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TESTS OF QCD AT LEP

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Abstract

In this report, some aspects of the reaction $Z^o \rightarrow q\bar{q}$ are presented and compared to the predictions of perturbative QCD. Recent results from LEP 1990 data are shown, concerning measurements of α_s with global event shape variables, of gluon properties through 3-jet event orientations and comparison of gluon and quark fragmentation.

1. Introduction

LEP provides a rich source of quarks from $Z^o \rightarrow q\ \bar{q}$ (~70% of Z^o decays) to study the different steps of hadronic production. With respect to $e^+\ e^-$ machines of lower center of mass energies, LEP offers,with $\sqrt{s} = 90$ GeV a high statistics sample of well collimated jets which allows the study of the behaviour of the strong interactions. This is because the jet structure should be governed by gluon emission, as predicted by Quantum Chromo Dynamics (QCD). The effect of the hadronization,i.e. the last step in the process of forming hadrons from partons, is less important at LEP than at lower energies machines, becoming $1/E_{c.m.}$ smaller. This helps in separating the elementary process, the gluon radiation, and therefore a better comparison with the theoretical expectations.

There exist excellent reviews of the studies of hadronic final states and their comparison with theoretical predictions [1], therefore the reader is invited to find there exhaustive information about tests of QCD performed at LEP. Here I would like to restrict myself to the description of only few aspects of very recent studies which I consider possible helps in establishing the validity of QCD as the theory of strong interactions.

2. Theory

Among models of strong interactions, QCD [2] is the one which provides the widest range of predictions, through many theoretical calculations.

The coupling constant α_s is the parameter of the theory, therefore the most important measurement the data should provide.

A limitation to the present tests is however that the calculations are performed most often up to the second order in α_s, while they are needed at higher orders to be able to extract from the LEP data reliable tests of the model.

Hadron production from $q\bar{q}$ can be described in two steps. First the tree development of partons from the quarks produced from the Z^o ,until the partons have virtual masses of the order of the mass of hadrons (i.e. O(1 GeV)). Up to this moment perturbative QCD describes the process. The final step at which partons hadronize to give observable π's, k 's,etc, cannot be described perturbatively,but it is modelled with Monte Carlo's. An adjustement to the data is therefore needed for the several parameters entering into a Monte Carlo.

There exist several sophisticated Monte Carlo generators [3] which provide the tools to describe the observed data. This however is a serious limitation ,especially because the tuning of the different Monte Carlo's to obtain agreement with the data , could affect and distort the validity of the comparison with the theoretical expectations.

3. The LEP Detectors

Four detectors [4] are taking data at LEP :

- ALEPH
- DELPHI
- L3
- OPAL

Each has collected about 100-150 KZ^o 's events during 1990, and a factor of 3 more will be probably obtained in 1991. The results shown in this talk are from the 1990 data.

All four are general purposes detectors, with good angular coverage ,good or excellent charge track measurement, and fine grain calorimetry to measure energy and direction of neutral particles.

4. Data corrections and Monte Carlo

Before comparing to theoretical expectations,data have been corrected for all possible known detector inefficiencies and distortions with Monte Carlo's. As the theoretical calculations are performed with partons and the observables are hadrons, one needs some kind of description for dressing of the partons into hadrons.

Several event generators are available: the ones listed below are all QCD inspired for the description of the parton tree,and differ mainly in the hadronization of the final partons.

- JETSET [5]. Hadronization is simulated by string fragmentation. It is available also with Matrix Element option (ME), but this version should not be used to estimate hadronization effects.
- HERWIG [6]. Hadronization is simulated by cluster fragmentation.
- ARIADNE [7]. The parton shower is based on the color dipole formalism. Hadronization is like in JETSET.

5. Measurement of α_s from global event shape variables

The most direct information on α_s at LEP comes from the partial width of the Z^o into hadrons Γ_{had} , which is related to α_s by:

$$\Gamma_{HAD} = \Gamma^{o}_{HAD}\left(1 + \frac{\alpha_s(M_Z^2)}{\pi} + 1.409\left(\frac{\alpha_s(M_Z^2)}{\pi}\right)^2 - 12.805\left(\frac{\alpha_s(M_Z^2)}{\pi}\right)^3\right)$$

and for which the perturbative calculation is reliable up to the 3^{rd} order [8]. However, the experimental errors are large for the moment [9].

Another simple quantity determined by the value of α_s is the fraction of 3-jet events. A compilation of existing measurements was done by L3 [1], and is shown in figure 1.

It was suggested [10] that it is important to test the perturbative QCD calculations concerning some infrared safe quantities related to jet characteristics, like thrust, sphericity, oblateness, etc. even if the theoretical predictions are affected by the lack of knowledge of the hadronization process, and a large uncertainty (~10-20%) coming from higher order corrections. For these variables in fact the radiative corrections are typically quite large (~ 30%).

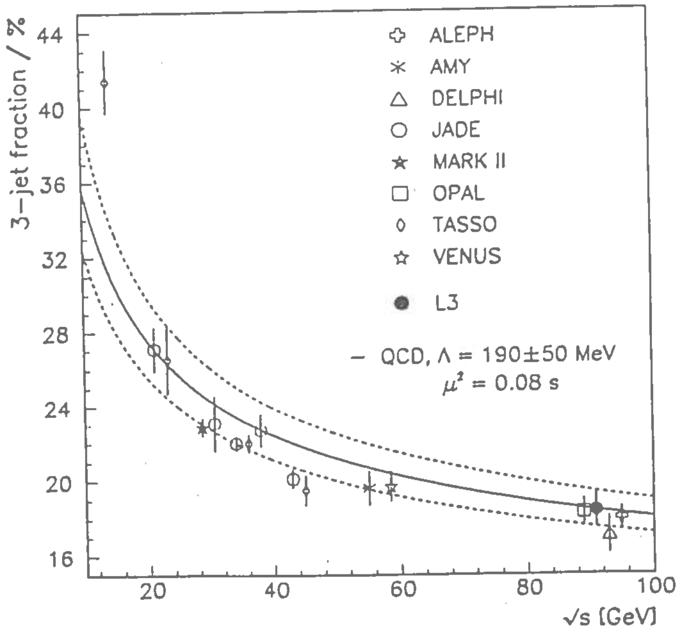

Fig.1 Compilation of 3-jet event production (from T.Hebbeker [1])

Many global shape variables have been compared to theoretical predictions to extract α_s [11]. The different measurements of α_s determined through them, should prove the consistency of the theory,if they are in agreement.

The procedure to extract α_s from the data is the following:

1. one has to define a range of the chosen variable V (V= *Thrust*, *Oblateness*, *C-planarity*, etc.) where the variable is least biased and best measured, and in the 3-jet region to increase the sensitivity to α_s.
2. As the theory is not able to describe the final step of the hadronization,it must be modeled in some way. Monte Carlo's are used to unfold the possible distortion due to the final hadronization:
$$\left(\frac{dN}{dV}\right)^{\mathrm{CORR}}_{\mathrm{PART}} = \left(\frac{dN}{dV}\right)_{\mathrm{MEAS}} \cdot \frac{(dN/dV)_{\mathrm{PARTONS}}}{(dN/dV)_{\mathrm{HADRONS}}}$$
where the last factor is evaluated by Monte Carlo. It is clear that the value of the parameter at which the parton shower has been stopped (usually indicated with Q_o) will contribute to the systematic error.
3. the differential cross section is then compared with the theoretical calculations, generally performed at order α_s^2 [12].
$$\frac{1}{\sigma_0}\frac{d\sigma}{dV} = \frac{\alpha_s(\mu^2)}{2\pi}A_V(V) + \left(\frac{\alpha_s(\mu^2)}{2\pi}\right)^2 \left[A_V(V)2\pi b_0 \log\frac{\mu^2}{s} + B_V(V)\right]$$
where b_o =(33-2n_f) / 12 π and A_V,B_V, are two universal functions depending on the definition of the variable V [13]. In the above formula,the scale μ=f E_{cm} appears explicitly.

In the fits, typically $\Lambda_{\overline{\mathrm{MS}}}$ and f are kept as free parameters. The theory does not tell explicitely what value of the scale μ must be taken,and its value determined from the data through f ,readjusts α_s to include the effects of the higher orders corrections missing in the calculations. For this reason the comparison of the data to the expectations is limited in its testing power. From the value of α_s at a given μ^2 the evolution to μ= M(Z^o) is done through:

$$\alpha_s(\mu^2) = \frac{1}{b_0 \log(\mu^2/\Lambda^2_{\overline{\mathrm{MS}}})}\left\{1 - \frac{b_1}{b_0}\frac{\log[\log(\mu^2/\Lambda^2)]}{\log(\mu^2/\Lambda^2)}\right\}$$

$$\text{where } b_1 = \frac{153 - 19n_f}{24\pi^2}$$

In fig.2 (from OPAL) the behaviour of the variable Thrust is shown: its distribution is well described by Monte Carlo, which determines the hadronization corrections for this variable (fig. 2b) to be not far from unity over the full range of T used for the fit (fig.2c).

In fig.3 (from DELPHI) the dependence of α_s on the scale factor μ^2/M_Z^2 is shown,for the different variables studied with the DELPHI detector. The differences that the variables show, indicate that the effects of higher order corrections vary depending on the variable which is considered. Fig. 4 shows the final result for α_s, averaged over all the variables (DELPHI). Hadronization corrections have been performed using JETSET PS Monte Carlo.

The measurement of α_s made with the global shape variable is affected by a systematic error which is determined essentially by the following contributions:

- the choice of the scale μ
- the value at which in the Monte Carlo the parton tree development has been stopped
- hadronization effects

Each contribution depends on the variable analysed, the typical total systematic error being ~ 5-6%.

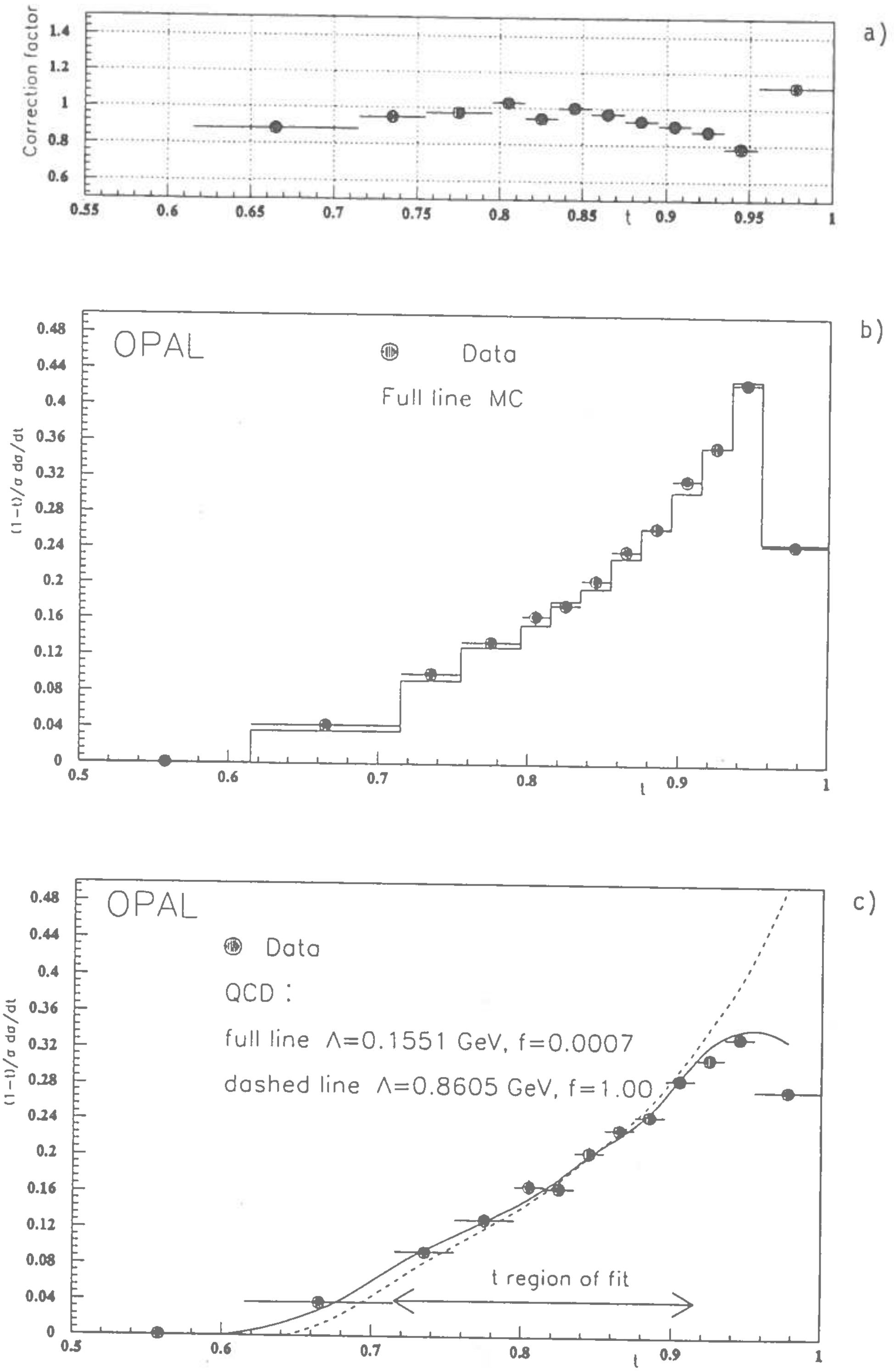

Fig. 2 Study of the variable thrust by OPAL. a) hadronisation correction factor in the full range of the variable . b) measured thrust compared to JETSET Monte Carlo. c) measured thrust compared to analytical QCD calculation. in the figure the range used for the fit is shown (from OPAL [11]).

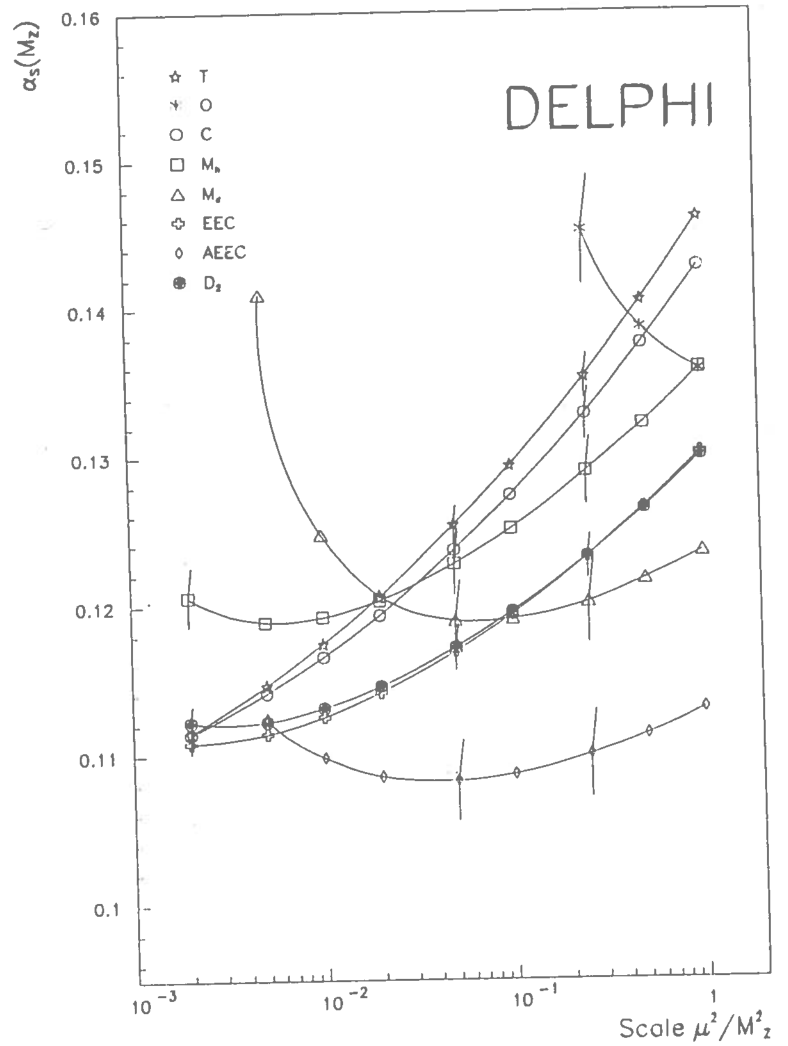

Fig. 3 Values of $\alpha_s(M_Z)$ for different values of the scale μ^2/M_Z^2 as determined with the different variables listed. Hadronization corrections are done with JETSET Monte Carlo (DELPHI [11]).

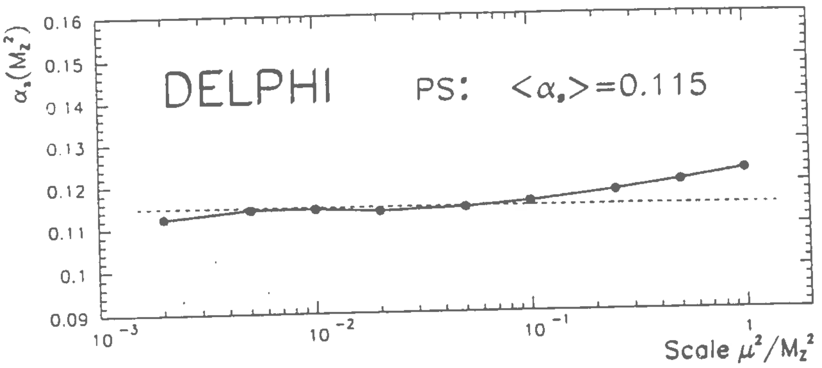

Fig. 4 Averaged values of $\alpha_s(M_Z^2)$ for different values of the scale μ^2/M_Z^2 The error band drawn in the figure represents the disagreement between the variables (see fig.3).

6. Gluon study

The quantum of the QCD theory is the gluon,and it has as characterics self interactions and spin one.

Some experimental efforts was put in trying to measure directly the triple gluon vertex [14], or indirectly, measuring the 4-partons production cross section [15].

Here I show new measurements of jet energies and orientations of the jets in the 3-jet events, which are related to the gluon spin [16,17,18]. Several results on this subject were available already from lower energy e^+e^- machines [19].

To test the nature of the gluon, one can compare the experimental distributions of the above quantities with the two hypothesis:

- vector,for which second order QCD calculations are available [20] or
- scalar [21]. In this case no systematic theory exists, but it is useful to point out the sensitivity of the measured quantities to possible alternative models.

Having defined x_i the energy of jet i normalized to the beam energy (with $x_1 > x_2 > x_3$), θ the polar angle of jet 1 with respect to e^- beam, χ the angle of jet plane with the plane jet 1 - e^- beam, (see figure 5), ω the angle of the perpendicular to the 3-jet plane with the beam ($\cos\omega = \sin\theta \, \sin\chi$) the cross section for massless partons and vector gluon is

$$\frac{d\sigma^V}{dx_1 dx_2} \approx \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$

The differential angular cross sections are:

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \alpha\cos^2\theta$$
$$\frac{d\sigma}{d\chi} \propto 1 + \beta\cos(2\chi)$$

where $\alpha = \sigma_U$ - 2 $\sigma_L/\sigma_U + 2\sigma_L$ and $\beta = \sigma_T/\sigma_U + \sigma_L$ Written in term of ω, the cross section is [33]

$$\frac{d\sigma}{d\cos\omega} \propto 1 + \gamma\cos^2\omega$$
$$\gamma = -\frac{1}{3}\frac{\sigma_v - 2\sigma_L + 6\sigma_T}{\sigma_v + \frac{2}{3}\sigma_L + \frac{2}{3}\sigma_T}$$

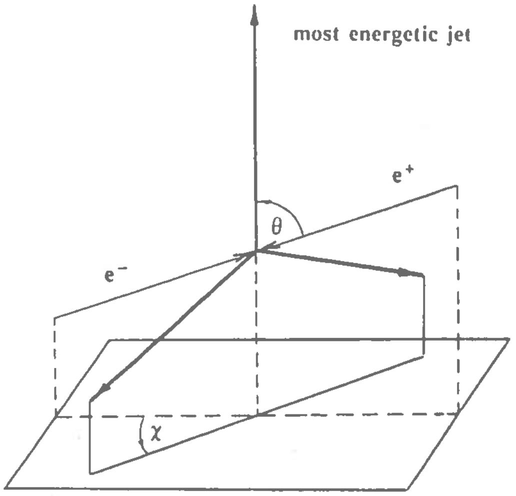

Fig. 5 Definition of the angles defining the orientation of a 3-jet event.

The 3-jet events are selected with the JADE algorithm [22] with y_{cut} =0.01 by OPAL [17], and y_{cut} = 0.02 by L3 [16], with the LUCLUS algorithm with $d_o = 6E_{vis}/\sqrt{s}$ by DELPHI [18].

The analysis is performed with 6308 events in DELPHI, 43000 events in L3, and 51797 events in OPAL.

Figure 6 shows the behaviour of α, β, γ appearing in the angular cross sections compared to the two hypothesis, vector and scalar.

Figure 7 shows the comparison for the jet reduced energy x_2 . The solid curve is drawn without higher order corrections,which would smear the peak giving better agreement to the data points.

In the figures a much better agreement with the data is evident in the case of the vector hypothesis rather than with the scalar one.

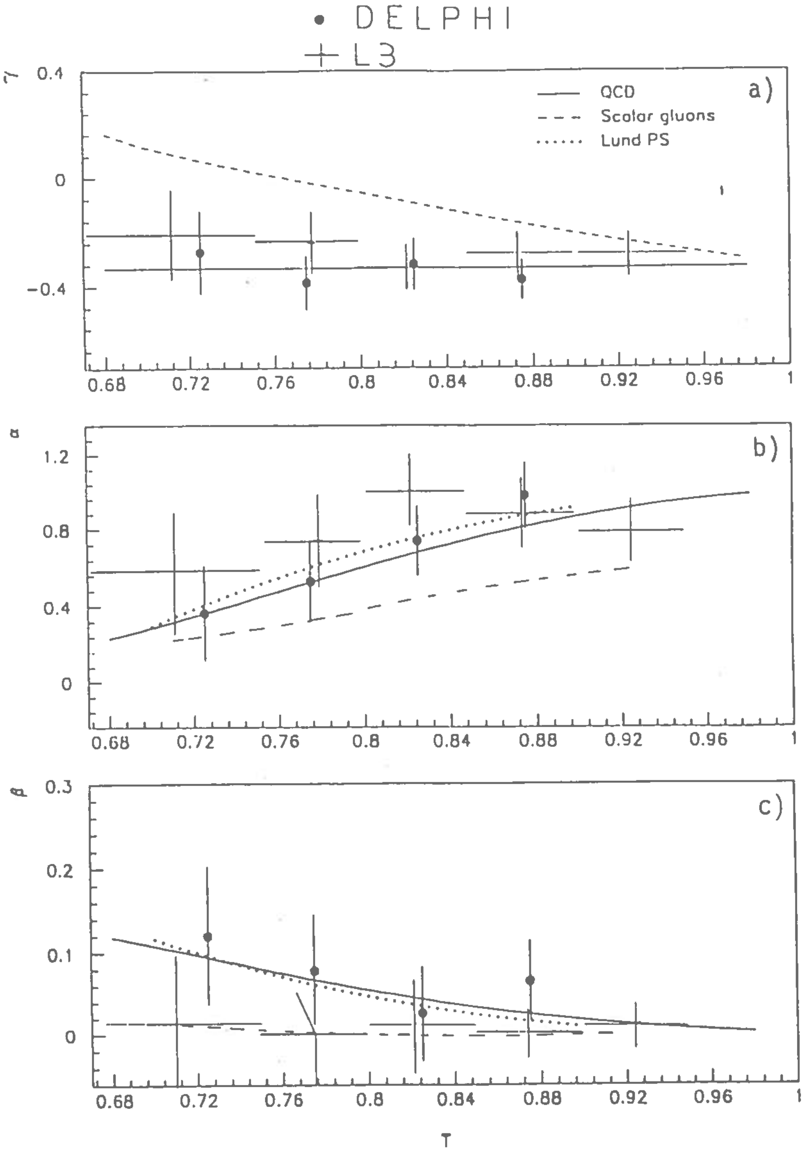

Fig. 6 Values of the parameters α,β, and γ measured and calculated.Solid line represents the predictions of QCD (vector gluons), the dashed line of scalar gluon hypothesis (from [16,18]).

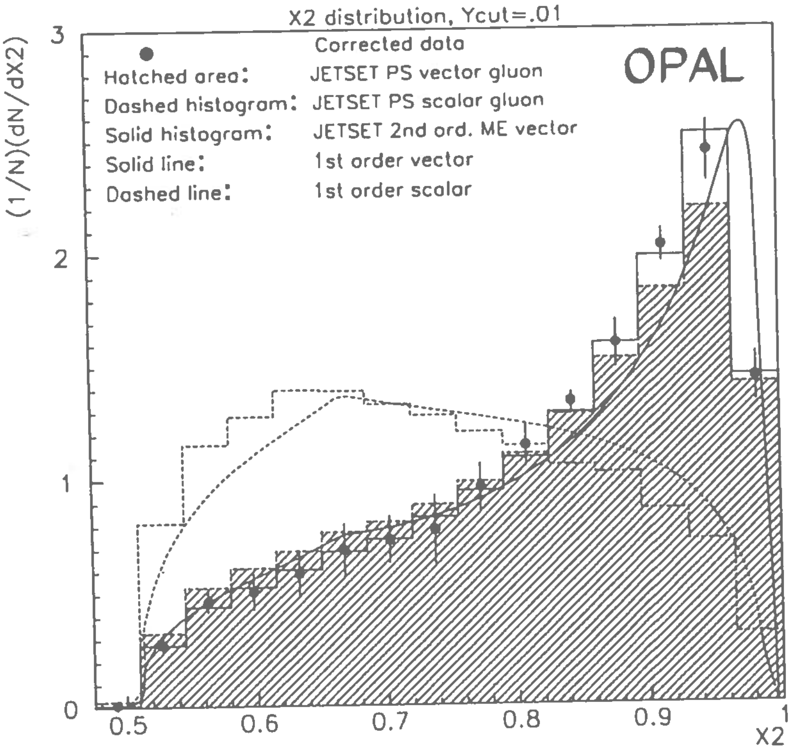

Fig. 7 Distribution of the reduced energy x_2 of the second jet . Points with errors are the data corrected to the parton level. Solid and dashed histograms represent JETSET simulation for vector and scalar gluons respectively. Solid and dashed curves are the first order calculations for vector and scalar gluon respectively (from OPAL [17]).

7. String effect

The string effect in the 3-jet events is the consequence of coherence of the radiation from the hard partons. One can show that the soft radiation is dynamically bound to lie between the color connected lines [23].

Therefore in the 3-jet events (q $\bar{q}$ g) one expects to observe it between the gluon and the quark and the gluon and the antiquark.

In order to measure different particle populations in these different angular regions, it was proposed to compare the final states $q\bar{q}g$ with q $\bar{q}$ γ [24], for which the radiation occurs predominantly between the quark and the antiquark.

At LEP, the jets are much better defined,therefore a definite improvement is expected over previous experimental measurements of the effect. Many experiments at e^+e^- machines studied the hadron population between jets with 'particle flow' technique [25].

An original procedure was introduced by OPAL [26], trying to identify the quark and the gluon jets in the semileptonic decays of quarks b and c, as follows:

1 3-jet events are selected on the basis of a modified version of the JADE jet finder algorithm [19,27] with $y_{cut} = 0.03$

2 only events having exactly 3 jets with the sum of their angle $> 358^o$ are kept for the analysis. 22721 3-jet events are selected in this way. The JETSET Monte Carlo gave the result that only $\sim$ 10% of these events are not 3 jet at the level of the partons. The energy and angular resolution,defined as the RMS of the difference between the quantity of a parton jet and the measured quantity of the associated hadron jet, turns out to be from

the Monte Carlo 8.1%, 11.4%, 22.1% for energy and 2.6°,3.9°, 10.6° for the angles, for jets ordered by decreasing energies.

3 a muon or an electron is then required in the event, and it must belong to one of the two less energetic jets. The highest energy jet being essentially the q or the $\bar{q}$, the jet containing the lepton is assigned to be the other $\bar{q}$ or q. The remaining is then the 'gluon jet'. 1311 events have been found :the purity of this gluon jet sample is found to be (84 ± 1)% using JETSET

4 another sample of events is defined containing 2 leptons, and in this case the q and $\bar{q}$ jets are the ones to which the two leptons belong,the gluon jet being the remaining one. OPAL finds 258 events in this category, and the purity of the gluon jet sample is (84 ± 2)%.

The flavor composition of such samples is strongly enriched in heavy quarks, and it is found to be 47% b's, 20% c's, 33% light $q\bar{q}$'s in the case of 1 lepton sample,and 70% b's, 21% c's,9% light $q\bar{q}$'s in the case of 2 lepton sample .

To investigate the string effect only those events are considered for which the angle between the gluon and the highest energy q jet is approximately equal to the angle between the 2 quarks jets ($\psi_A \sim \psi_C \sim 150^o \pm 10^o$ or $130^o \pm 10^o$,see fig.8) .

In figure 9 the particle density $1/N\ dN/d\psi$ is shown, where ψ is the angle between a particle and the highest energy quark jet (the events are planar). The angle is formed once starting at the higher energy quark jet axis (θ=0°), through the second quark (ψ=150° or 130°) and the gluon jet (ψ=210° or 230°), and a second time proceeding through the gluon jet (ψ=150° or 130°), and then to the lower energy quark (ψ=210° or 230°).

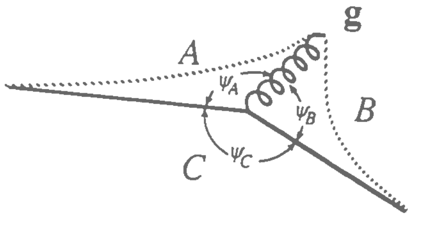

Fig. 8 Definition of the angular regions which define the environment of a jet.

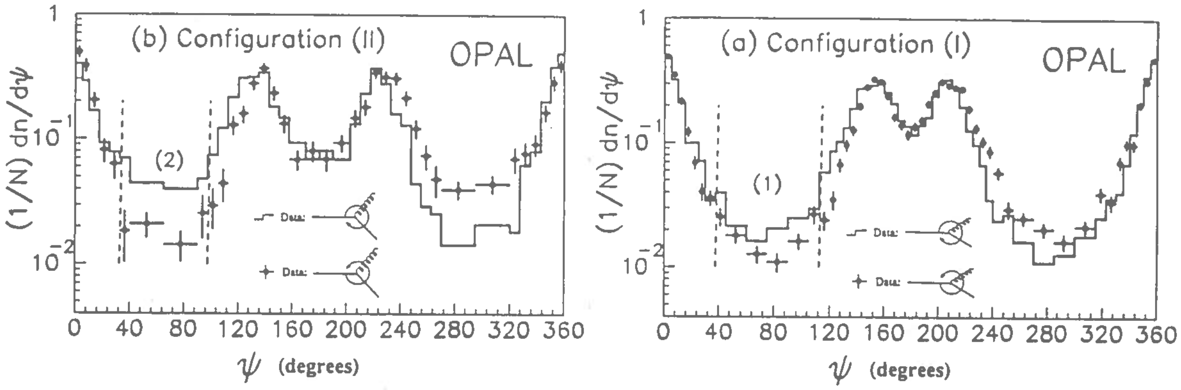

Fig. 9 Particle flow distribution $1/N\ dn/d\psi$ for events with angular configuration $\psi_A \sim \psi_C \sim 150^o \pm 10^o$ and $\psi_A \sim \psi_C \sim 130^o \pm 10^o$. The points with errors show the flow from the high energy quark jet to the low energy quark jet the to the gluon jet; the histogram shows the measured particle flow for the same event, again starting at the high energy quark jet but then proceeding in the opposite sense. The dashed lines show the regions used for calculation of the asymmetry ratio R (from OPAL [26]).

Combining several angular regions, keeping always the geometrical and kinematical symmetry for g-q and q-$\bar{q}$ angular distances, the ratio of density of particles in the quark-gluon and quark-antiquark region is found to be

$R = 1.62 \pm 0.07$

This ratio is determined independently of any model, for the data are plotted as observed in the detector,without corrections. Such a high ratio (it differs from 1 by 8.9 s.d) is not reproduceble by Monte Carlo, except from JETSET, which includes a simulation of soft gluon radiation and fragments partons along string of color.

8. Gluon fragmentation

The OPAL method described in the previous paragraph,i.e.to identify the gluon jet tagging the quark with a lepton, can also be used to study the details of the gluon framgentation compared to quark fragmentation [28] with no need of Monte Carlo and keeping the particle environment completely symmetric geometrically and kinematically.

In previous studies [29] the gluon jet was defined typically as the lowest energy jet in a 3-jet events, and then compared to 2 jet q $\bar{q}$ events at lower center of mass energy.

In the OPAL analysis the assignement is the following:

- the jet with the lepton is a quark jet
- the highest energy jet in the 3-jet events ia also a quark jet (true in ~ 96% of cases)
- the remaining jet is assumed to be the gluon jet. The purity of the gluon sample is 77%.

The gluon jet is then compared to the quark jet which has the same energy (between 20 and 30 GeV) and the same event environment, i.e. $\psi_{qq} \sim \psi_{qg} \sim 150^o \pm 10^o$. The sample selected in this way is highly enriched in b's and c's quarks. To have an unbiased sample of quarks,a second sample is selected requiring the same conditions for the two lower energy jets ($\theta_{12} = \theta_{13} = 150^o \pm 10^o$ and 20 GeV $< E_2 < E_3 <$ 30 GeV), but without requiring the presence of a lepton. 2189 events are found which have a 'normal' mixture of flavors, but it is not known which of the lower energy jet is a quark and which is the gluon. This last sample is used to obtain, by subtracting the gluon jet distribution of the first sample, the quark jet properties in the case of 'normal' mixture.This avoids any possible bias in the quark fragmentation due to its semileptonic decay. The result of the comparison is:

- the mean multiplicity of particles is very similar for gluon and quark jets.
  $< n >_g = 1.03 \pm 0.03^{+.15}_{-0.0}$
- the average energy of the particles is lower in the gluon than in the quark jet (fig.10).

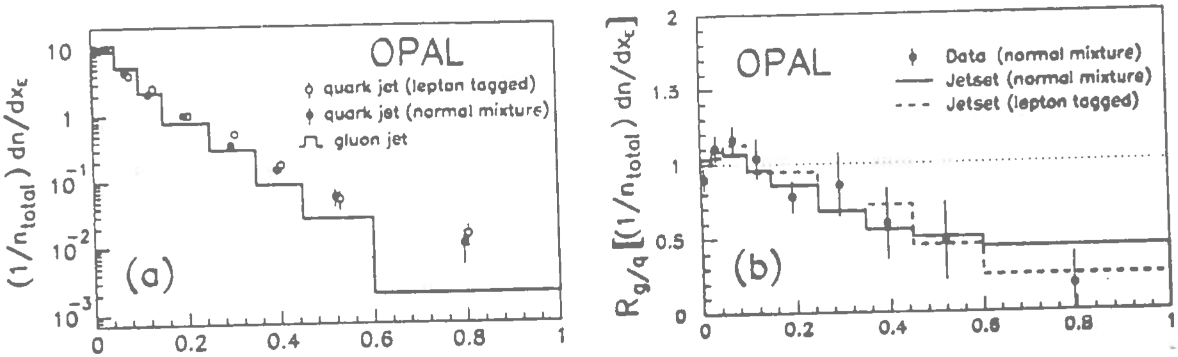

Fig. 10 The scaled inclusive energy spectrum of particles from the core region of the jet.

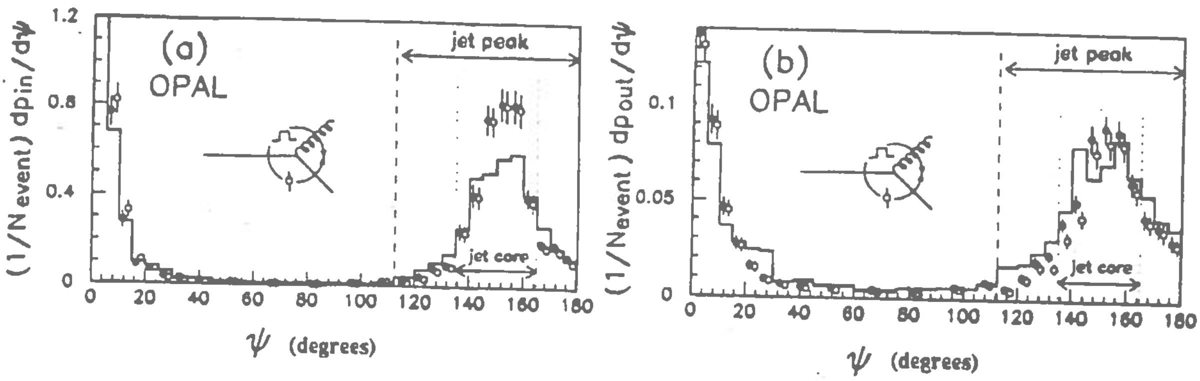

Fig. 11 The inclusive momentum distribution for (a) the component in the event plane p^{in} and (b) the component out of the event plane p^{out}. The open points and histograms show the distribution for the lepton tagged data.For the open points,the distribution starts at the high energy quark jet ,then proceed to the low energy quark jet.The histogram shows the other event halves:from the high energy quark to the gluon jet. The solid points show the equivalent of the open points,for data representing a normal mixture of quark flavors (from OPAL [28]).

- the distribution of the p^{in} and p^{out} (*in* and *out* the 3-jet event plane) versus the azimuthal angle ψ ,have different width for gluon and quark jets (fig.11). A gaussian fit obtains:
  $\sigma_g^{in}/\sigma_q^{in} = 1.42 \pm 0.08^{+0.04}_{-0.0}$
  $\sigma_g^{out}/\sigma_q^{out} = 1.46 \pm 0.14^{+0.06}_{-0.0}$
  indicating that gluon jets are broader than quark jets.

No corrections have been applied to the data,therefore the comparison does not depend on models.

9. Conclusions

At LEP,compared with lower center of mass energy machines, a larger class of variables become available to study q-g coupling. QCD gives a consistent picture of $Z^{o} \rightarrow hadrons$ but more precise (higher order) theoretical calculations are necessary before stating that the comparisons data-theory performed up to now, are real tests of QCD.

10. Acknowledgements

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REFERENCES

[1] T. Hebbeker,XX International Symposium on Multiparticle Dynamics , Gut-Holmecke Sept 10-14 1990
W.de Boer, CERN-PPE/90-161 Nov.1990
S.Bethke,*Proceed.of QCD* 90 *Conf. Montpellier* 8 – 13 *July*, 1990
[2] M.Gell-Mann,*ActaPhysicaAustriacaSuppl.IX*(1972) 733
D.J.Gross,F.Wilczek,*Phys.Rev.Lett.* 30 (1973) 1343
H.D.Politzer, *Phys.Rev.Lett.* 30 (1973) 1346
[3] T.Sjostrand, Z Physics at LEP I, CERN Report 89-08 Vol.III p.143
[4] ALEPH Collaboration , NIM , A294 (1990) 121
DELPHI Collaboration , NIM , A303 (1991) 233
L3 Collaboration , to be published
OPAL Collaboration , CERN-PPE/90-114
[5] T.Sjostrand,*Comput.Phys.Commun.* 39 (1986) 347
T.Sjostrand,M.Bengtsson,*Comput.Phys.Commun.* 43 (1987) 367
[6] G.Marchesini,B.Webber, *Nucl.Phys.*B310 (1988) 461.
[7] L.Lonnblad,U.Petterson, LU TP 88-15 (1988)
[8] L.R.Surguladze and M.A.Samuel, *Phys.Rev.Lett* 66 (1991) 56
S.G.Gorishny,A.L.Kataev,S.A.Larin,*Univ. of Michigan Report* UM-TH-91-01
[9] ALEPH Collaboration, CERN-PPE /91-105
DELPHI Collaboration , CERN-PPE /91-95
L3 Collaboration , Preprint 28 ,Feb.1991
OPAL Collaboration , CERN-PPE/91-67
[10] P.Nason,N.Magnoli,R.Rattazzi, UPRF 90-292 , 1990
[11] ALEPH Collaboration , *Phys.Lett.* 255B (1991) 623
ALEPH Collaboration , *Phys.Lett.* 257B (1991) 479
DELPHI Collaboration , CERN-PPE Sept 1991
L3 Collaboration , to be published
OPAL Collaboration , PN033 April 1991
OPAL Collaboration , PN032 April 1991
[12] K.Ellis,Ross,Terrano , *Nucl.Phys.*B178 (1981) 421.
[13] Z.Kunszt et al., Z Physics at LEP, CERN Report 89-08
[14] DELPHI Collaboration , *Phys.Lett.* 255B (1991) 466
[15] L3 Collaboration,*Phys.Lett.*B248,(1990),227
DELPHI Collaboration Communication to Singapore Conference.
OPAL Collaboration CERN-PPE /90 -97.
[16] L3 Collaboration Preprint 30, May 1991.
[17] OPAL Collaboration CERN-PN031, April 1991
[18] DELPHI Collaboration CERN-PPE 91-79 May 1991
[19] R.Brandelik et al., *Phys.Lett.*97B (1980) 453
H.J.Berends et al, *Phys.Lett.*110B (1982) 329
Ch.Berger et al., *Phys.Lett.* 97B (1980) 459
Physics Report 107 (1984) 163
K.Koller,H.Krasemann *Phys.Lett.* 88B (1979) 119
[20] E.Laerman,K.H.Streng,P.M.Zerwas, *Z.Phys.* C3 (1980) 289
J.G.Korner,G.A.Schuler,F.Barreiro, *Phys.Lett.*B188 (1987) 272
K.Koller,H.G.Sander,T.F.Walsh,P.M.Zerwas, *Z.Phys.* C6 (1986) 131

[21] P.Hoyer et al., *Nucl.Phys.* B161 (1979) 349
[22] W.Bartel et al., *Z.Phys.*C33 (1986) 23
[23] D.Amati, G.Veneziano, *Phys.Lett.* B83 (1979) 87
Ya.I.Azimov et al., *Z.Phys.* C27 (1985) 65
[24] H.Aihara et al., *Phys.Rev.* 57 (1986) 945
[25] W.Bartel et al., *Phys.Lett.* B101 (1981) 129
W.Bartel et al., *Z.Phys.* C21 (1983) 37
M.Althoff et al., *Z.Phys.* C29 (1985) 29
P.D.Sheldon et al., *Phys.Rev.Lett.* 57 (1986) 139
AMY Collaboration, *Phys.Rev.Lett.* 63 (1989) 1772
[26] OPAL Collaboration,*Phys.Lett.* 261B (1991) 334
[27] OPAL Collaboration, CERN-PPE /90-143
[28] OPAL Collaboration, CERN-PPE /91-91
[29] W.Bartel et al.,*Phys.Lett.* 123B (1983) 460
P.Bagnaia et al.,*Phys.Lett.* 144B (1984) 291
M.Derrick et al.,*Phys.Lett.* 165B (1985) 449
A.Petersen et al.,*Phys.Rev.Lett.* 55 (1985) 1954
G.Arnison et al.,*Nucl.Phys.* B276 (1986) 253
W.Braunschweig et al.,*Z.Phys.* C45 (1989) 1
Y.K.Kim et al.,*Phys.Rev.Lett.* 63 (1989) 1772