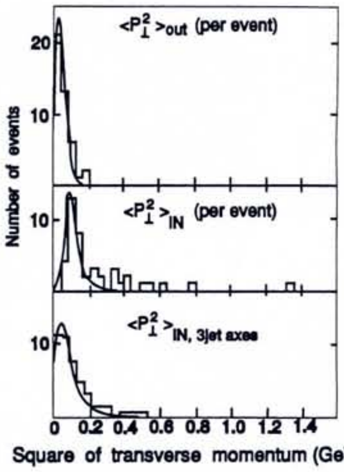

Fig. 3 - Histograms of the number of events plotted as a function of the square of the transverse momentum P_T for momentum components perpendicular to ("out") and in the plane of ("in") the event plane for e^+e^--collisions at PETRA as reported by the TASSO Collaboration in June 1979. The results (curves) of Monte Carlo simulations assuming only two-jet events accurately predicted the "out" distribution (top panel) but not the "in" distribution (middle panel). For the latter one needed three-jet events (bottom panel) for an accurate prediction.

In the summer of 1978 G. Wolf, in describing the PETRA's programme at a summer school at Les Houches, pointed out that going further up in energy was of great interest because one can then "*differentiate between the 'naive' jet picture, whereby jet members have a fixed transverse momentum with respect to the jet axis, from expectations based on QCD according to which gluon emission leads to a widening of the jet with increasing centre-of-mass energy*".

A Photofinish

PETRA was commissioned very quickly under the supervision of Gustav-Adolf Voss and gave, in the early summer of 1979, sufficient luminosity at high energy to supply experiments with data on the production of hadrons. The bulk of the hadronic events showed the typical two-jet pattern manifesting quark-antiquark pair production. At the higher PETRA energies, the jets became more collimated than at lower energies and were fairly easy to see. This allowed a more efficient study of jet broadening as well as a search for three-jet patterns that would provide direct evidence for gluon emission by one of the quarks. However, since the energy region opened up a few years earlier by SLAC's SPEAR and DESY's DORIS colliders had shown so many surprises, attention was focussed more on possible new discoveries (*e.g.*, toponium, open-top production, new charge-1/3 quarks, heavy leptons) as anything could reveal itself in the vast energy region which was now accessible.

The four Collaborations lined up in the race to be first to find evidence for new phenomena. PLUTO had a certain advantage at the start since the apparatus had been running at DORIS and was already well tested. MARK-J and JADE had a more complete coverage than TASSO, including neutral-particle detection capabilities, but one needed to understand fully how their calorimeters worked. The TASSO Collaboration was still in the process of completing the calorimeter and hadron identification systems. In order to have an early start, the detector had been moved into the beams with only the tracking and triggering systems operational and TASSO could therefore concentrate on charged-particle detection. Novel methods for topology analysis were developed by groups working with all four detectors, and one had to get used to words such as sphericity, triplicity, thrust, planarity, aplanarity, oblateness, and the JADE jet-finding algorithm.

All four Collaborations reported data at the 1979 *Lepton-Photon Conference* (held at the Fermi National Accelerator Laboratory, USA) at the end of August 1979 showing convincing independent evidence for an admixture of planar-event topologies which fitted well to a three-jet topology (presentations were made by S. Orito for JADE, H.B. Newman for MARK-J, Ch. Berger for PLUTO, and G. Wolf for TASSO). A session summary by E. Lohrmann stressed the deviation from rotational symmetry around the jet axis at the highest PETRA energy, *i.e.*, a developing planar structure, as evidence for gluon bremsstrahlung.

While all four Collaborations were very close in obtaining and evaluating data, TASSO was able to report interesting results in June 1979. It had developed early on a method to analyze three-jet events [Wu & Zobernig] along with Monte Carlo models to simulate the hadronization effects of the quarks and gluons. It became clear that the effects of QCD were large — energy was more important than statistics — and as soon as PETRA reached energies well above 20 GeV in the centre of mass, TASSO immediately saw the footprints of QCD in its data.

The TASSO Collaboration disclosed results indicating planar events in June 1979 at conferences in Bergen (presented by B. Wiik) and Geneva (presented by P. Söding) which were confirmed on the basis of improved statistics at the Fermilab conference. Analyses of the planar events demonstrated that they could not be fitted with only two jets: one of the jets was broader than the other indicating an abnormal transverse momentum structure in the event plane. The evidence, referring mainly to the tail of the distribution of the square of the transverse momentum P_T, which was presented in Geneva is shown in Fig. 3. On the other hand, selected planar events could be accurately fitted by three-jet axes, where all jets now showed similar and normal fragmentation behaviour. TASSO submitted a publication detailing the work on 29 August [*Phys. Lett. B* **86** (1979) 243], slightly before the other collaborations submitted their own reports. It described a planar event rate "*which is well above the rate computed for statistical fluctuations of q-qbar jets. The planar events exhibit three axes, the average transverse momentum of the hadrons with respect to these axes being 0.30 GeV/c... The data are most naturally explained by hard noncollinear bremsstrahlung...* (of gluons)".

The early data clearly suffered from low statistics, and subsequent textbook representations of hard gluon emission in clear-cut events with well-separated jets did not accumulate very rapidly. Nonetheless, the first such events indicating a well-resolved three-jet topology stimulated much interest.

Since the amount of data reported in the first presentations was limited it was very important to see if an unusual topology could be produced in simulations of two-jet events. So the rather sophisticated analyses of jet broadening carried out from the beginning by the Collaboration represented an important step. The planarity of the events clearly pointed to an underlying three-particle process, but careful Monte Carlo calculations were needed to rule out the possibility that these topologies could be faked by, for instance, heavy-quark decays. Such calculations were included in the early TASSO analyses (and eventually by all the Collaborations in their analyses). The 1995 HEPP Prize acknowledges TASSO's careful study of planar events. The special Prize honours the four Collaborations' major ongoing efforts.

Understanding the Strong Interaction

At the 1978 Les Houches summer school, B. Wiik in a talk on the PETRA experiments, when touching upon the issue of QCD, pointed out that observing three-jet events did not prove QCD since such a feature arose in any field theory of the strong interaction. To test QCD additional information was required about the gluon, namely its vector nature (spin 1), flavour, and non-abelian nature (*i.e.*, the existence of gluon-gluon coupling). His best bet at the time for such studies were top-antitop resonances (so-called toponium), where one hoped for the existence of sufficiently heavy toponium giving clear jet signatures in the decays.

It turned out that the decays of the ypsilon states were difficult to analyze, and that toponium did not show up. So it took some time before ypsilon decays could be used to demonstrate the gluon, and indeed the vector nature of the gluon [PLUTO Collaboration, *Phys. Lett B.* **88** (1979) 119 & *DESY Rep.* **80-117** (1980); LENA Collaboration, *DESY Rep.* **81-008** (1981)]. Among the PETRA experiments, TASSO and PLUTO both presented evidence for the vector nature of the gluon [*Phys. Lett. B* **97** (1980) 453, 459 respectively]. The gluon self-coupling, showing the gluon's non-abelian nature, was much harder to observe and required another energy upgrade, in fact another collider, namely CERN's LEP machine that started taking data in 1989.

G. Jarlskog, *Chairman, HEPP Division*

FURTHER READING

"Experimental evidence on QCD" by P. Söding & G. Wolf, *Ann. Rev. of Nucl. & Particle Science* **31** (1981).

"Review of e^+e^- physics at PETRA" by P. Duinker, *Rev. Mod. Phys.* **54** (1982).

"e^+e^- physics at PETRA - The first five years" by Sau Lan Wu, *Phys. Rep.* **107** (1984).