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GLUON JETS[1]

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Abstract

In 1979, the electron positron collider PETRA attained center of mass energies of around 30 GeV, three times higher than any previous e^+e^- machine. The physicists in the four PETRA experiments observed the phenomena of jet broadening and of three jet events soon after the first data were collected in this high energy range. Jet broadening and three jet events had been predicted, to some extent, by theorists in papers published in the previous year. Some theorists pointed out the importance of separating jet broadening due to gluon emission from the effect of massive b quark (and potentially t quark) production and decay. To prove that hard gluon emission in quark pair production was the correct explanation for their observations, the experimenters compared their results to models based on QCD.

There has been a good deal of controversy concerning priority in the identification of jets from gluon emission. In this paper, I will analyze the 1979 papers of the four PETRA experiments on these topics. I will stick to the published record and avoid adding after the fact analyses. While conference reports will be quoted, it is critical to evaluate them in the light of what the experiments put into subsequent publications. In any case, the speed with which these results were obtained indicates that a good deal of the credit for them should go to those who built the accelerator and promptly produced the high energy beam-beam collisions used by the experimenters.

1 INTRODUCTION

Scaling, in deep inelastic scattering [1] of electrons from protons, showed that the proton was composed of quarks that behaved very much like free particles at high energy. This was understood in QCD, the SU(3) Yang-Mills theory of the strong interactions, to be due to "Asymptotic Freedom": the weakening of the coupling constant as the energy

[1]Invited Talk at the International Conference on the History of Basic Dicoveries and Original Ideas in Particle Physics, Erice, Siciliy, July 1994

scale is increased. The scaling data showed that only approximately half of the proton's momentum was carried by the charged quarks. In QCD, the remainder could be attributed to the neutral gluons inside the proton.

Further measurements of deep inelastic scattering by the CERN bubble chamber [2] group and by CDHS [3] confirmed the predictions of QCD in the moments of the cross sections. These tested QCD quantitatively and determined that the scale parameter Λ_{QCD} was about 0.5 GeV.

In the meantime, the MARK-1 group at SPEAR showed that the quarks, pair produced in electron positron reactions, began to appear as jets [4] of hadrons. This indicated that, not only do quarks exist, but we can see their effects on the shape of the events through the formation of jets. They used the variable sphericity (S) to measure how well the particles in an event were distributed along an event axis. Sphericity is defined as

$$S = \frac{3}{2}\frac{\min \sum P_{\perp}^2}{\sum P^2}$$

where the summed transverse momentum of particles is measured relative to an event axis which is varied to minimize the sphericity. Sphericity approaches zero for a two-jet-like event and one for a spherically symmetric momentum distribution. In Figure 1 the mean sphericity is plotted versus the center of mass energy. While production of particles according to a phase space distribution predicted an increasing mean sphericity $< S >$ with center of mass energy, the measured distribution gave $< S >$ values that fell sharply over the SPEAR energy range. It is actually the leveling off of this precipitous fall that was later detected at PETRA.

2 Predictions from Theory

Just before PETRA began to run, theorists calculated what they would expect, from QCD, for jets from high energy electron positron collisions. De Rujula et al. [5] showed that gluon emission should cause events to spread out into a planar configuration. Figure 2 shows their expectation for the energy flow in events of different thrusts T. Thrust is defined as the maximum total momentum parallel to an event axis divided by the total momentum,

$$T = \frac{\max \sum P_{\parallel}}{\sum P},$$

where the event axis is varied to find the maximum. Thust approaches 1.0 for for a very two-jet-like event and 0.5 for a spherically symmetric energy distribution. These authors

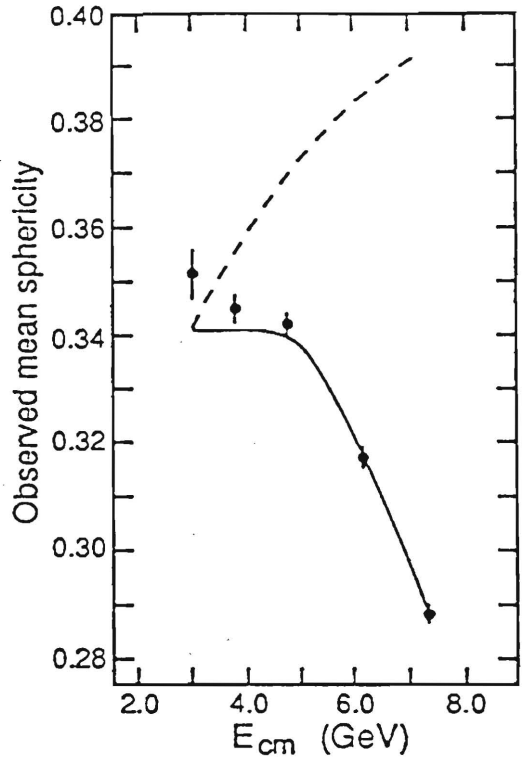

Figure 1: **MARK-1:** Observed mean sphericity versus center-of-mass energy E_{cm} for data, a two jet model with $\langle P_\perp \rangle = 315$ MeV/c (solid curve), and a phase-space model (dashed curve).

chose thrust over sphericity because it is "infrared safe". That is, the thrust is unchanged if a one particle is split into two particles with the same total momentum. Sphericity, since it depends on the square of momentum, is not infrared safe and therefore depends on very soft processes not calculable in perturbative QCD.

Ali et al. [6] showed that the cascade decays of heavy quarks could give rise to broader events than expected in simple two jet models. Since PETRA was the first accelerator where b-quark jets could be observed, these had to be understood in terms of possible sources of new phenomena. Also new heavier flavors could certainly produce events with many quark jets from weak decays. In the early days of PETRA, top quarks with unusual decays, scalar quarks, and many other more exotic possibilities had not yet been excluded. They concluded, "Our calculations show that, for energies as high as the endpoint PETRA energy, the jet broadening phenomenon due to the production and weak decay of bottom and top quarks is at least as important as the QCD process $e^+e^- \to q\bar{q}g$."

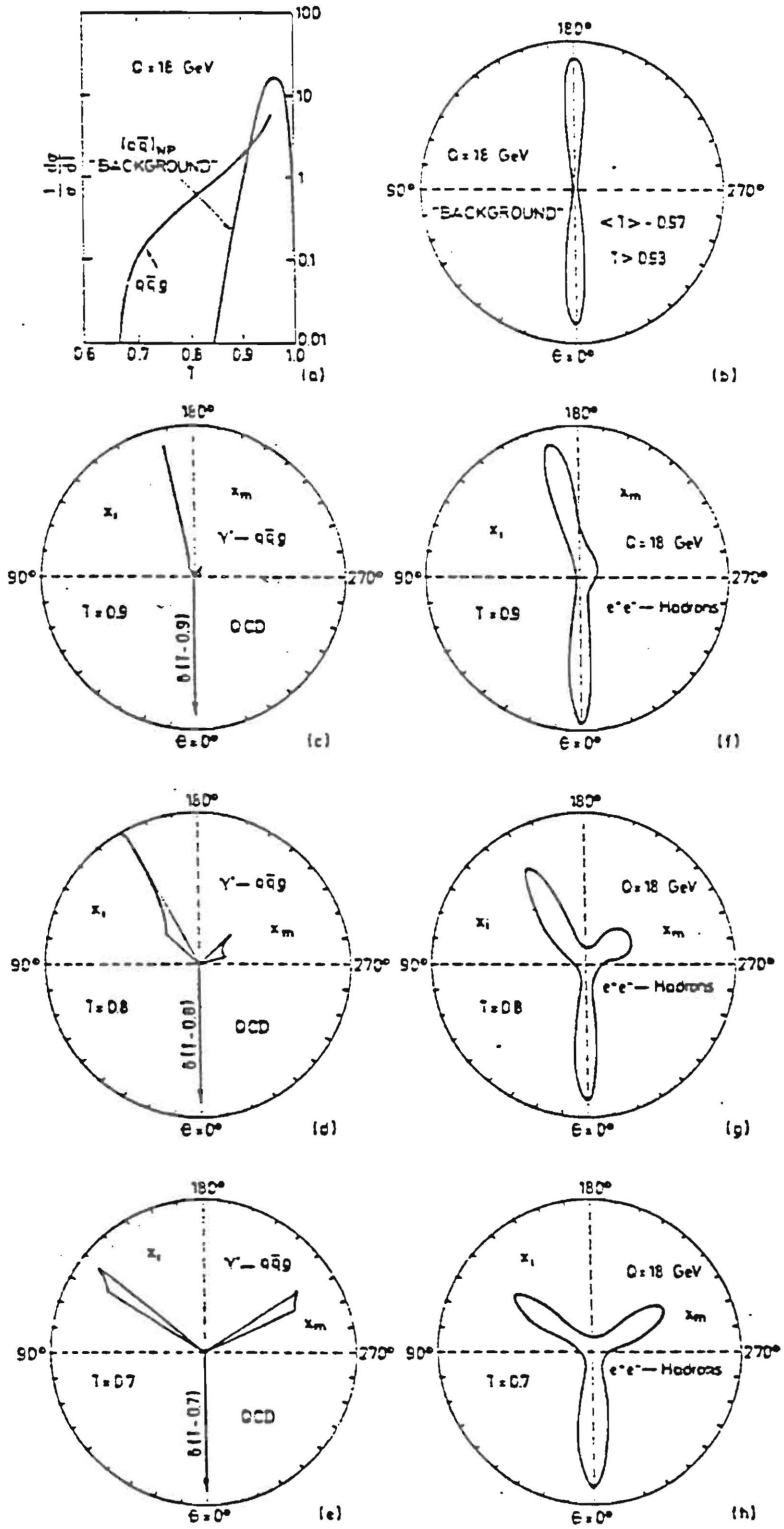

Figure 2: **DeRujula et al.:** Energy flow cross sections for $q\bar{q}g$ jets and background $q\bar{q}$ jets, with or without smoothing for infra-red effects.

In addition to the studies above, two groups produced Monte Carlo generators based on perturbative QCD. The generator of Hoyer et al. [7] was used for the earliest studies described below. The experimental groups enhanced this generator by including some heavy meson decays. Ali et al. [8] produced another complete Monte Carlo program which was used by many because it included additional important effects, such as the q^2 evolution of the fragmentation function and the process $e^+e^- \rightarrow q\bar{q}gg$. Both of the above were based on perturbative QCD plus Feynman-Field [9] fragmentation of two, three or four final state partons.

3 The Geneva EPS Conference

By the summer of 1979, PETRA had collected data at 13 and 17 GeV and was running at 27.4 GeV. DORIS had been running for some time at the Υ. At the EPS conference (June 27- July 4) S. Brandt showed a PLUTO comparison [10] of thrust, triplicity, two jet energies and two jet angles for events from Υ decays and from the continuum. Triplicity (T_3) is a thrust-like variable in which the momentum parallel to three jet axes is maximized. The jet energies and angles were obtained from this triplicity analysis. The data, on and off resonance, were compared to Feynman-Field fragmentation, phase space, and a model with three gluon decay of the Υ. Figure 3 shows the PLUTO distributions. The distinction of the Υ data from the phase space prediction is fairly clear. This was a rather sophisticated analysis of the data, with good statistics. The data are in reasonable agreement with the three gluon decay model although, at that energy, effects of resonances in the decays of the Υ were hard to calculate.

At the same conference, P. Söding showed an early analysis [11] of the high energy TASSO data. A similar presentation [12] of the TASSO data was made by B. Wiik at the Bergen conference. Söding showed several distributions indicating broader than expected jets. Figure 4 shows the so called seagull effect in which the average $P_\perp^2$ of particles relative to the sphericity axis is plotted versus $z = \frac{P}{P_{beam}}$. The plot resembles a seagull when the narrow jet and wide jet are shown on two halves of the graph. The comparison with models shows that this effect can be fit with a QCD model. Figure 5 shows three more detailed differential distributions. We see that in the event plane, the $P_\perp^2$ relative to the sphericity axis of the event is larger than predicted by the Feynman-Field model (with a fixed transverse momentum distribution), while the $P_\perp^2$ perpendicular to the event plane is consistent with that model. The event plane has been chosen to maximize the momentum in the plane so that jet broadening must show up first there, because the number of measured particles is too small to provide cylindrical symmetry

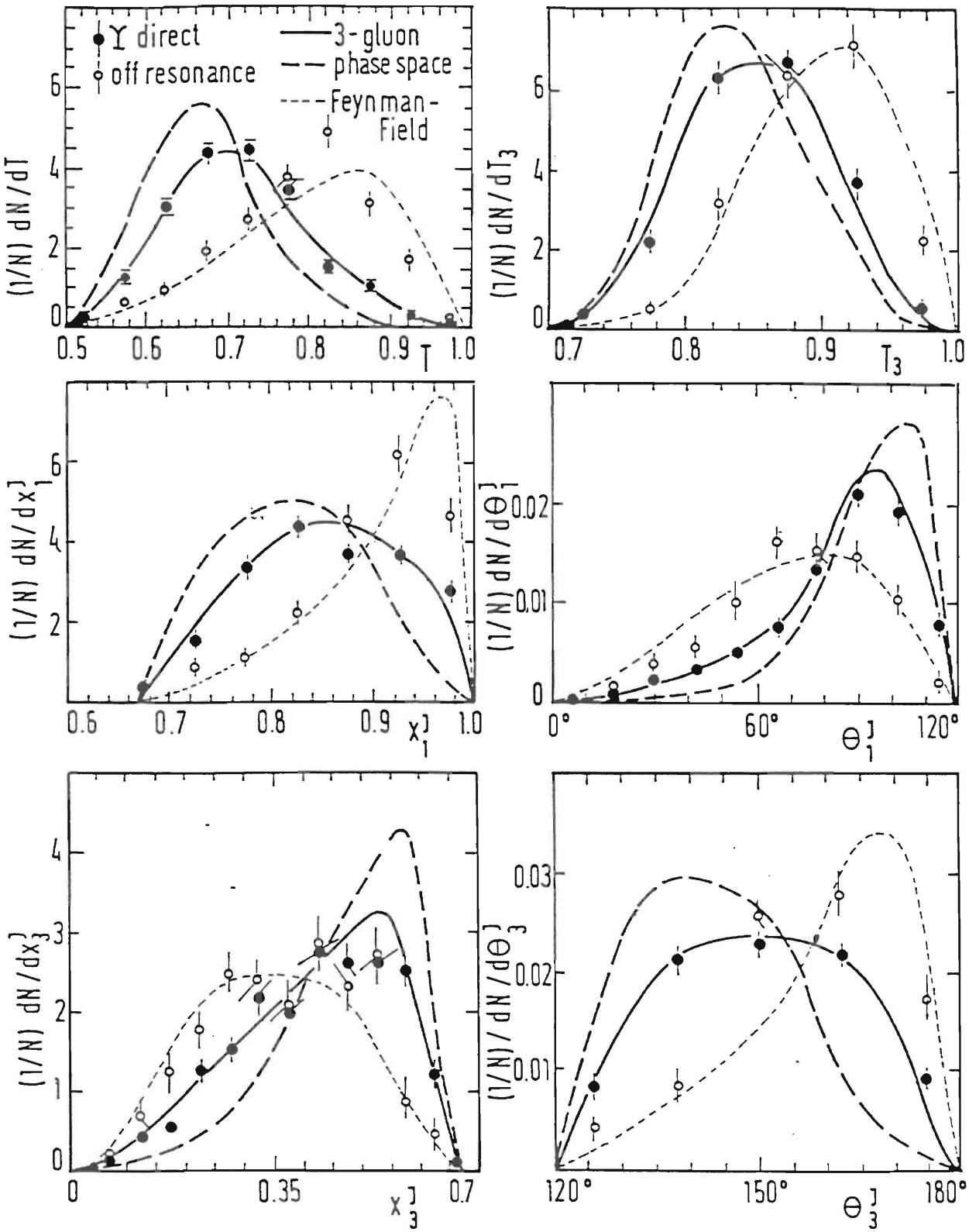

Figure 3: **PLUTO:** Experimental distributions of thrust T, triplicity T_3 reconstructed gluon energies x_1^J, x_3^J and reconstructed angles θ_1^J, θ_3^J between gluons compared to Monte-Carlo calculations based on various models.

(due to statistical fluctuations in $P_\perp^2$). The last part of the figure shows the average $P_\perp^2$ relative to three jet axes where the axes have been chosen to minimize this quantity. We expect three jet events to have lower $P_\perp^2$ relative to three axes; but we also expect the free choice of three axes to lower the $P_\perp^2$ for any type of broadening.

An important weakness of the presentation in this figure is that there is no quantitative comparison to QCD. It is very hard to determine what the source of event broadening is. Another important, but unavoidable, weakness is the very small number of events analyzed. There are, in total, less than 50 hadron events in these distributions and only a handful of these are broad events. We will see from later TASSO papers, that an increase in the fragmentation transverse momentum brings the simple $q\bar{q}$ fragmentation model into much better agreement with these data.

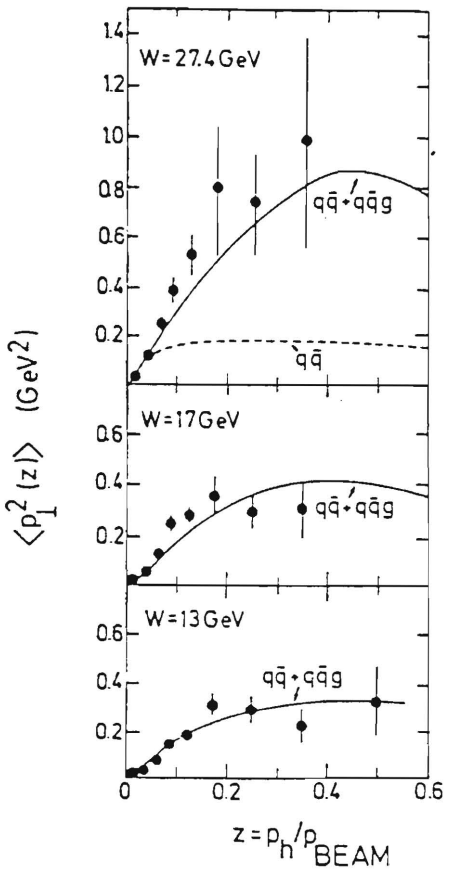

Figure 4: **TASSO:** Mean square transverse momentum of the charged hadrons with respect to the jet axis $\langle P_\perp \rangle$, as a function of the fractional hadron momentum z, at different total e^+e^- cms energies W.

Four events from TASSO which, as quoted by Söding "have topologies suggesting

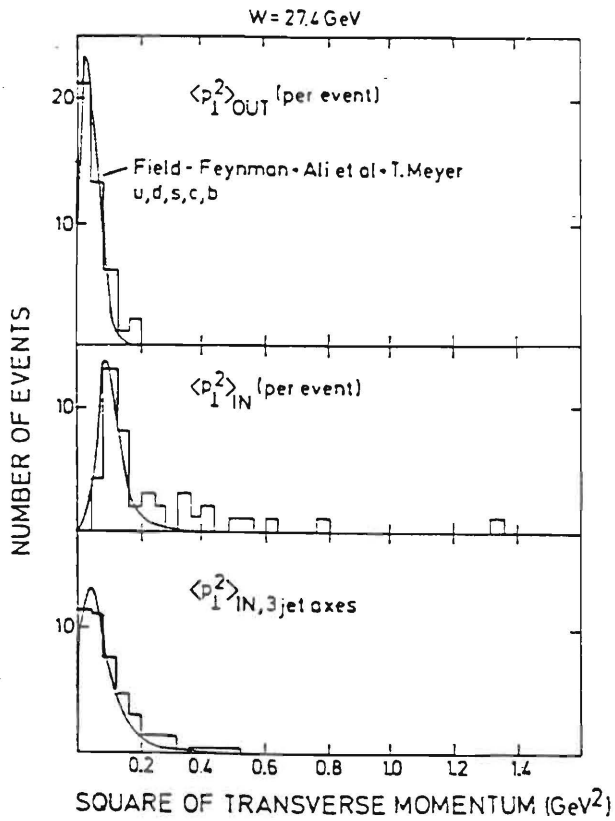

Figure 5: **TASSO:** Distribution of the average squared transverse momentum component out of the event plane (top), and in the event plane (center), for events at $W = 27.4$ GeV (averaging over charged hadrons only). The curves are for $q\bar{q}$ jets without gluon bremsstrahlung. Comparison of these distributions gives evidence that broadening (compared to $q\bar{q}$ jets) occurs in one plane. The bottom figure shows $\langle p_\perp^2 \rangle$ per jet when 3 jet axes are fitted, again compared with the model with only q and $\bar{q}$ jets.

deviations from the simple $q\bar{q}$ quark jet picture" also were shown, and are reproduced here in Figure 6. Each solid line in the figure represents the momentum of a charged particle. Note that the dotted lines represent the fitted jet directions (under the assumption that there are three jets) and don't add significance to the figure. In looking closely at these events I see fitted jets that are completely dominated by one particle, and events where a three jet structure is far from obvious. This evidence again suffers from the lack of comparison with models, on a statistical basis. It is hard now, and it was much harder then, to draw conclusions on the source of these diagrammed events.

Figure 7 shows two events measured by the MARK-J experiment, from a run at 12 GeV. The first has an apparent three jet structure while the second is spread out in a plane, with the jet structure looking more like four jets. We know that we should not see three narrow jets at 12 GeV except due to fluctuations in the fragmentation of quarks into jets, and from some heavy quark decays. Therefore it was crucial at the time that

more quantitative evidence be presented. This was of course quite difficult with the small number of events analyzed.

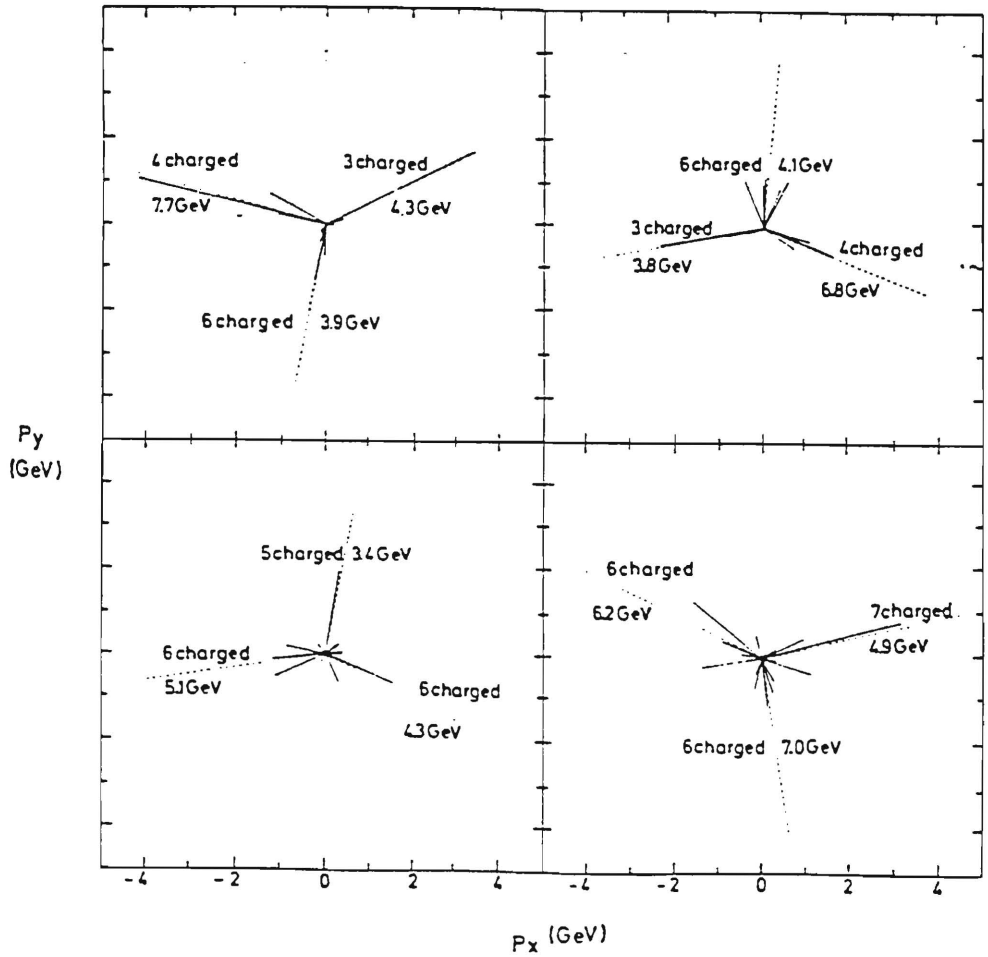

Figure 6: **TASSO:** Four events having topologies suggesting deviations from the simple $q\bar{q}$ quark jet picture, measured at $W = 27.4$ GeV. Plotted are the momentum vectors of the charged particles, projected on the 'event plane'. The events are rotated such that if a single jet axis is fitted, it will point in the x direction. The dotted lines show the directions of the jet axes when three axes are fitted.

Söding did attempt to make a quantitative comparison with the limitted statistics available. Based on the three jet axis analysis, he selected events with more than a 40 degree angle between the two lowest energy jets and with less than a 160 degree angle between the two highest energy jets. He concluded:

> "We find 5 candidates, while the prediction is 9 (assuming 5 flavors and $\Lambda = 0.5$ GeV in the calculation of $\alpha_s(W^2)$). I consider this as good an agreement as can be expected in view of the small statistics, the uncertainty from escaping neutrals, and the high degree of preliminarity of this analysis."

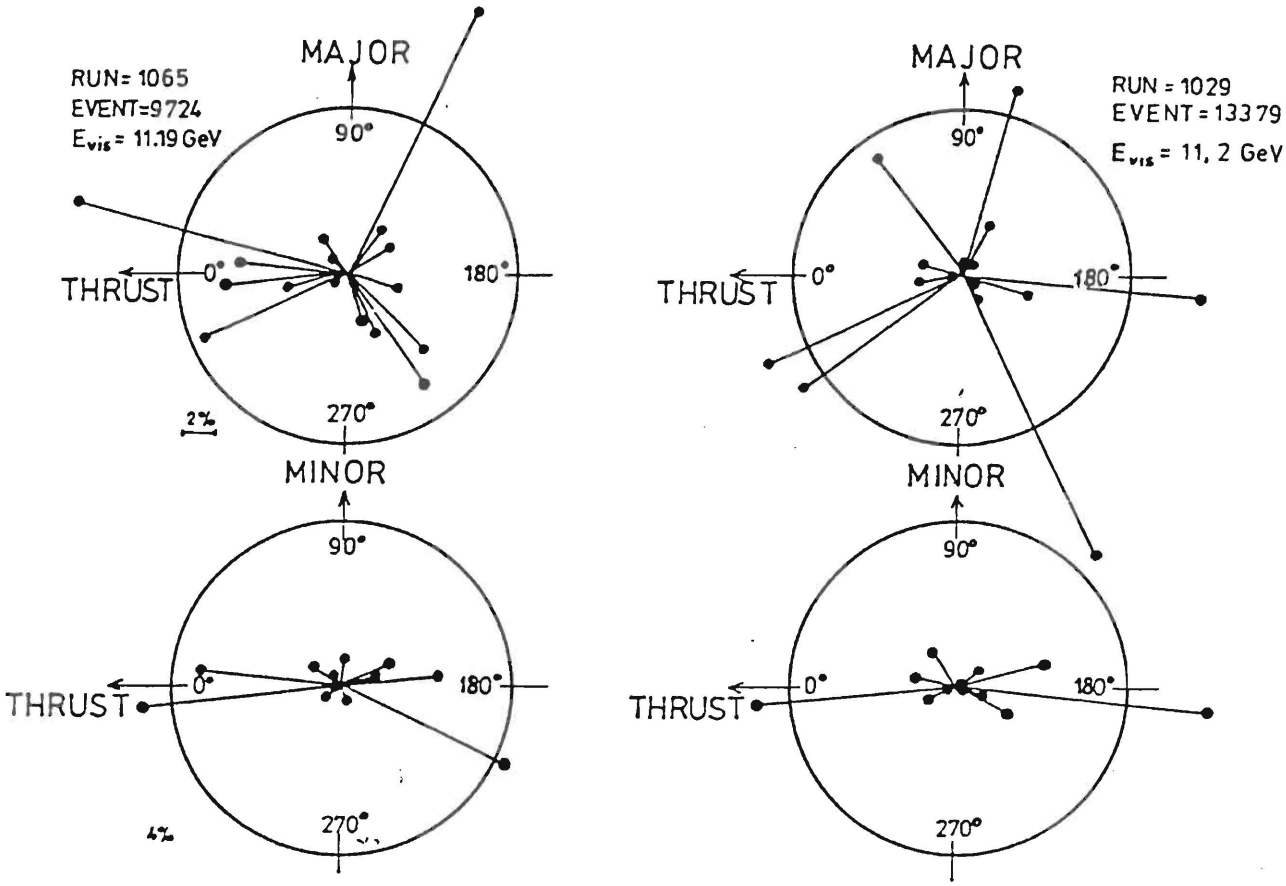

Figure 7: Two events measured by ther MARK-J at $\sqrt{s}$ = 12 GeV, with the lines showing the direction and magnitude of energy deposited in the calorimeter displayed in two projections. The events appear to have a multijet structure in the thrust-major plane. The view in the thrust-minor plane shows the events are flat.

Given the amount of data that TASSO had available at the time, this was a very reasonable conclusion. Quantitative comparisons which rest on the event shapes of five candidates would have been extremely difficult, even after a long careful analysis. **But Söding had convincingly shown that the narrowing of jets as the energy increases, which was first seen at SPEAR, was breaking down at the highest PETRA energies.**

4 The Fermilab Lepton-Photon Conference and Subsequent Papers

PETRA delivered more data quickly, in the ensuing weeks. By the time of the Fermilab conference, August 23-29 1979, each of the experiments had about 500 high energy hadron events. All four of the PETRA experiments (MARK-J, PLUTO, TASSO and JADE) presented results on jet broadening or gluon jets, and a good deal of attention was focused on the PETRA results on this subject. Partially because of this interest, publications were submitted soon after the conference. These publications are the best evidence of the state of the analysis of the experiments and of the confidence in results at that time.

In the case of MARK-J and TASSO, the papers were submitted within days of the conference and were published very rapidly. The MARK-J paper [13] was submitted August 31 and published on September 17. The TASSO paper [14] was submitted on August 29 and published on September 24. I am sure that the timing of these two papers was influenced by the interest at the Lepton Photon conference, but that the papers were independent and essentially simultaneous.

The MARK-J paper [13] shows very clear evidence of an excess of planar events at high oblateness. Oblateness is an infrared safe, thrust-like variable which is large for planar events. It uses the momentum transverse to the thrust axis in and out of the event plane chosen to maximize O:

$$O = \frac{\max[\sum P_{\perp}^{in} - \sum P_{\perp}^{out}]}{\sum P}.$$

After finding the thrust axis, a plane containing that axis is found which maximizes the oblateness, an infrared safe quantity. Figure 8 shows the oblateness distributions at low and high energy. The data are compared to models with and without gluon emission. A very clear excess in the data is seen at high energy in the large oblateness region when compared to models without gluon emission. These are simple fragmentation models with large variations in the Feynman-Field parameter σ_q, the RMS transverse momentum from fragmentation. This variation in the models, shown in the figure, demonstrates that oblateness is insensitive to mere jet broadening. Because the oblateness subtracts the momentum out of the event plane, it also is quite insensitive to simple fragmentation effects. Oblateness is large for events that broaden in one plane but not perpendicular to that plane.

The MARK-J oblateness distribution showed that the effect seen was not merely an

increase in the average fragmentation $P_\perp$ with energy. The O distribution also showed that the rate of events with jet broadening in one plane was in agreement with what is expected from QCD, with $\Lambda_{QCD} = 0.5$ GeV. In addition, MARK-J showed the average oblateness versus energy, and by comparing these results to models without gluons, demonstrated that the sensitivity to planar events grows with increasing energy.

In Figure 9, the highly oblate events, with oblateness larger than 0.1 and thrust less than 0.8, are picked out of the 27.4 - 31.6 GeV data sample for closer examination, to see if the energy flow in these events is as expected in QCD. Each event is oriented with the thrust axis horizontal, and the event plane is chosen by the oblateness method so that the plane is oriented in the plane of the figure. Finally, the event is flipped over in the plane to have the lowest energy jet in the upper half plane. The energy flow distribution was compared to QCD, and was found to agree, with a χ^2 of 67 for 70 degrees of freedom.

While others have tended to focus on the three lobed structure as evidence in itself for three jets from gluon emission, I have always thought that the importance was in a quantitative comparison of the planar events to QCD. MARK-J pointed out in the same paper that one can obtain a three lobed structure by adding phase space decays (presumably of heavy particles) to the normal two jet fragmentation. These however do not fit the data at all, giving a χ^2 of 222 for 70 degrees of freedom. One can also get a three lobed distribution from normal fragmentation models, but the rate of those events is very low and clearly inconsistent with the data. To get this three lobed structure from the sum of many events, oriented in this way, requires that each event have a three lobed structure of some kind very similar to the sum. This again only emphasizes the point that we cannot just take individual events that look like they have three jets as evidence for gluon emission. One must compare the distribution in a large sample of events to QCD.

The MARK-J paper [13] showed that the effect of jet broadening could be analyzed in a way that was not sensitive of fragmentation effects. It also showed that the large excess of events, selected by the oblateness method to be of a planar nature, had a three jet structure that was in agreement with the prediction of QCD. The rate of these events was also in agreement with the expectation for $\Lambda_{QCD} = 0.5$ GeV. Neither modified fragmentation models, nor models with a fraction of phase space could come close to fitting the data. **MARK-J had shown that the source of jet broadening was gluon emission as predicted in QCD. They also showed that, with cuts on thrust and oblateness, we could see these gluons as jets.**

The TASSO paper [14] discusses many of the same distributions that they presented

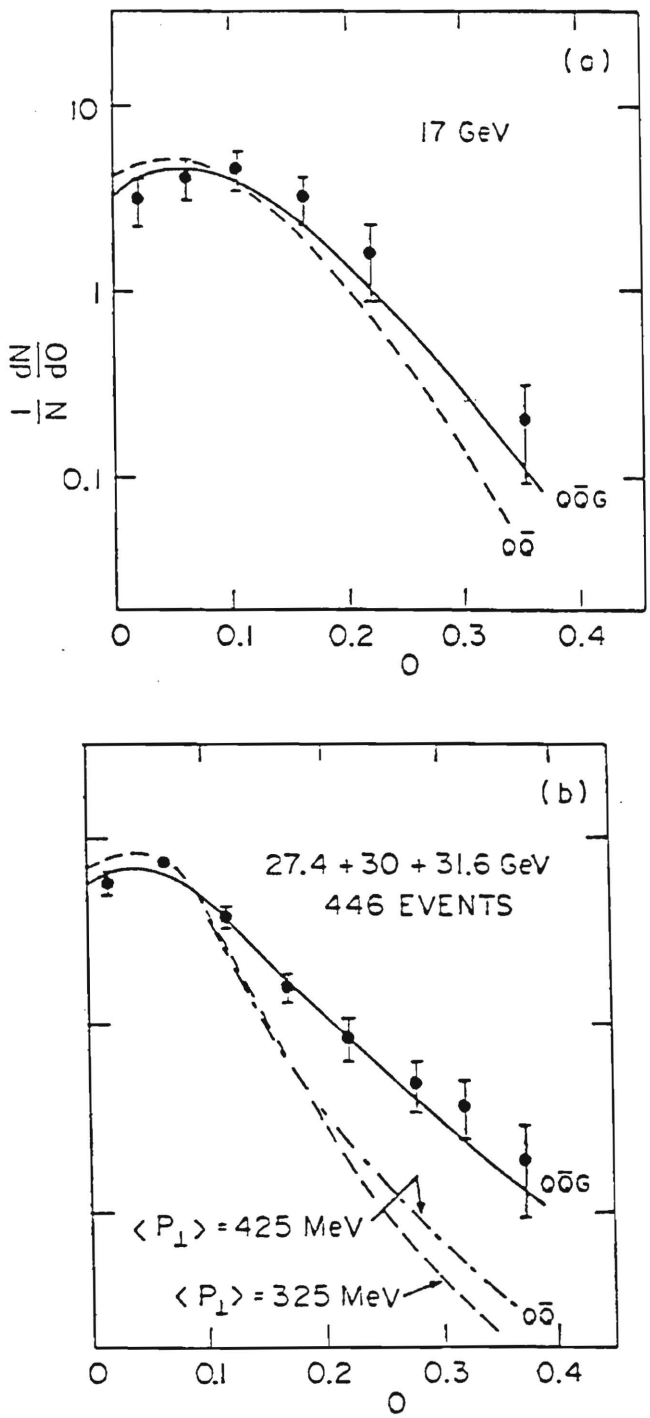

Figure 8: **MARK-J:** (a) The distribution $\frac{1}{N}\frac{dN}{dO}$ as a function of oblateness at $\sqrt{s} = 17$ GeV. (b) The distribution $\frac{1}{N}\frac{dN}{dO}$ as function of oblateness at $\sqrt{s} = 27.4 - 31.6$ GeV. In both (a) and (b) the solid curves are the predictions based on the $q\bar{q}g$ model and the dashed curve is based on the standard $q\bar{q}$ model with $\langle P_\perp \rangle = 325$ MeV. The dash-dotted curve in (b) is the $q\bar{q}$ model prediction with $\langle P_\perp \rangle = 425$ MeV.

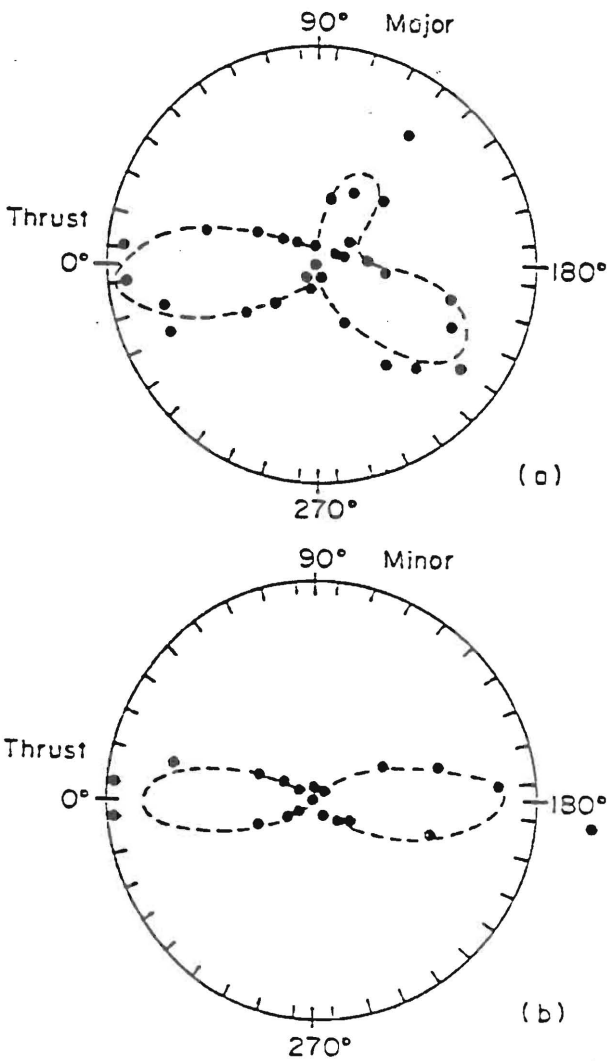

Figure 9: **MARK-J:** (a) Energy distribution in the plane as defined by the thrust and the major axes for all the events with $T < 0.8$ and $O > 0.1$ at $\sqrt{s} = 27.4$, 30, and 31.6 GeV. The energy value is proportional to the radial distances. The superimposed dashed line represents the distribution calculated with use of the $q\bar{q}g$ model. (b) The measured and calculated energy distribution in the plane defined by the thrust and the minor axes.

at the EPS conference, with higher statistics. They again show the seagull effect, Figure 10, but also show that their seagull data can be fit by increasing the fragmentation transverse momentum σ_q in a simple Feynman-Field model including heavy quarks. By again looking at the average $P_\perp^2$ in the event plane, shown in Figure 11, they do find that the tail of the distribution does not agree with the Feynman-Field model, even with a higher transverse momentum in the fragmentation. This shows that simple fragmentation cannot account for their higher statistics data. It should be pointed out, however, that the tail which does not fit (above 0.6 GeV^2), contained only three events at the time of the EPS conference; a small number of events to find a qualitatively new phe-

nomenon. TASSO shows one three jet event in this paper, again with a jet dominated by one charged particle.

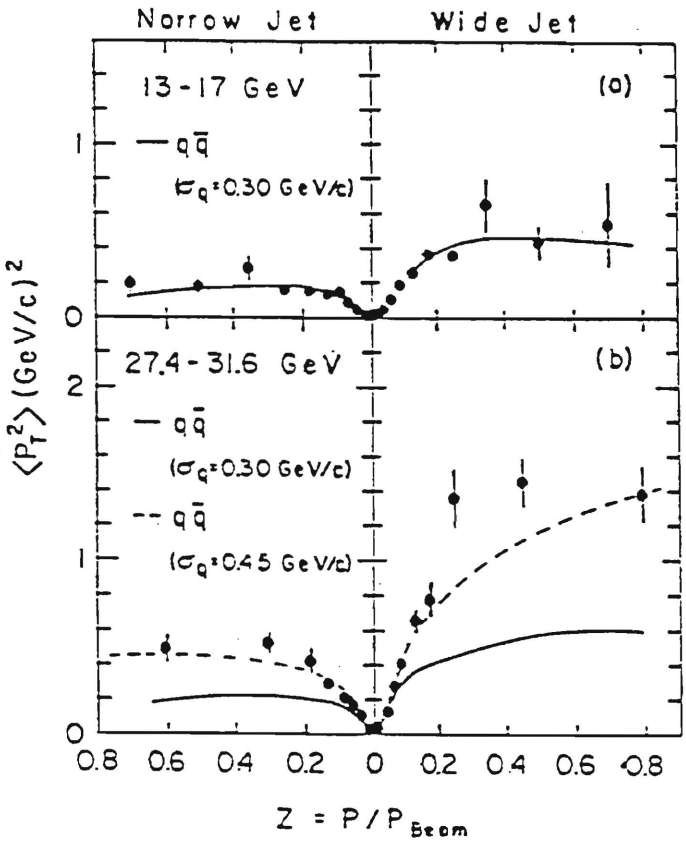

Figure 10: **TASSO:** $\langle P_\perp^2 \rangle$ as a function of $z = \frac{P}{P_{beam}}$ for the wide jet and the narrow jet separately, where each event hemisphere perpendicular to the sphericity axis is analyzed as a single jet, for the (a) low energy and (b) high energy data. The curves show the predictions of the $q\bar{q}$ model with $\sigma_q = 0.30$ GeV/c (solid curve) and $\sigma_q = 0.45$ GeV (dotted curve). The model includes u, d, s, c and b quarks.

Finally TASSO makes a new selection of planar events by requiring that the sphericity be greater than 0.25 and that the aplanarity be less than 0.04. Aplanarity is based on the $P_\perp^2$ out of the event plane. These cuts quite effectively select events which are broad in the event plane but narrow perpendicular to it, in many ways similar to the oblateness selection (but as noted earlier, using variables that are not infrared safe). They find 18 events with 4.5 expected from (normal low $P_\perp$) fragmentation. Unfortunately, they do not compare this rate to what is expected from QCD. This would have been an important check at the time, to see if QCD is consistent with being the source of the planar events in their data. They show no distributions comparing QCD predictions with these selected events, but do quote the following result. "The events were analyzed

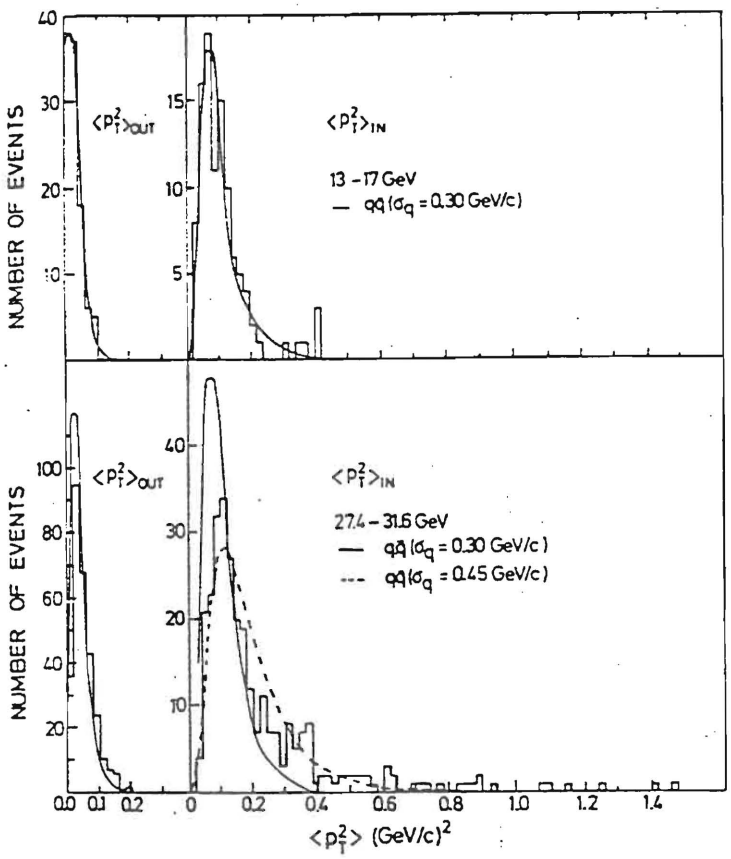

Figure 11: **TASSO:** The mean transverse momentum squared normal to the event plane $\langle P_\perp^2 \rangle_{out}$ and in the event plane $\langle P_\perp^2 \rangle_{in}$ per event, for the low-energy and the high-energy data. The predictions of the quark model are shown assuming $\sigma_q = 0.30$ GeV/c (solid curves) and $\sigma_q = 0.45$ GeV/c (dotted curve). The model includes u, d, s, c and b quarks.

for a thee-jet structure as described in reference [15]. All the coplanar events have a good fit to the three jet hypothesis. We further determined the transverse momenta of the hadrons with respect to the axis to which they were assigned. For the 18 events defined above, we find an average transverse momentum of about 0.30 GeV/c, close to the mean $P_\perp$ observed in two jet events at low energies."

It is not at all surprising that by choosing three jet axes (instead of one!) that the average momentum transverse to those axes goes down. If one were to do that to low energy two jet events, it would go down even further. While this statement is quite imprecise in general, the critical thing that is missing is any comparison to QCD (or alternative) model predictions. Not a single indication that the predictions of QCD agree with the data is given in the TASSO paper. The comparison to the earlier analysis

made by PLUTO, who had investigated the three gluon decay of the Υ is quite telling. **TASSO had confirmed their results giving evidence for increased $P_\perp$ in jet fragmentation, but, had not added much else in the analysis presented in this paper.** The emphasis of this paper is entirely consistent with its title: "Evidence for Planar Events...".

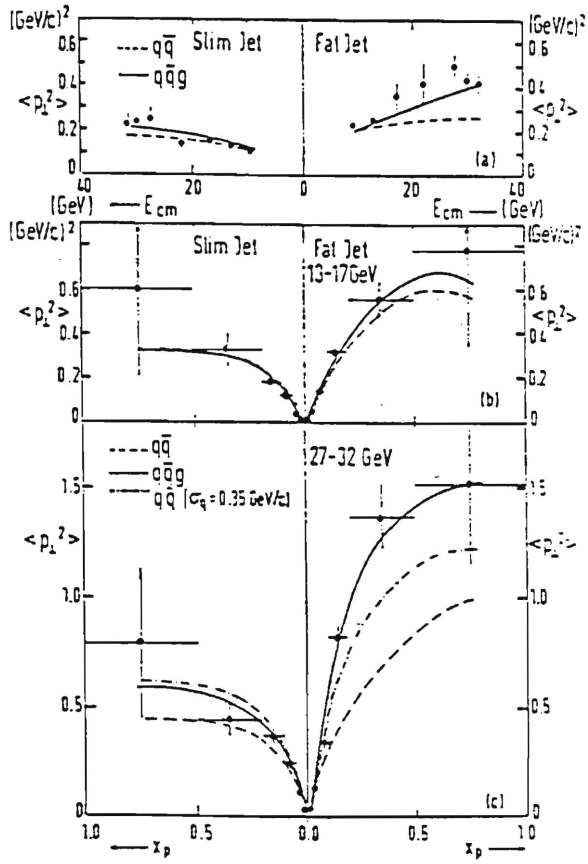

Figure 12: **PLUTO:** Averaged observed $p_\perp^2$ of charged particles in the slim and broad jets, respectively, as a function of the c.m. energy (a). Sea-gull plots ($\langle P_\perp^2 \rangle$ of charged particles as a function of x_P) for slim and broad jets in two separate energy ranges (b), (c). The solid and dashed lines are $q\bar{q}g$ and $q\bar{q}$ predictions, respectively.

The PLUTO collaboration submitted a paper [16] on September 13, only a few weeks later. The paper, published on October 8, studied many aspects of their evidence for gluon emission. They again showed that the seagull effect, Figure 12, is quite sensitive to σ_q, the transverse momentum assumed in the fragmentation process. The figure shows that a change in average $P_\perp$ from 250 MeV/c to 350 MeV/c moves a long way toward fitting the data in both the broad and narrow jet (where each hemisphere of the event perpendicular to the sphericity axis is analyzed as a single jet). While a further increase

in $P_\perp$ would be hard to justify, it does point out at a minimum that this effect needs to be studied in great detail to understand its relevance.

PLUTO studied their events in terms of Thrust and Triplicity, both infrared safe variables which can be compared to the prediction of perturbative QCD. Figure 13 shows the two dimensional distribution in those variables. They select events with low thrust ($T < 0.8$) and high triplicity $T_3 > 0.9$), and compare the rates to different models. Their table of results is reproduced below in Figure 14.

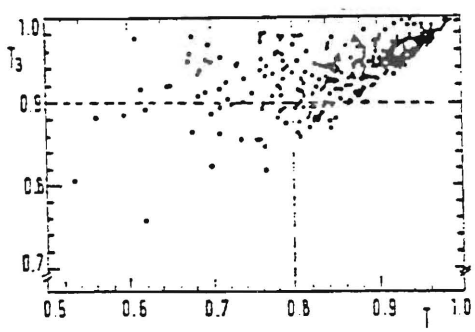

Figure 13: **PLUTO:** The data at $E_{cm} = 27.6$, 30, and 31.6 GeV are shown in a scatter diagram of triplicity vs. thrust. Planar events will be in the upper left of the plot characterized by low thrust and high triplicity.

The table shows that in the high energy region that even this type of selection is rather sensitive to the $P_\perp$ of fragmentation σ_q, but that the rate of events in the data are only fit well with the QCD-based model. A modified Feynman-Field model with a longer tail in $P_\perp$ may still be dangerous for this type of measurement.

Nevertheless, **PLUTO had shown significant evidence, and unlike the TASSO paper had compared their data to models with and without gluon emission.** They showed a similar analysis of the average $P_\perp^2$ both in and out of the event plane which is reproduced in Figure 15. Again they compare to the same models, and show that only from this detailed comparison can one conclude that gluon emission is favored. They concluded that "the data do not agree with a simple $q\bar{q}$ model. At the same time, the data are very well described by perturbative QCD taking into account gluon bremsstrahlung."

E_{cm} (GeV)	Selected region	Events observed	Events expected (σ_q = 250 MeV/c)		Events expected (σ_q = 300 MeV/c)		Events expected (σ_q = 350 MeV/c)
			$q\bar{q}$	$q\bar{q}g$	$q\bar{q}$	$q\bar{q}g$	$q\bar{q}$
13–17	$T_3 > 0.9$, $T < 0.8$ (three-jet events)	24	11	15	15.5	17.5	20
	$\theta_3 < 150°$	32	25	32	27	33	29
	$\langle p^2_{\perp in}\rangle > 0.5$ GeV$^2/c^2$	5	5	5	7	10	9
	$S > 0.25$, $Q_1 < 0.03$ (planar events)	7	8	8	9	9	11
27–32	$T_3 > 0.9$, $T < 0.8$ (three-jet events)	48	11	43	23.5	48.5	36
	$\theta_3 < 150°$	52	19	51	25	50	31
	$\langle p^2_{\perp in}\rangle > 0.5$ GeV$^2/c^2$	68	23	56	30	61	37
	$S > 0.25$, $Q_1 < 0.03$ (planar events)	35	12	30	17	30	22

Figure 14: **PLUTO:** Observed and expected numbers of events obeying different selection criteria.

E_{cm} (GeV)	Variable (GeV/c)^2	Observed value	Predicted value (σ_q = 250 MeV/c)		Predicted value (σ_q = 300 MeV/c)		Predicted value (σ_q = 350 MeV/c)
			$q\bar{q}$	$q\bar{q}g$	$q\bar{q}$	$q\bar{q}g$	$q\bar{q}$
13–17	$\langle\langle p^2_{\perp in}\rangle\rangle$	0.17 ±0.01	0.13	0.13	0.16	0.17	0.20
	$\langle\langle p^2_{\perp out}\rangle\rangle$	0.055 ±0.003	0.050	0.050	0.057	0.060	0.065
27–32	$\langle\langle p^2_{\perp in}\rangle\rangle$	0.290 ±0.06	0.176	0.276	0.21	0.30	0.250
	$\langle\langle p^2_{\perp out}\rangle\rangle$	0.076 ±0.003	0.067	0.076	0.077	0.086	0.086

Figure 15: **PLUTO:** Observed and predicted mean values of $\langle P^2_{\perp in}\rangle$ and $\langle P^2_{\perp out}\rangle$.

5 Later Papers

JADE submitted a paper [17] on December 7 that was published on March 14, 1980. They showed a clear excess of planar events using an analysis which was rather insensitive to fragmentation. They presented a detailed study of 3-jet events. As an example, in Figure 16, they show that both the angular distribution and energy distribution of the smallest of three jets agree with the QCD model. They compare both the rate of events and the distributions, and they find a clear distinction between models. They used these data to determine α_s to be 0.17 ± 0.04. **This was the first determination of α_s from 3-jet events.**

Finally, TASSO submitted a paper [18] in May of 1980 which was published in August. This showed a comparison of their data to QCD for the first time in a publication.

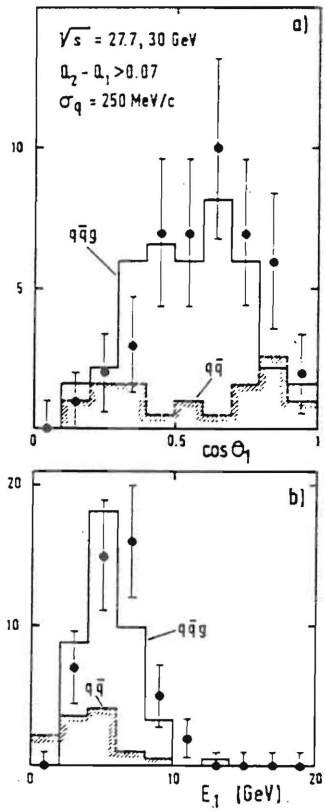

Figure 16: **JADE:** Result of the three-jet analysis in the laboratory system for the planar events. (a) Angular distribution of the jet with the smallest energy relative to the primary jet axis. The data are compared with $q\bar{q}$ model ($\sigma_q = 250$ MeV/c) and $q\bar{q}g$ model expectations. (b) Energy distribution of the jet with the smallest energy.

Figure 17 shows several distributions compared to QCD. They compare the $P_\perp^2$ distribution, the charged multiplicity and the angles between jets when analyzed as three jet events. They also use J_3, a sphericity-inspired three jet variable to show that they can distinguish QCD from "disklike" events.

By mid-1980, all of the experiments had presented clear evidence for gluon jets. Many papers exploring the nature of the 3-jet events followed from each of the collaborations. Many important measurements were made, and most of the techniques used today to study multijet events in e^+e^- were developed by the PETRA groups.

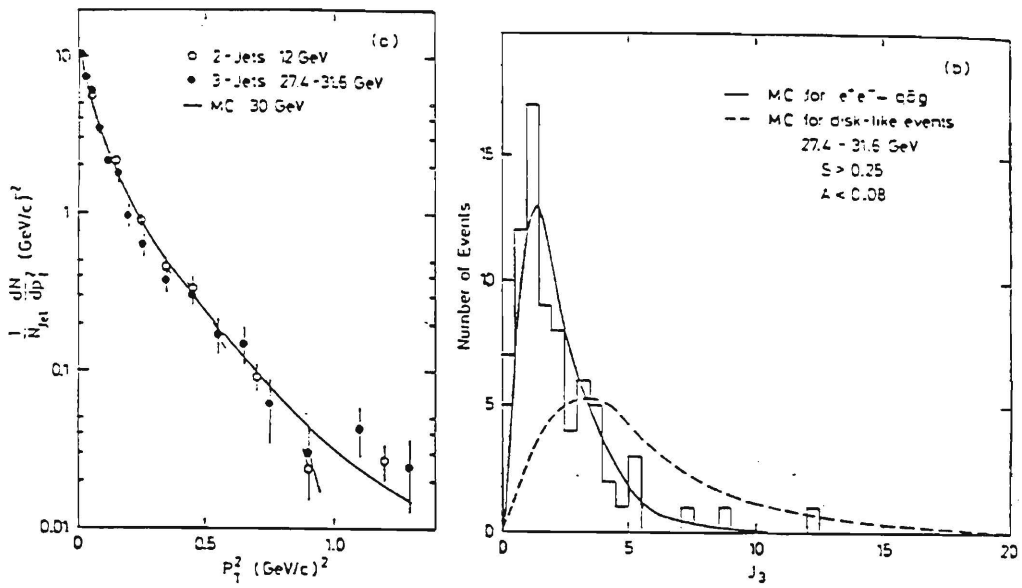

Figure 17: **TASSO:** (a) Observed transverse momentum distribution of the hadrons from the planar region ($S > 0.25, A < 0.08$) with respect to the three axes found with the generalized sphericity method, at $W = 30$ GeV (solid points). It is compared with the transverse momentum distribution relative to the sphericity axis for *all* events (no S or A cut) at $W = 12$ GeV, analyzed as two-jet events (open points). It is also compared with the result from QCD model at 30 GeV (curve). (b) Comparison of the trijettiness distribution for the planar event sample at $W = 30$ GeV, with the distribution for disk-like events (dashed curve) and the QCD model (solid curve). The curves are normalized to the number of events.

6 Schopper's Review

In September of 1979, Herwig Schopper reviewed [19] the new results from e^+e^- annihilation. He showed results on the subject of gluon emission from all the PETRA experiments. In Figure 18, he showed the evidence from TASSO on the increase in the average $P_\perp^2$ with energy. The high energy data require a fragmentation parameter σ_q of 450 MeV. In Figure 19, he again showed the TASSO $P_\perp^2$ distribution. In this case, the tail of the distribution cannot be reproduced even for 450 MeV average $P_\perp$. He showed the MARK-J energy flow distribution in an unfolded plot, Figure 20, stating that MARK-J showed the "first statistically relevant observation of the 3-jet pattern". This showed the quantitative agreement of event shapes between the QCD model and the data.

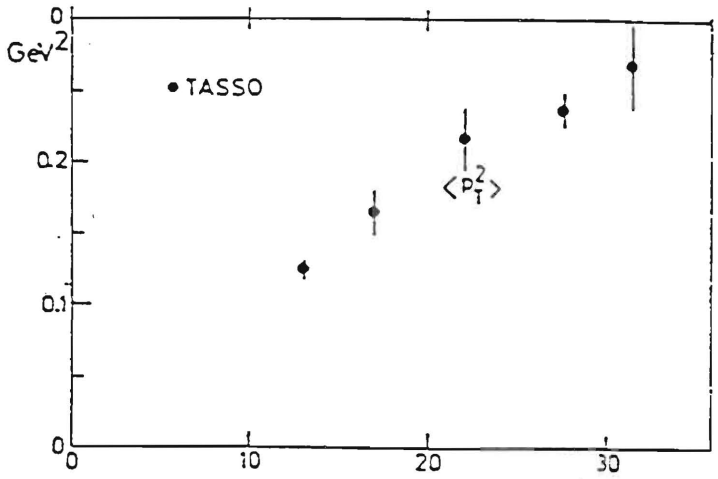

Figure 18: **TASSO:** The dependence of $\langle p_\perp^2 \rangle$ on the center of mass energy $W = \sqrt{s}$, as measured by TASSO.

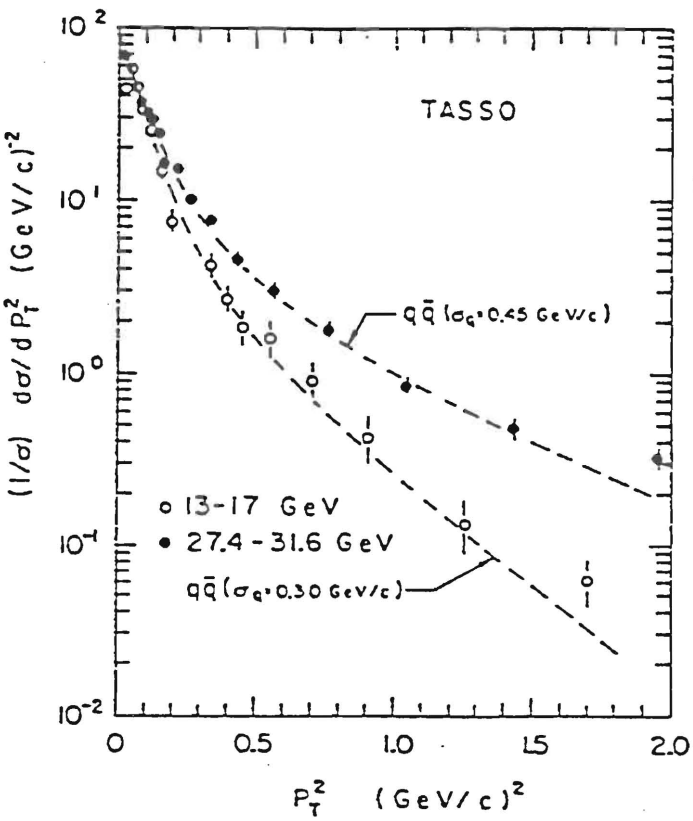

Figure 19: **TASSO:** The distribution of $p_\perp^2$ for two different energy ranges. The dashed curves are the expectations for two different parameters σ_q in the quark fragmentation function.

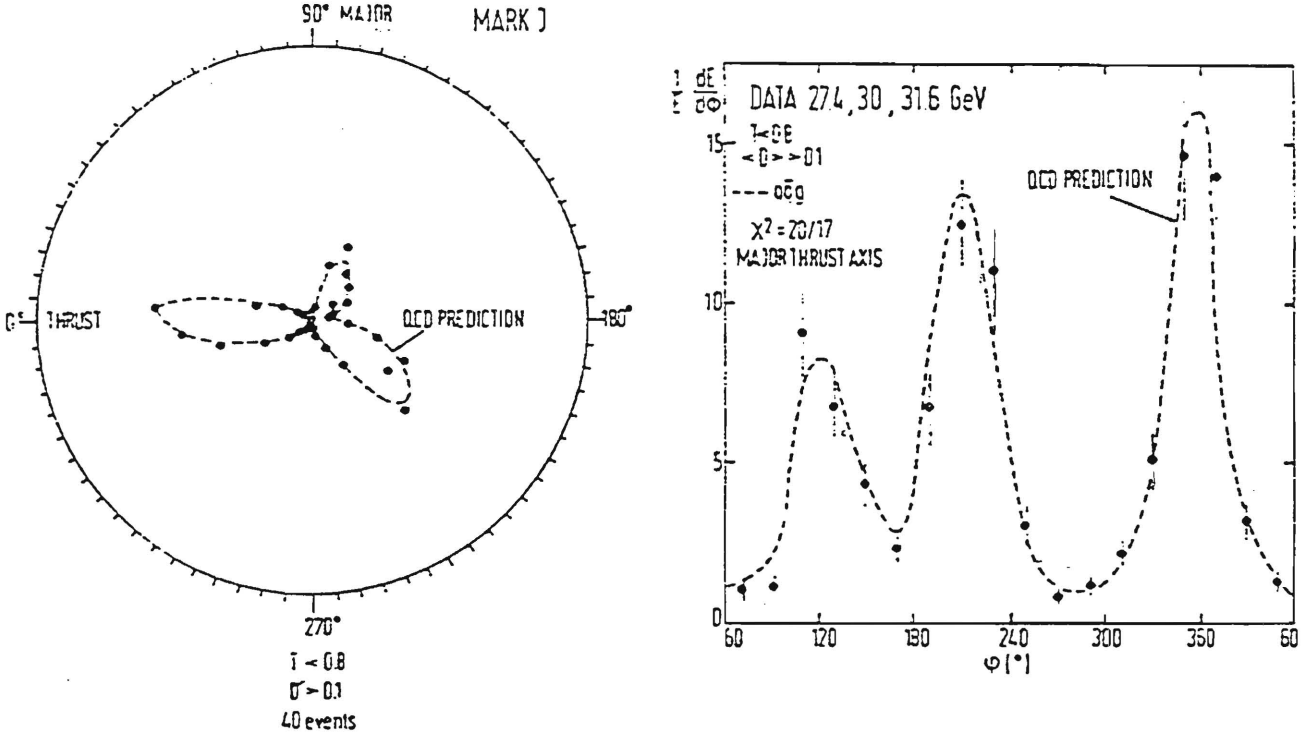

Figure 20: **MARK-J:** (a) Energy distribution in the event plane. The energy value is proportional to the radial distances. The dashed line is the prediction of the $q\bar{q}g$ model. (b) Energy flow in the event plane as a function of the polar angle ϕ.

7 Comment on Some of the Early Methods

By now many sophisticated techniques have been developed to study three jet events. Most of the earliest ones have not proven useful over the long run. In particular, methods based on squares of momentum and transverse momentum have in most cases been discarded for testing perturbative QCD because of the infrared problem. In contrast, thrust is a very standard basic variable which has been used even in higher order determinations of α_s. Sphericity, Oblateness, and Triplicity are sometimes plotted in the more complete studies. The energy flow plot has been put to use to study the details of the gluon interference. JADE [20] was the first to use the energy flow plot, on a much larger statistical sample, to show that string fragmentation models fit the data better

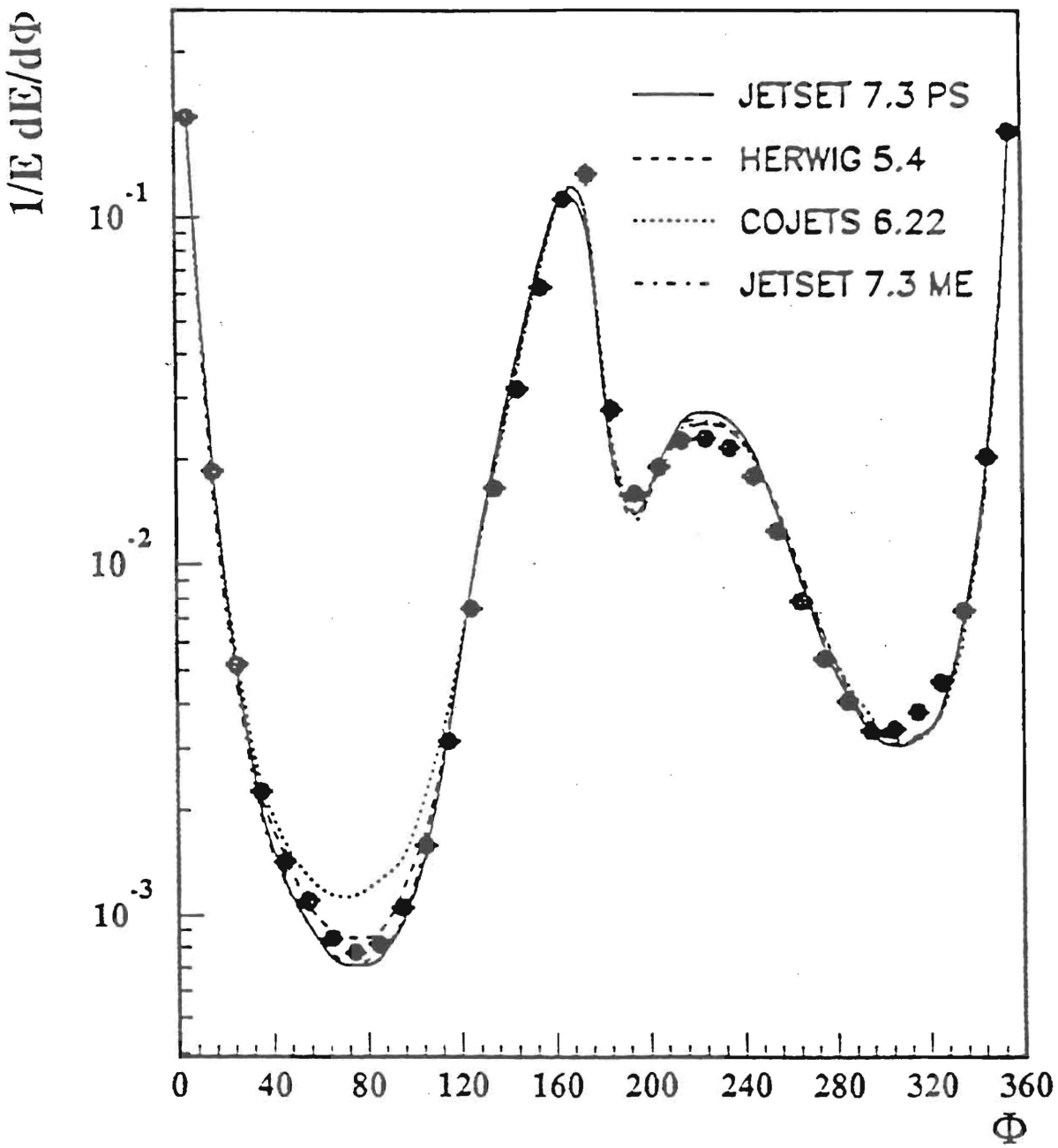

Figure 21: The energy flow diagram on a log plot is used in a modern analysis to distinguish between Monte Carlos with different assumptions about coherence in the parton shower. The region between the quark jets shows the greatest sensitivity.

than independent jet fragmentation. One modern example of this type of analysis [21] is shown in Figure 21. The plot, on a log scale, is used to study the region between jets. This plot compares several different QCD-inspired fragmentation models, showing a strong preference for models with interference between multiple emitted gluons.

8 Conclusion

By simply reviewing the published results, one gets a clear picture of the step-by-step progress that was made, especially in 1978-1980, toward seeing gluons as jets. PLUTO's Υ decay analysis was a very clear first step. At conferences, TASSO showed that a description of the data in terms of simple Feynman-Field fragmentation broke down as the energy increased. They showed low statistics evidence that this breakdown was due to planar events. Just after the Lepton-Photon conference, TASSO, MARK-J, and PLUTO published their analyses. TASSO showed reasonable evidence for planar events, but made no comparison to QCD and showed no significant evidence that the events had three separated jets. This paper should be read by anyone trying to evaluate the contributions of the various experiments. The MARK-J paper showed clear evidence for planar events using a distribution that was insensitive to variations in the simple fragmentation models. They showed that the rate and shape of these planar events was well-fitted by the predictions of QCD, and that this body of data could not be explained by Feynman-Field fragmentation, even with increased $P_\perp$ in $q\bar{q}$ events or with an additional admixture of phase space decays. Only a few weeks later, PLUTO also showed very clear evidence that their data were not fit by Feynman-Field fragmentation alone but agreed well with QCD expectations. JADE first published after a few months but again compared the rate and shape of the planar events to QCD and used their data to extract α_s for the first time.

Looking back, the thing that impresses me is that all of these important results came only about one month after sufficient data were collected. The initial TASSO results were reported with only 50 high energy events. With 500 events, each experiment had fairly significant results. While it is clear that those analyzing the data did some very good work and developed some methods still used today, I conclude that the "discovery of the gluon" was a near-certainty, once sufficient luminosity was delivered around 30 GeV. It is a result for which a large share of the credit should go to those who designed and built the accelerator and to those who designed and built the experiments.

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