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Measurement of Isolated Photon Production in Hadronic Z Decays

The ALEPH Collaboration*

Abstract

The production of high energy isolated photons in hadronic Z decays is measured with the ALEPH detector at LEP using a sample of 180000 hadronic events. Such photons are mainly radiated by quarks, thus giving direct insights into the early parton showering mechanism. The observed rate is compared with a QCD calculation of final state radiation from quarks.

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1 Introduction

In this paper, a measurement of the production of high energy isolated photons in hadronic Z decays is presented.

The decay of hadrons, mainly π^0 and η^0 , produces a copious rate of photons (“non-prompt” photons). However, photons coming from the point-like e^+e^- interaction (“prompt” photons) can dominate over the non-prompt background if they are emitted away from the jet directions and with an energy of several GeV.

In the Standard Model, prompt photons are mainly produced by final state radiation (FSR) from the quarks, with a small contribution from initial state radiation (ISR), which is suppressed at the Z pole. Hard photons emitted from the quarks are the only “partons” produced in the primary interaction that are detectable free of fragmentation effects, thus providing a test of the theoretical understanding of the early hadronic shower development, and in particular of the interplay between electromagnetic and strong interactions.

Since the electric charge of u-type quarks is twice the electric charge of d-type quarks, a sample of hadronic events with a FSR photon is enriched in u-type quarks by a factor 4. This fact could be used to extract the couplings of the quarks to the Z [1, 2]. However, this can only be done provided the dynamics of photon radiation from quarks is well understood.

Prompt-photons are also a signature for new physics (composite quarks, composite particles, exotic Higgs particles, exotic decays of the b' etc...). A search for these new processes requires a good knowledge of FSR photons which form the main background.

This measurement is based on a sample of 186040 hadronic Z decays collected in 1989 and 1990 at centre of mass energies between 88 and 95 GeV, corresponding to an integrated luminosity of 8.5 pb^{-1} . The percentage of events collected at the peak was 70%.

The ALEPH detector, including its trigger, is described in detail elsewhere [3].

2 Hadronic Event Selection

The selection of hadronic events is based on charged tracks [4].

Charged particle tracking is provided by a drift chamber (ITC), surrounded by a large cylindrical time projection chamber (TPC), inside a 1.5 T superconducting solenoid. Tracks traverse at least 6 TPC pad rows down to polar angles of 18.2° . The momentum resolution, determined from dimuon events, is $\Delta p_\perp/p_\perp^2 = 0.8 \cdot 10^{-3}(\text{GeV}/c)^{-1}$. The single track finding efficiency in hadronic events is about 99% for transverse momenta above 200 MeV/c.

Tracks are required to originate in a cylinder centred on the interaction point, with a 2.5 cm radius in the plane transverse to the beam direction, and a ± 7 cm length along the beam direction, to have a polar angle $\theta > 18.2^\circ$ and a minimum of 4 reconstructed TPC coordinates. An event must have at least 5 such “good” tracks and the sum of the energies of the tracks must be greater than 10% of the centre of mass energy. This selection has an efficiency of $97.4 \pm 0.2\%$, including a trigger efficiency of $99.96 \pm 0.02\%$. The background from τ pairs and two-photon production is less than 0.25% [4].

The polar angle of the thrust axis, θ_{Thrust} , determined with charged tracks must lie in

the range $25^\circ \leq \theta_{Thrust} \leq 155^\circ$. After this cut, the sample reduces to 172391 events.

3 Photon Identification

Photons are detected in the electromagnetic calorimeter (ECAL) surrounding the TPC and placed inside the coil. The calorimeter is instrumented down to 11° from the beam. It is divided into a barrel and two end-caps, each separated in azimuth into 12 modules. Each module consists of 45 lead plates interspersed with proportional tubes filled with a mixture of Xe(80%) and CO₂(20%). These plates are grouped in three stacks of 4, 9 and 9 radiation lengths in depth. Ionization in the gas induces charges that are collected on segmented cathode planes ("pads"). The pads from consecutive planes are connected to form projective towers covering an angular region of $0.8^\circ \times 0.8^\circ$ each on average. Each tower is read out in three successive storeys in depth, corresponding to the three stacks. Anode wire signals are summed plane by plane, giving 45 read-out channels per module.

The response of the ECAL to electrons and photons has been studied with $e^+e^- \rightarrow e^+e^-$, $(e^+e^-)e^+e^-$, $e^+e^- \gamma$ and $\mu^+\mu^- \gamma$ events. The energy resolution has been measured in the energy range from 1 GeV to the beam energy to be $(\Delta E/E)^2 = ((2.5 \pm 0.1)\%)^2 + ((19.9 \pm 0.3)\%/\sqrt{E})^2$ (E in GeV). The angular resolution is typically $4 \text{ mr}/\sqrt{E}$ (E in GeV).

Photons deposit their energy in a cluster of storeys. A cluster is reconstructed as a set of connected storeys each with an energy above 30, 30 and 60 MeV respectively in the 3 stacks. There must be at least one storey with more than 90 MeV in a cluster.

Photons are searched for among clusters that are not linked to a reconstructed charged track ("neutral" clusters), and whose barycentre positions are in the range $18^\circ < \theta < 162^\circ$ and are not near a crack between two ECAL modules (the position of the barycentre of the cluster must not be within the pad row at the edge of a module in ϕ ; this causes a 6% loss in the barrel). Clusters originating from neutral hadrons are rejected by requiring that the fraction of energy deposited in the third stack be less than 40%. The efficiency for this cut to retain photons of more than 10 GeV is $97.0 \pm 0.2\%$ for such "electromagnetic neutral" clusters, independent of energy.

The lateral spread of the cluster is used to separate a single photon from a π^0 or η or several unrelated photons : the transverse shape of a cluster is characterized by the fraction F_4 of its total energy that is contained in the subcluster of 2×2 adjacent towers whose energy is maximum (leading subcluster).

A sample of identified single photons has been obtained from radiative dimuon and Bhabha events, using their 3-body kinematics. The corresponding F_4 distribution is shown in figure 1:a a single photon of more than 5 GeV deposits on average 86% of its energy in the leading subcluster, with an r.m.s spread of 4%.

In contrast, a high energy π^0 materializes as a cluster whose width depends on its energy. A rich sample of such clusters is available in τ pair events. The corresponding F_4 distribution is shown in figure 1:b for clusters of more than 10 GeV.

Photon candidates are defined by the cut $F_4 > 0.75$. The measured efficiency for this cut is $99.5 \pm 0.4\%$ for photons, independent of energy. The efficiency for π^0 s is 20% at 10 GeV, 50% at 15 GeV and reaches 95% at 30 GeV.

From the agreement between data and the simulation shown in figure 1, it is concluded that the behaviour of photons and π^0 s is well understood in the ALEPH electromagnetic calorimeter. A systematic error of 1% on the acceptance of photons is assigned.

4 Photons in Hadronic Events

For hadronic Z decays, the bulk of the photons in the final state come from π^0 decay. This is illustrated in figure 2:a, which shows the distribution of F_4 for neutral electromagnetic clusters of energy greater than 10 GeV.

4.1 Isolated Photon Selection

The production of π^0 s or η s results from a series of cascades in the hadronization of quarks and gluons. Consequently their energy spectrum is much softer than that of photons from FSR and they are less isolated from other fragmentation remnants. Therefore events are selected with a high energy isolated neutral electromagnetic cluster.

The isolation condition is defined in terms of a cone with a 20° half opening angle around the direction of the candidate photon. It is required that no charged track with momentum greater than 500 MeV/c is found inside the cone, nor any other neutral electromagnetic cluster with an energy above 500 MeV.

A total of 733 events have a neutral electromagnetic cluster with energy greater than 10 GeV which satisfies the above isolation criteria.

This definition of the isolation has been chosen in order to keep a large number of prompt photons while being efficient in rejecting the background. However this definition is sensitive to the distribution of low energy fragments around jets and to the presence of noise in the ECAL. This effect has been studied using randomly oriented vectors which were inserted into hadronic events in the data and in the simulation. The fractions surviving the isolation condition applied to them were compared. Figure 3: shows the variation of these fractions as a function of their angle θ_{jet} to the nearest jet. Jets are defined using the jet finding algorithm of JADE [9], using charged tracks only, with a scaled invariant mass cut of $y_{cut} = 0.02$. Data and simulation agree to better than 2% for $\theta_{jet} > 30^\circ$. However the fraction of isolated vectors in the data exceeds that of the simulation by 15% for $\theta_{jet} < 20^\circ$.

As a result of this systematic check the analysis of isolated neutral clusters has been restricted to the region $\theta_{jet} > 30^\circ$. After this cut the number of isolated prompt photon candidates is reduced to 621. Figure 2:b shows the F_4 distribution of the selected clusters in this sample. One can see from this figure that the isolation plays an important role in reducing the background.

After the final photon identification cut ($F_4 > 0.75$) 419 candidates remain.

A display of a prompt photon candidate with $E_\gamma = 29$ GeV is shown in figure 4:. As described in ref [5], events with such a striking topology have been used as a control sample in the search for the standard Higgs boson.

Other definitions for the isolation criterion have been considered. The energy thresholds for the charged tracks and the ECAL clusters within the cone were varied from 250 MeV to 1

GeV; several types of ECAL clusters were used in the isolation cone ranging from raw neutral ECAL clusters to identified photons with all selection criteria as described in section 3. Each definition has been tested using random vectors. From the differences between data and the simulation the systematic error on the acceptance due to the isolation is estimated to be 6%.

4.2 Background Subtraction

With the same isolation criteria, a high statistics Monte Carlo simulation of hadronic events with the JETSET 6.3 generator [6] predicts 71 ± 7 events from background sources in the signal region ($F_4 > 0.75$) of which 15 are from ISR.

In order to verify the Monte Carlo prediction for the rate of non-prompt background the following checks have been performed using the data.

The number of isolated clusters from non-FSR sources has been monitored in the region $F_4 < 0.75$. Comparison with the simulation (fig. 2:b) shows an excess of data of $29 \pm 10\%$, independent of energy within errors. Monte Carlo studies show that π^0 s and η s account for 95% of the background for $F_4 < 0.75$. This excess could therefore be due to an underestimate of the number of isolated π^0 s or η s in the fragmentation model. This was checked for π^0 energies less than 20 GeV, where the two photons from a π^0 can be resolved with an efficiency of 25%. The number of resolved and isolated π^0 s in the data exceeds that from the simulation by $43 \pm 15\%$.

The numbers of events with isolated charged tracks also provides a test of the validity of the fragmentation model. For the same isolation criteria as described in section 4.1, but replacing the ECAL cluster by a charged track, the yield of isolated charged tracks of more than 10 GeV/c momentum is $14 \pm 5\%$ greater than predicted by the Monte Carlo simulation.

These comparisons indicate an underestimate of the π^0 background from the simulation in the signal region $F_4 > 0.75$. Therefore the Monte Carlo prediction for the background from non ISR sources in this signal region is rescaled by 30% leading to an increase of the total background from 17% to 21%. A systematic error of $\pm 15\%$ is assigned to the background level. With the 21% background achieved in this analysis, this uncertainty translates to a 3% uncertainty on the prompt photon rate.

5 The Prompt Photon Signal and Interpretation

The final number of events is given in table 1 as a function of the photon energy. The total background is the sum of the initial state radiation and the non-prompt contribution increased by 30% as explained previously.

The systematic errors are summarized in table 2. The total systematic error is 7%, mainly due to uncertainties in the isolation and the background subtraction.

The number of events with $E_\gamma > 10$ GeV is $331 \pm 22(stat.) \pm 23(syst.)$. A clear signal of prompt photons is observed. In the following this signal will be interpreted within the Standard Model in terms of FSR from quarks.

The calculation of FSR given by the JETSET 7.3 program is used [7]. At present, this is the only available calculation of final state radiation from quarks in the framework of QCD.

Photons are produced in the parton shower in the same way as gluons. This prediction depends on the values of the QCD scale parameter Λ_{QCD} and the minimum parton invariant masses allowed in the showering, M_{min}^g for a gluon radiation and M_{min}^γ for photon radiation. The assumed values for these parameters are given in table 2 together with the effect of a change within the range allowed by measurements for Λ_{QCD} and M_{min}^g ([8]). A change of M_{min}^γ over a large range does not affect the rate of high energy isolated FSR photons. The total theoretical uncertainty within the JETSET 7.3 model is estimated to be 3%.

From the results in table 1, the ratio of data divided by the JETSET 7.3 prediction is: $1.19 \pm 0.12(exp.) \pm 0.04(theor.)$. The distributions of the photon energy (figure 5:a) and of the transverse momentum $p_\perp$ of the photon with respect to the thrust axis (figure 5:b) follow qualitatively the JETSET 7.3 prediction. At the present level of statistics, a possible excess cannot be assigned to a particular region of phase space.

As a final systematic check, the effect of varying the θ_{jet} cut is shown on figure 6:. For a θ_{jet} cut smaller than 30° , the ratio of the data divided by the JETSET 7.3 prediction is increased. This was expected from the systematic study using random vectors presented in section 4.1. For θ_{jet} cut larger than 30° , the ratio is stable. For instance for θ_{jet} cut = 50° the observed number of final state prompt photons is $258 \pm 19(stat.)$ while the JETSET 7.3 prediction is $218 \pm 5(stat.)$, giving a ratio of $1.18 \pm 0.08(stat.)$. This indicates that the systematic uncertainties due to the definition of the isolation are under control.

6 Summary

Using a sample of 172391 hadronic events collected by the ALEPH collaboration in 1989 and 1990, a clear signal of

$$331 \pm 22(stat.) \pm 23(syst.)$$

isolated final state prompt photons has been observed for $E_\gamma > 10$ GeV.

Since the contribution of initial state radiation has been already subtracted, the isolated prompt photons, within the Standard Model, come from final state radiation of quarks. The expected number of such photons in the framework of the JETSET 7.3 model is:

$$279 \pm 6(stat.) \pm 8(theor.)$$

The observed rate is larger than the prediction by $19 \pm 13\%$. However, at the time of this analysis, it is not known whether the JETSET 7.3 model provides an adequate theoretical description of the photon radiation from quarks, a process which is sensitive to strong interaction effects.

This sensitivity can be demonstrated by comparing JETSET 7.3 with DYMU3 [10], a generator producing fermion pairs in the absence of gluons but with electroweak radiative effects included. Parton showering and hadronization are then treated by JETSET 6.3. In this case, the expected number of isolated photons with $E_\gamma > 10$ GeV is $538 \pm 18(stat.)$ significantly higher than both the data and the JETSET 7.3 prediction. This indicates the need for an accurate treatment of the interplay between photon and gluon radiation in the final state.

The measurement described in this paper can then be used to test our understanding of the quark gluon showering process.

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Table 1: Number of events observed as a function of the energy of the isolated photon candidate, and estimates for background and FSR. Errors are statistical only.

Energy (GeV)	Data	Background (MC estimate)		Total Background (corrected)		Data (background subtracted)	FSR prediction
		ISR	non-prompt				
10-15	120	11.3 ± 2.7	15.7 ± 3.1	31.7 ± 4.9		88.3 ± 12.1	82.6 ± 3.1
15-20	82	0.6 ± 0.6	12.6 ± 2.8	17.0 ± 3.7		65.0 ± 9.7	55.3 ± 2.5
20-25	64	0.6 ± 0.6	4.4 ± 1.7	6.3 ± 2.2		57.7 ± 8.3	42.3 ± 2.2
25-30	42	0.6 ± 0.6	6.3 ± 2.0	8.8 ± 2.7		33.2 ± 7.0	32.4 ± 1.9
30-35	45	0.0 ± 0.0	5.0 ± 1.8	6.5 ± 2.3		38.5 ± 7.1	25.9 ± 1.7
35-40	38	0.0 ± 0.0	8.2 ± 2.2	10.6 ± 2.9		27.4 ± 6.8	25.5 ± 1.7
> 40	28	1.9 ± 1.1	3.8 ± 1.5	6.8 ± 2.3		21.2 ± 5.8	14.7 ± 1.3
Total	419	15.1 ± 3.1	55.9 ± 5.9	87.8 ± 8.3		331.2 ± 22.1	278.7 ± 5.6

Table 2: Summary of errors for the isolated photon sample with $E_\gamma > 10$ GeV. For the theoretical errors, the changes in the yield of FSR isolated photons correspond to the changes of the parameters of the model in the quoted ranges. The 1σ total error corresponds to half of the parameter ranges.

Experimental Errors	Photon identification	1%
	ECAL energy calibration	1%
	Isolation	6%
	Background subtraction	3%
	Total systematic error	7%
	Statistical error	7%
	Total experimental error	10%
Theoretical Errors on the prediction for FSR (JETSET7.3)	$\Lambda_{QCD} = 300$ MeV (tuned, see [8]) range 260 $\rightarrow$ 400 MeV	-2%
	Invariant mass cut-off for gluons: $M_{min}^g = 1.5$ GeV (tuned, see [8]) range 1 $\rightarrow$ 2 GeV	+5%
	Invariant mass cut-off for photons: $M_{min}^\gamma = 1$ GeV (default) range 100 MeV $\rightarrow$ 5 GeV	<1%
	Total theoretical error ($\pm 1\sigma$)	$\pm 3\%$

Figure Captions

- Figure 1: Fraction of cluster energy in the leading subcluster for (a) tagged photons in $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ events (b) π^0 s in $\tau^+\tau^-$ events. The histogram represents the Monte Carlo simulation.
- Figure 2:: Fraction F_4 of cluster energy, for neutral electromagnetic clusters of energy greater than 10 GeV in hadronic events (a) not isolated (b) isolated. The shaded area represents the background. The black area represents the ISR contribution. The histogram represents the total simulation including FSR.
- Figure 3:: (a) Fraction of isolated random vectors as a function of the angle to the nearest jet θ_{jet} for data (full circles) and simulation (histogram). (b) Ratio of the fraction of isolated random vectors in the data divided by the same fraction in the simulation.
- Figure 4:: A display of an event with a prompt photon candidate with $E_\gamma = 29$ GeV.
- Figure 5:: Prompt photon candidates (a) energy spectrum (b) $p_\perp$ with respect to the thrust axis. The shaded area represents the corrected background. The black area represents the ISR contribution. The histogram represents the total simulation including FSR.
- Figure 6:: Ratio of prompt photon rate in the data over the simulation as a function of the cut on the angle θ_{jet} to the nearest charged jet. Errors are statistical only.

Figure 1:a

Figure 1:b

Figure 2:a

Figure 2:b

Figure 3:

HCAL 2 GeV |————|

ECAL 10 GeV |————|

ECAL wires 2 GeV |————|

Figure 4:

Figure 5a:

Figure 5b:

Figure 6: