PROCEEDINGS OF SCIENCE

# Final state QCD studies at LEP: Part I

**Pedro Abreu**[*]
*LIP/IST*
*Av. Elias Garcia, 14, 1st, 1000-149 Lisboa, Portugal*
*E-mail:* abreu@lip.pt

**for the DELPHI and OPAL Collaborations**
*CERN*
*1211 Geneva 23, Switzerland*
*E-mail:* Jan.Timmermans@cern.ch,David.Plane@cern.ch

This is the first of two summaries presented in this conference, of results obtained by the DELPHI and OPAL Collaborations in studies of QCD in the final state, in two-photon and electron-positron collisions at LEP. This talk presents measurements of hadronic cross-sections in two-photon collisions from DELPHI, and thorough studies of QCD in events with 3 jets from DELPHI and from OPAL Collaborations at CERN. DELPHI has studied the charge of leading systems in quark and gluon jets, as well as the contribution of quark and gluon jets to the average event charged multiplicity as a function of the jet energy, and from it measured the ratio $C_A/C_F = 2.261 \pm 0.014(stat.) \pm 0.036(exp.) \pm 0.066(theo.)$. OPAL submitted a report of scaling violations in the quark and gluon fragmentation functions, of which a resume is here included, and measured the average charged particle multiplicity in inclusive hadronic $Z^0$ decays at several centre of mass energies and in flavour selected $Z^0$ decays, obtaining for the inclusive case at $\sqrt{s} = M_{Z^0}$ the value $\langle n_{ch}(M_{Z^0})\rangle = 20.93 \pm 0.01(stat.) \pm 0.23(syst.)$. All results are preliminary.

*European Physical Society*
*HEP2005 International Europhysics Conference on High Energy Physics*
*EPS (July 21st-27th 2005) in Lisboa, Portugal*

[*] Speaker





PoS(HEP2005)038

## 1. Introduction

The Large Electron Positron collider at CERN (LEP) provided the four experiments ALEPH, DELPHI, L3, and OPAL, with about 20 millions of hadronic $Z^0$ decays and 40 thousand pairs of W decays, in its running period of 1989 to 2000. The richness of its data, with an initial state free from partons to interfere with the final state and centre of mass energies well defined and in the large range of 89-209 GeV, constitutes an ideal environment for final state QCD studies and new results are still coming out and submitted to international conferences.

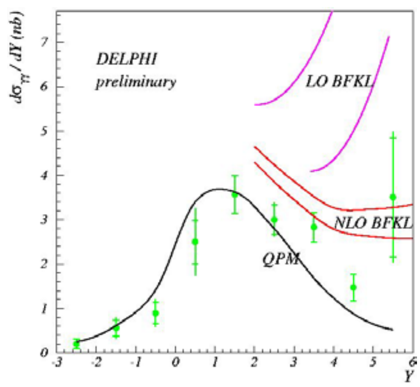
The characteristics of the data samples analysed are as follows:

| Collaboration | DELPHI (D) | | | OPAL (O) | |
|---|---|---|---|---|---|
| Contrib. Title | X-sect.$\gamma^*\gamma^*$ | Rapid. gaps | <$n_{ch}$> 3j 2g | Scal.Violat. q,g frag. func. | |
| Contrib.ref. | EPS#088 | EPS#096 | EPS#084 | EPS#256 | |
| Data Period | 1998-2000 | 1994-1995 | 1992-1995 | 1993-95 | 1997-2000 |
| Int. Luminos. | 550 $pb^{-1}$ | 70 $pb^{-1}$ | 175 $pb^{-1}$ | 130 $pb^{-1}$ | 690 $pb^{-1}$ |
| c.m.energies | 189-209 GeV | $\cong M_Z$ | $\cong M_Z$ | $\cong M_Z$ | 183-209 GeV |

This contribution is structured as follows. Section 2 presents results in two-photon collisions submitted by the DELPHI Collaboration [1], section 3 presents the studies in 3-jets events performed by the DELPHI and OPAL Collaborations [2-4], and in section 4 some conclusions are drawn. Because the list of references would be rather large, I refer the reader to the references cited in the submitted contributions [1-4], and all results are preliminary.

## 2. Double tagged Cross-sections in two-photon collisions

The collisions between two virtual photons coming from the initial state electrons[*] is a good system to probe QCD close to the non-perturbative regime, controlled by BFKL dynamics, more so in the case when both electrons are detected, because the kinematics of the two photon collision process is completely constrained. The figure shows the differential cross-section for the two-photon collisions into hadrons and compared with various model predictions. The Leading Order BFKL calculations disagree with the data, whereas the Next-to-Leading Order BFKL calculations are found in good agreement. The total cross-section for the process $e^+e^- \rightarrow e^+e^-$ + hadrons was measured to be $\sigma_{ee}$=2.09 ± 0.09(*stat.*) ± 0.19(*syst.*) pb, for the domain $Q_i^2$ between 10 and 200 $GeV^2$ and $W_{\mu\mu}$ between 2 and 50 GeV/$c^2$, with the corrections for detector based on the TWOGAM generator. The DELPHI data are in good agreement with the results of the other LEP experiments.




[*] in this contribution, electron stands both for electron and positron, and particles include both particles and its respective antiparticles.

## 3. Studies of QCD in events with 3 jets in the final state

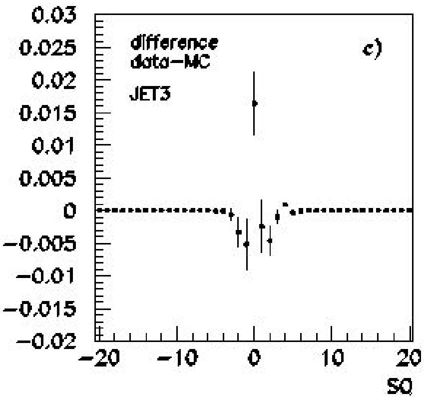
The $e^+e^-$ events with 3 jets in the final state constitute a wonderful laboratory to study the differences between the quark and gluon fragmentation processes. Depending on the selection criteria, the quark and gluon jets can be identified with high purities, and assuming massless jet kinematics, the energies of the three jets in planar events can be well estimated from the precise measurements of angles of the jets in the detectors; with $\vartheta_i$ being the angle between the two jets opposite to jet *i*, the energy of jet *i* is obtained from $E_i = \sqrt{s}\sin\theta_i / (\sin\theta_1 + \sin\theta_2 + \sin\theta_3)$.

Common criteria for the selection of events with 3 jets include the clustering of the event using Durham for a value of the jet resolution parameter $y_{\mathrm{cut}}$ =0.015, and the sum of interjet angles greater than 355 degrees (DELPHI) or 358 degrees (OPAL). For some samples, it was also required that the event contained b quarks (using a b-tagging algorithm), or that the selected quark jet had similar energy as the gluon jet (symmetrical Y events, that is, similar values for the two largest angles).

For the details about the analyses of the experiments at the specific centre of mass energies please consult the submitted contributions [2-4]. The main results from each of these contributions is now summarised.

### 3.1. Charge of leading systems in quark and gluon fragmentation

The neutralisation of the gluon colour field is implemented in most simulation models through the emission of double quark-antiquark pairs (double colour triplet fragmentation). But it could be via the emission of a pair of gluons (colour octet neutralisation), thus creating leading systems of two gluons. This effect would be enhanced, if in addition to gluon jets, an early decoupling of the gluonic system is requested (with rapidity gaps in the data).




Events with three jets and the two largest interjet angles in the range 135º±35º were used. For the jets in the study it was required a rapidity gap of $\Delta y$=1.5. The differences between the data and the model, as a function of the charge of the leading system, were found to be compatible to zero for the quark jets, whereas they are shown in the figure for 48 500 selected gluon jets, indicating an excess of 10% in data with respect to Monte-Carlo simulation with a significance of 3 standard deviations.

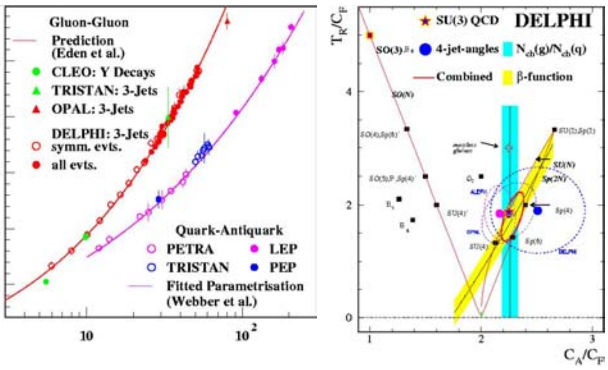
### 3.2. Scaling violations in quark and gluon jet fragmentation functions

OPAL has studied in great detail events with 3-jets, and from many distributions obtained, measured the fragmentation functions in quark and gluon jets, verifying the existence of scaling violations. From the integration of the fragmentation functions, obtained the following average charged particle multiplicities for several centre of mass energies and flavour selected events (the first error is statistical and the second error is the systematic contribution):

| $\sqrt{s}$ (GeV) | <N$_{ch}$> | <N$_{ch}$>(udsc) | <N$_{ch}$>(b) |
|---|---|---|---|
| 91.2 | 20.93±0.01±0.23 | 20.32±0.03±0.07 | 23.28±0.09±0.70 |
| 187.6 | 26.80±0.24±0.46 | 26.43±0.26±0.81 | 30.01±0.53±0.82 (samples merged at 197.0 GeV) |
| 198.0 | 27.68±0.26±0.50 | 27.38±0.31±0.85 | |
| 206.2 | 27.75±0.29±0.67 | 26.87±0.32±0.99 | |

### 3.3. Evolution of the charged particle multiplicities in events with 3 jets

The evolution of the charged particle multiplicity in $e^+e^-$ hadronic events with 3 jets can be used to probe QCD, in the approximation of Local Parton Hadron Duality, and particularly to extract a measurement of the ratio of the colour factors $C_A$ over $C_F$. A measurement of the multiplicity in the two-gluon system can be obtained from fits to the data, and this is compared to the multiplicity in quark jets in the figure (left). The measurement of $C_A/C_F$ yielded:




$$C_A/C_F = 2.261 \pm 0.014_{\text{stat.}} \pm 0.036_{\text{exp.}} \pm 0.066_{\text{theo.}}$$

The results can be used to restrict the QCD group structure to SU(3)$_C$, as shown in the figure (right). It was also shown that prediction Eden B is disfavoured with respect to Eden A.

## 4. Conclusions

From the contributions included in this analysis, it can be concluded that the QCD group structure is confirmed to be SU(3)$_C$, that most predictions agree with the data, but that there is an excess at the level of 10% of neutral leading systems in gluon jets, when compared to Monte Carlo simulated expectations, with a significance higher than 3 standard deviations.

## References

[1] V. Pozdnyakov and Yu. Vertogradova, *Double Tagged Cross-sections in Two-Photon collisions*, *DELPHI note* **2005-007** *CONF* **728** (2005) , contribution EPS#088 to this conference [http://delphiwww.cern.ch/delnote/…].

[2] M. Siebel, K. Hamacher, J. Drees, *Charged Particle Multiplicity in Three-jet events and Two-gluon systems* , *DELPHI note* **2005-012** *CONF* **732** (2005) , contribution EPS#084 to this conference [http://delphiwww.cern.ch/delnote/…].

[3] B. Bushbeck, F. Mandl, *Study of the Charge of Leading Hadrons in Gluon and Quark Fragmentation, DELPHI note* **2005-015** *CONF* **735** (2005) , contribution EPS#096 to this conference [http://delphiwww.cern.ch/delnote/…].

[4] G. Abbiendi *et al., Scaling violations of quark and gluon jet fragmentation functions in $e^+e^-$ annihilations at $\sqrt{s}$ =91.2 and 183–209 GeV, CERN* **PH-EP/2004-11**, *submitted to Eur. Phys. J. C.*, contribution EPS#256 to this conference .