PHOTON RADIATION FROM QUARKS AT LEP

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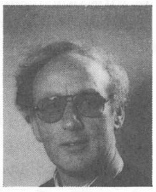

Abstract

Earlier measurements at LEP of isolated hard photons in hadronic Z^0 decays attributed to radiation from primary quark pairs, have been extended in the ALEPH experiment to include their production *inside* hadron jets. Events are selected where all particles combine "democratically" to form 2 hadron jets, one of which contains a photon with a fractional energy $z \geq 0.7$. After the statistical subtraction of events arising from non-prompt photons, the quark-to-photon fragmentation function, $D(z)$, is extracted directly from the measured prompt production rate. Taking into account the perturbative contributions to $D(z)$ obtained in an $O(\alpha\alpha_s)$ $\overline{MS}$ renormalisation scheme enables the unknown non-perturbative component of $D(z)$ to be determined at high z. This measurement provides a better description of quark bremmstrahlung than hitherto employed in high energy hadron-hadron collisions. A updated analysis is also presented from OPAL of comparisons between 1-jet plus isolated photon rates and different QCD matrix element calculations.

1 Introduction

Several studies have been made of the production of hard isolated prompt photons accompanying hadronic decays of the Z at LEP [1]. Their origin has been attributed to final state radiation (FSR) emitted at an early stage in the QCD parton evolution process initiated from the primary quark-antiquark pair. The main thrust of this work has been to compare with QCD $\mathcal{O}(\alpha\alpha_S)$ calculations at the parton level, and to test the detailed predictions of the parton shower models, JETSET, HERWIG, and ARIADNE to gain some insight into the parton evolution mechanism. Many features of the data are well described by the QCD calculations giving confidence that the process is well measured and understood.

In all these analyses, the candidate photon was isolated from the hadronic debris in an event using a geometrical cone centred around its direction inside of which a minimal residue of accompanying hadronic energy was allowed. This procedure was considered necessary to reduce the non-prompt photon backgrounds from hadron decays. In the next step, the photon was removed from the event before jets were formed with the other particles using a clustering recombination algorithm. The consequence was that any particles associated with the photon were incorporated into the other jets. Finally, an event was retained only if the candidate photon remained apart from the jets in a second application of the clustering algorithm. The appropriate QCD calculations available [2, 3] employ different procedures to avoid the infra-red and collinear singularities in the cross section at the parton level. This leads to complications in matching the resulting phase space to that defined for the data.

It was pointed out [2] that a safer approach would be to apply a jet recombination scheme simultaneously to all particles in an event, including the photon. This "democratic" approach does give an unambiguous matching definition of phase space between experiment and theory for all event topologies and handles correctly those hadrons which are associated naturally with the photon. However, it introduces a significant non-perturbative contribution to the cross section which depends upon the amount of accompanying energy allowed in the "photon jet". At first sight, this would appear to prevent the accurate comparison of data with the QCD predictions employed earlier. However, this previously unknown parton fragmentation contribution can be measured, thus adding new information to the dynamics of quark radiation; and at the same time giving an improved comparison of all FSR data with the QCD calculations.

The ALEPH experiment have adopted the "democratic" approach. A sample of 1.17M selected hadronic Z decay events are subdivided into 2-jet, 3-jet and $\geq$ 4-jet topologies using the DURHAM E0 algorithm with the resolution parameter, y_{cut}, varied between 0.001 and 0.33. Events are kept where at least one of the reconstructed hadron jets contains a photon ($E_\gamma > 5$ GeV) carrying $\geq 70\%$ of the total energy of the jet. The fractional energy z_γ of such a photon within a jet is defined as:

$$z_\gamma = \frac{E_\gamma}{(E_\gamma + E_{had})}$$

where E_{had} is the energy of all accompanying hadrons in the "photon jet" found by the clustering algorithm. Thus, events with completely isolated photons appear at $z_\gamma = 1$. Currently, the measured z_γ range is limited to $0.7 < z_\gamma < 1.0$ by residual hadronic decay backgrounds which are large for the 2-jet sample: ie events with a single hadron + "photon jet" topology. The z_γ distribution is divided into 6 equal bins between 0.7 and 1. In order to separate more clearly the large contribution coming from the hard photon component sitting at $z_\gamma = 1$, the last bin is split into the ranges $0.95 < z_\gamma < 0.99$ and $0.99 < z_\gamma \leq 1$.

Recently, a massless QCD $\mathcal{O}(\alpha\alpha_S)$ calculation [4] which includes the non-perturbative photon fragmentation diagrams has shown that the 2-jet z_γ distribution measures directly the quark-to-photon fragmentation function, $D(z_\gamma)$, when the final state partons and photon are treated "democratically". In this calculation the non-perturbative part of the $D(z_\gamma)$ function is described by a leading order (LO) evolution equation which can only be specified when the initial contribution at some unknown mass scale, μ_0, is known; this mass scale is expected to be near $\Lambda_{\overline{MS}}$. Relating reconstructed 2-jet event rates in the data directly to calculated parton 2-jet rates, a preferred value of μ_0 and an estimate of this initial non-perturbative contribution can be found.

2 Background subtraction and Systematic Errors

The non-FSR background in the selected 2-jet sample arises mainly from the decays of neutral hadrons ($\pi^0, \eta, \ldots$) where the photon depositions completely overlap in the electromagnetic calorimeter. Their contribution together with those from initial state radiation (ISR), and misidentified neutral hadrons is determined from a full simulation of JETSET events in the detector, and subtracted statistically from the data bin-by-bin in z_γ for each value of y_{cut}. A small contribution from $Z \to \tau^+\tau^-$ decays which pass the hadronic event selection is taken into account. At $y_{cut} = 0.1$, the ratio of measured FSR signal to predicted background is found to be 0.41 ± 0.05 for $z_\gamma > 0.7$ where 88% of this background arises from π^0s. Two independent methods are applied to determine the precision of the Monte Carlo simulation for the π^0s. In the first, it is noted that at least 90% of inclusively produced π^0s with $z_\gamma > 0.7$ originate from primary quark fragmentation or strong decays of resonances according to the parton-shower models. Hence, their production rate is equal to the average of the $\pi^\pm$ production in the same kinematic region according to isospin invariance. The latter has been determined in ALEPH with the charged tracks identified as $\pi^\pm$s by dE/dx measurements for values of z up to 0.8. The result agrees with JETSET predictions to $\pm 6\%$ at detector level between $0.6 < z < 0.8$. Thus, assuming that the efficiency of identifying $\pi^\pm$ is well simulated, JETSET describes inclusive π^0 production to an accuracy of 6% in this z range. The second method is less precise but extends over the full range of z_γ up to 1.0. Hard π^0s (and ηs) above 30 GeV are reconstructed from the 2-jet sample where one photon converts in the materials surrounding the interaction region to produce an e^+e^- pair. The ratio of the data to JETSET prediction is 1.04 ± 0.12 for $z > 0.7$, limited by statistics.

These results confirm the validity of the JETSET Monte Carlo for the background subtraction and quantify the systematic errors given in Fig 1 to the corrected FSR rate. The uncertainties in the z_γ distributions are dominated by statistical errors except in the region $0.85 < z < 0.90$.

3 Extraction of the Quark-to-Photon Fragmentation Function and Isolated Photon Components

After the subtraction of backgrounds, the measured z_γ distributions at each value of y_{cut} are corrected for acceptance and reconstruction inefficiencies, taking into account also the mixing of event topologies which can lead to a mis-measurement of z_γ. The corrections are obtained using the ARIADNE Monte Carlo; the results from HERWIG are consistent within statistics.

Between $0.7 < z_\gamma < 0.95$, the corrected differential z_γ distributions show a monotonically decreasing behaviour as expected for values of y_{cut} from 0.01 to the kinematic limit of 0.33. However, there is clear evidence that a fraction (about 20% at $y_{cut} = 0.1$) of the isolated photon component populates the $0.95 < z_\gamma < 0.99$ bin even though the experimental z_γ resolution is better than 0.01 for 2-jet events. This effect becomes more pronounced with increasing y_{cut}. It is attributed to the mis-association of very soft detected hadrons to the "photon jet" which does not occur at the parton level according to the ARIADNE and HERWIG Monte Carlos. Consequently, the z_γ distributions are analysed in two parts subdivided at $z_\gamma = 0.95$.

3.1 Jet Fragmentation region: $0.7 < z_\gamma < 0.95$

In ref[4], the non-perturbative component of the quark fragmentation function, $D(z_\gamma, y_{cut}, \mu_F)$, is separated from the calculable perturbative part at a non-physical scale μ_F. At fixed order, the evolution of this component can be described analytically in such a way as to cancel the $\ln(1 - z_\gamma)^2$ divergences and remove any overall μ_F dependence in the fragmentation function. The non-perturbative component is written as:

$$D_{np} = [A(z_\gamma, \mu_F^2/\mu_0^2) + B(z_\gamma, \mu_0)]/R_{LEP}$$

where A is the prescribed evolution term which together with B specifies the starting value of D_{np} when $\mu_F = \mu_0$. The value of μ_F is set arbitrarily to 10 GeV. At the Z, $R_{LEP} = 3.98 \times 10^3$ [4].

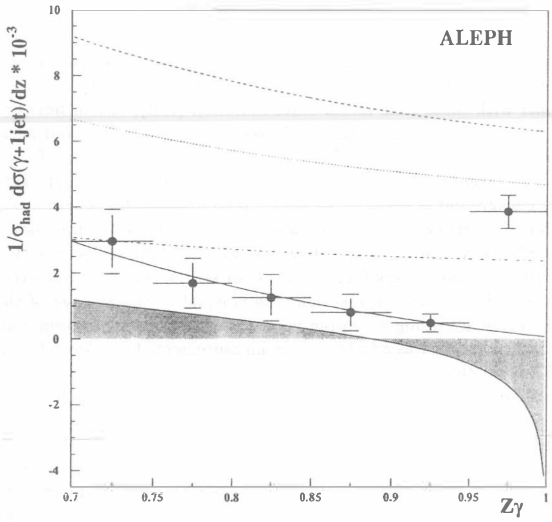

Figure 1: Fit to the data in the jet fragmentation region: the shaded area is the perturbative contribution to the fragmentation function ($\mu_F = 10$ GeV). The dashed, dotted and dashed-dotted curves show the addition of the A term to the perturbative contribution for values of μ_0 of 0.2, 1 and 10 GeV respectively.

Various parametrisations of B have been tried in fitting $D(z_\gamma, y_{cut}, \mu_F)$ to the data at $y_{cut} =$ 0.008,0.02,0.06, 0.1 and 0.33. These included a form : $B(z_\gamma, \mu_0) = C\ (1 + z_\gamma)^\beta$ in which the free parameters are μ_0, C and β. The data do not support full exploration of this parameter space, but it was found that the best fits are obtained when $\mu_0 \sim 0.2$ GeV and $\beta = 0.$. Fig 1 shows a fit obtained at $y_{cut} = 0.1$ to the 5 data points in the fragmentation region up to $z_\gamma = 0.95$. This is a 2 parameter fit from which values of C and μ_0 are found to be:

$$C = (-25.8 \pm 4.7)$$
$$\mu_0 = 0.16 \pm 0.16\ GeV$$

Thus, a low value of the initial scale is preferred, and a constant off-set must be ***subtracted*** from the LO evolution term to match the data. Fixing μ_0 to 0.2 GeV, single parameter fits are made to the z_γ distributions at the 5 y_{cut} values above. Consistent values for C are found, showing that the D function is universal in this formalism.

3.2 Isolated photon region: $0.95 < z_\gamma < 1$

The measured contribution of the D function in this region can now be added to the $\mathcal{O}(\alpha\alpha_S)$ calculation of the isolated photon component, which in the "democratic" approach depends only on y_{cut}, e_q and the quark electro-weak couplings at this order [4]. Fig 2 shows the comparison of the integrated normalised rate for 2-jet production in this z_γ region with this calculation as a function of y_{cut}. Overall, the agreement is very good even down to $y_{cut} = 0.005$. The 20% discrepancy at high y_{cut} may be accounted for by higher order corrections [5]. In contrast to ARIADNE and HERWIG predictions which compare well with the data, Fig 2 shows that the agreement with JETSET is very poor indicating that the treatment of the hard photon emission in the matrix elements is incorrect.

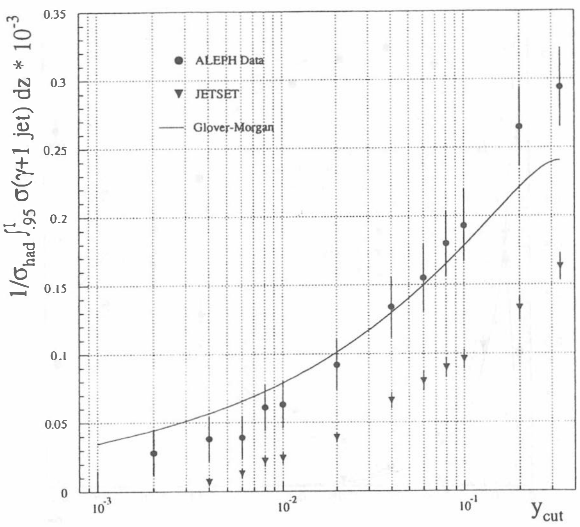

Figure 2: The 2-jet rate above $z_\gamma = .95$ as function of y_{cut}.

4 The 2-step Cone Analysis

The OPAL collaboration [6] have made a further more detailed comparison of the properties of isolated FSR photon events with two $\mathcal{O}(\alpha\alpha_S)$ calculations, namely GNJETS [3] and EEPRAD [2]. The cone half-angle is reduced to 10° and the detected angular coverage increased. They show that provided the photon energy is below 40 GeV and has non-zero transverse momentum to the thrust axis, then the *absolute* 2-jet + photon and 3-jet + photon rates dominate and they both agree very well with the QCD calculations for the same chosen value of α_S. Hence, these selections are suitable for the extraction of the electroweak couplings. However, the 1-jet + photon rates do not agree so well, especially for EEPRAD as shown in Fig 3 where relative jet rates are shown as a function of y_{cut} (using the JADE clustering algorithm). In contrast to the "democratic" method, this 1-jet rate is also sensitive to α_S.

Although the differences between GNJETS and EEPRAD when applied to this analysis are not understood, it is clear that the phase space cuts which have to be introduced to avoid singularities do not give reliable predictions for this part of the cross section.

5 Conclusions

Using the "democratic" approach, the ALEPH collaboration have measured the high z part of the LO quark fragmentation function and shown that its contribution can be taken into account in the extraction of the isolated photon rates. It is also possible to show that this procedure can be extended to higher jet multipicities and with an appropriate choice of α_S gives excellent agreement with the data. This measurement of the quark fragmentation function provides a better description of the bremsstrahlung contribution in prompt photon production in high energy hadron-hadron collisions than was available hitherto.

The OPAL analysis highlights the problems of the 2-step cone analysis and suggests that the solution for a complete desciption of the full range of photon energies lies in the introduction of the

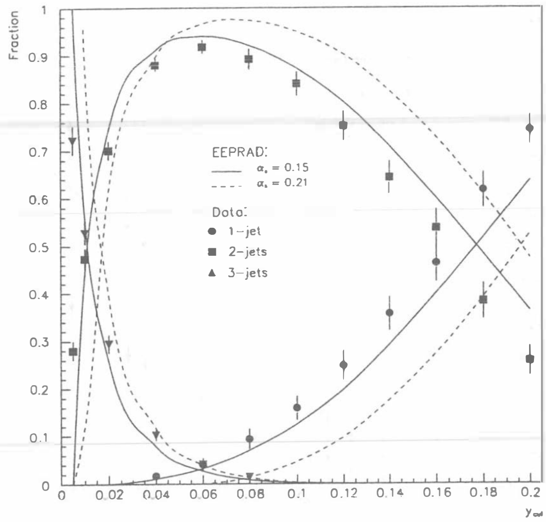

Figure 3: OPAL relative jet rates.

quark fragmentation function.

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References

[1] OPAL Collaboration, P. D. Acton et al., *Z Phys.* **C58** (1993) 405,
ALEPH Collaboration, D. Buskulic et al., *Z Phys.* **C57** (1993) 17,
DELPHI Collaboration, P. Abreu et al., *Z Phys.* **C53** (1992) 555,
L3 Collaboration, O. Adriani et al., *Phys. Lett.* **B292** (1992) 472.

[2] E.W.N.Glover and W.J.Stirling, *Phys. Lett.* **B295** (1992) 128.

[3] G.Kramer and H.Spiesberger, Workshop on Photon Radiation from Quarks, Annecy, Dec 1991, CERN 92-04.

[4] E.W.N.Glover and A.G.Morgan, DTP/93/50.

[5] E.W.N.Glover and A.G.Morgan, *Phys. Lett.* **B324** (1994) 487.

[6] W.Zeuner, Contribution to this conference.