Radiation from Quarks: Data Samples of the LEP Experiments

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Abstract

Results on extraction of final state radiation in hadronic events from the four LEP experiments are presented. Agreement amongst the four LEP experiments is excellent, but theoretical predictions of the rate of final state radiation are systematically about 20% below the experimental data.

1 Introduction

Final state radiation from quarks is important (a) as a probe of fragmentation and hadronisation, i.e. as a probe of QCD, (b) as a way to measure the quark couplings[1], and (c) as a sensitive signal of new physics beyond the standard model, e.g. as a sign of compositeness.

In the workshop title 'Radiation from Quarks', the use of the word 'quarks' implies hadronic events, and the use of the word 'radiation' implies isolated photons in those hadronic events. Photon isolation from the hadrons is necessary because of an otherwise overwhelming background from hadronic decays, especially $\pi^0$'s. There are on average about 20 charged particles and approximately the same number of neutral particles produced in the hadronic decay of a $Z^0$ boson. These particles are the end-products of the fragmentation and hadronisation of the quark-antiquark pair into which the $Z^0$ decays with a branching fraction of about 70%.

Selection of hadronic, i.e. $q\bar{q}$, decays of the $Z^0$ is relatively straightforward and can be accomplished with approximately 100% efficiency by each of the four LEP experiments, thanks largely to the high multiplicity. Each LEP experiment has a standard hadronic event selection procedure which was used to determine the parameters of the $Z^0$ line shape into hadrons.

The photons in hadronic events are detected in an electromagnetic calorimeter. Characteristics of the calorimeters vary significantly from experiment to experiment, and in fact the differences in the electromagnetic calorimeters account for most of the differences in the analyses by the four LEP experiments.

2 General Experimental Characteristics

The principal ingredients of the analysis are as follows:

(1) Select hadronic events. This is relatively straightforward, and can be accomplished with essentially 100% efficiency by each of the four LEP experiments.

(2) Select photons. This involves a series of selections to secure a sample of hadronic events which contain isolated photons as candidates for final state radiation.
(a) \( E_\gamma > E_\gamma^{\text{min}} \). Such a cut is necessary because at low photon energies the background from photons arising from the decay of low energy \( \pi^0 \)s is large. In addition, the electromagnetic calorimeters have reduced efficiency at low energy, but the cut on lowest photon energy imposed by physics considerations is generally much higher than any limit imposed by calorimeter efficiency.

(b) \( |\cos \theta_\gamma| < |\cos \theta_\gamma^{\text{max}}| \), where \( \theta_\gamma \) is the polar angle of the photon with respect to the beam axis. Such a cut on polar angle is necessary to reduce background from initial state radiation which is intrinsically peaked much more in the forward direction than is final state radiation. In addition, the electromagnetic calorimeters cover limited solid angles, and generally do not extend their coverage too far into the forward direction.

(c) **Particle Identification.** In general, at low enough energy, single isolated photons can be distinguished from close-by pairs of photons which arise from the decay \( \pi^0 \rightarrow \gamma \gamma \). This may be accomplished by study of the shower shape in the electromagnetic calorimeter, and therefore depends critically on the specific characteristics of each calorimeter.

(d) **Photon Isolation.** This is the most powerful cut of all in extracting a signal of candidates for final state radiation. Isolation criteria are generally of two types. The first is called 'particle isolation' in which events are rejected if there is evidence of any other particles, charged or neutral, within a cone of so-many degrees about the photon candidate. The second is called 'jet isolation' in which events are rejected if there is a hadronic jet axis within a cone of so-many degrees about the photon candidate. The different LEP experiments use the different isolation criteria, and on occasion use both. A variation on 'jet isolation' uses the \( y \) variable to help select isolated photons. The \( y \) variable is the square of a scaled invariant mass, i.e. \( y_{ij} = M_{ij}^2 / E_{\text{cm}}^2 \) or \( y_{ij} = M_{ij}^2 / E_{\text{vis}}^2 \), where \( M_{ij} \) is the invariant mass of jets \( i \) and \( j \), \( E_{\text{cm}} \) is the total center of mass energy, and \( E_{\text{vis}} \) is the total visible energy in the event. Isolation is imposed by requiring that \( y_{\gamma \gamma} \) be larger than some value \( y_{\gamma \gamma}^{\text{cut}} \), where \( y_{\gamma \gamma} \) is the scaled square of the invariant mass of the photon and the \( i \)-th jet.

(e) **Other Cuts.** These may be needed to improve the signal-to-noise ratio. For example, a cut may require the transverse momentum of the photon with respect to a jet axis or the event thrust axis be larger than some value. This is useful because Monte Carlo studies show that final state radiation from quarks has a significantly broader distribution in transverse momentum than photons from e.g. \( \pi^0 \) decay.

(3) The processes contributing to the sample are: (i) final state radiation, which is the signal, and the background processes (ii) initial state radiation, (iii) QCD processes, e.g. \( \pi^0 \) decays, and (iv) \( \tau \) decays.

3 **The LEP Experiments**

The experiments were performed at the LEP \( e^+ e^- \) collider. Results are reported from the ALEPH\[2, 3\], DELPHI\[4\], L3\[5\], and OPAL\[6, 7, 8\] experiments.

Figure 1 shows the distributions of the photon energy and of the transverse momentum \( p_\perp \) of the photon with respect to the thrust axis from the ALEPH experiment. The distributions follow qualitatively the JETSET 7.3 predictions. At the present level of statistics the ALEPH analysis cannot assign a possible excess to a particular region of phase space. However, the \( p_\perp \) distribution shows that the large \( p_\perp \) region is relatively free of background.
Figure 1: Prompt photon candidates (a) energy spectrum (b) $p_T$ 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 2 shows the distribution of the transverse momentum with respect to the thrust axis for energetic isolated photons in the DELPHI experiment. Also shown are the predictions of the Monte Carlo calculation for final state radiation (FSR), and for the background processes (ISR + QCD + $\tau$) plus final state radiation. The background dominates the region $p_T < 5$ GeV/c. A cut of $p_T > 5$ GeV/c reduces the number of energetic isolated photons from background processes (ISR + QCD + $\tau$) by more than a factor of two, but reduces the signal (FSR) by only 12%. In the region $p_T > 5$ GeV/c, the Monte Carlo prediction for background plus final state radiation agrees well with the observed data.

Figure 3 shows the distribution of $E_\perp$ with respect to the thrust axis after application of the “local isolation” cuts for the L3 experiment, but before any cluster analysis was performed. A clear signal from prompt photons is observed. According to JETSET more than 3/4 of the events selected by the local isolation cuts are final state photons, while this figure is only about 1/4 for the “jet isolation” analysis.

Figure 4 shows the distribution in the corrected fraction of multihadronic events with final state photons as a function of $y_{cut}$ in the OPAL experiment. The yield decreases by about a factor of 10 for an increase of $y_{cut}$ from 0.005 to 0.2. At these high $y_{cut}$ values the photon and the jets are mostly in different hemispheres, and a further increase of $y_{cut}$ has only a marginal effect on the fraction. The matrix element calculation[9] is in good agreement with the data for $y_{cut} < 0.12$ but is one to two standard deviations below the data at high $y_{cut}$ (fig. 4a). Note that data at different values of $y_{cut}$ are correlated. As can be seen from figure 4b, at low $y_{cut} < 0.02$, the three jet rate is
Figure 2: Transverse momentum distribution of isolated energetic photons with respect to the event thrust axis, showing data (points with errors), simulation including only FSR (cross hatched area), and simulation including FSR plus the backgrounds from ISR, QCD and \(\tau\) decays. The event thrust axis is calculated using all the charged particles in the event.

At \(y_{\text{cut}} > 0.14\) the one jet rate becomes prominent. Also shown are the expectations from the matrix element calculation. The theoretical two jet rate is in good agreement with the measured rate for all \(y_{\text{cut}}\). However, the theoretical calculation underestimates the one-jet rate significantly.

4 Comparison of the LEP Experiments

Table I shows a detailed comparison of the analysis of the four LEP experiments to extract a signal of final state radiation and the results of that analysis.

In the first horizontal data section of Table I the numbers of hadronic events selected for this analysis are listed. Each experiment uses the full 1990 data sample except for L3 which has restricted its analysis to data taken at \(\sqrt{s} = 91.2\) GeV, i.e. atop the \(Z^0\) peak only. This was done because initial state radiation is suppressed on the \(Z^0\) peak as is interference between ISR and FSR. None of the Monte Carlo simulations include such interference.

In the second horizontal data section of Table I the cuts to select photons apart from the isolation criteria are listed. For experiment L3, only the "local isolation" analysis results are shown. Each experiment imposes a minimum photon energy and a minimum photon angle with respect to the beam for the photon to be accepted. These are similar in all four experiments except for the angle cut in the ALEPH experiment which allows photons well into the forward region while the other three experiments confine their samples to the barrel region, i.e. \(45^\circ < \vartheta_\gamma < 135^\circ\). The quantity \(\epsilon(\gamma \text{ ID})\) is the efficiency of photon identification. Since the DELPHI experiment does not rely on detailed shower shape information to separate single photons from \(\pi^0\) decays into several photons,
Figure 3: L3 Experiment. The $E_1$ distribution for data and JETSET after the "local isolation" cuts. No cluster shape analysis applied yet.

This entry is the efficiency caused by photon losses due to conversions in material in front of the DELPHI electromagnetic calorimeter. The last entry in this section is the efficiency for $\pi^0$ rejection which in general is a function of energy, but which is shown at a value of 20 GeV except for the DELPHI experiment which did not use this technique.

The third horizontal data section of Table I shows the isolation criteria used by each experiment. In each experiment a candidate photon was rejected if the detector showed evidence of 'significant' activity in a cone about the candidate photon direction. The cone angle is similar in each case, and the energies listed for charged and neutral activity respectively are the maximum energies below which some low-level noise would not cause the photon candidate to be rejected. These levels depend on detailed knowledge of the electromagnetic calorimeters, including noise levels, granularity, energy resolution, reconstruction efficiency of low energy objects, etc.

In addition, three of the four LEP experiments impose another cut to improve the signal-to-noise ratio. The ALEPH experiment requires that the angle between the photon direction and the axis of the nearest jet be larger than 30°. This was done because the jet axis is probably a more robust quantity than the momenta of particles near the edge of a jet. The DELPHI experiment imposes a cut that the transverse momentum of the candidate photon with respect to the event thrust axis be larger than 5 GeV/c. Since final state radiation has a broader distribution in $p_T$ than the backgrounds, this cut significantly improves signal-to-noise which is necessary for the DELPHI analysis since no explicit shower shape analysis was performed. The OPAL experiment analysis considers many values of $y_{cut}$, but the results shown here are for $y_{cut} = 0.005$ (see fig. 4). As discussed earlier, the $y$ variable is the scaled square of the invariant mass of a candidate photon and an hadronic jet as defined in a standard jet-finding algorithm. This analysis requires that the scaled square of the invariant mass of a photon with any jet be larger than $y_{cut}$. Thus, if $y_{cut}$
Figure 4: Observed fraction of multihadronic events with final state radiation of all multihadronic events as a function of $y_{cut}$ and comparison to theoretical predictions (a) matrix element calculation of Kramer and Lampe[9]. The area between adjacent lines indicates the theoretical uncertainty due to $\alpha_s$. (b) Yields per 1000 multihadronic $Z^0$ decays for one, two and three jets and a photon. The bands show the expectation of the matrix element calculation[9].

is made large enough the only events to survive this cut will be those with an energetic isolated photon in one hemisphere and all the hadrons emerging as a single undifferentiated jet opposite to the photon.

The fourth horizontal data section of Table I shows the number of isolated photon events surviving all the above cuts. These are the candidate events for final state radiation, but residual backgrounds remain.

The fifth horizontal data section of Table I shows the numbers of background events due to (i) initial state radiation, (ii) QCD process such as $\pi^0$ decay, and (iii) $\tau$ decays. In each experiment the contributions from initial state radiation and from $\tau$ decays were calculated by Monte Carlo methods. The QCD background was also calculated by Monte Carlo methods, but in the OPAL and DELPHI experiments an attempt was also made to use the data themselves to estimate the QCD background by repeating the isolated photon analysis but for charged particles. There are questions of normalisation, and the OPAL analysis uses a version of isospin invariance while the DELPHI analysis renormalizes the charged particle $p_T$ distribution to the data in the region $p_T < 5$ GeV/c where QCD background is expected to dominate. However, the DELPHI analysis uses this calculation only as confiruation of the Monte Carlo result. This background is a complicated question and is discussed in detail in the talk of Patrice Perez.

The last horizontal section of Table I presents the results of the analysis, and is discussed in the conclusions section.
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Table 1: Summary of final state radiation data from the four LEP experiments

5 Conclusions

Despite major differences in the analyses, the four LEP experiments extract signals of final state radiation which are remarkably similar. Refer to the last horizontal section of Table I. Essential characteristics are:

1. After selections each LEP experiment finds between 175 and 419 qqγ events in the 1990 data. For 1991 one may expect a factor of 2 1/2 more. These data are currently being analysed.

2. Backgrounds vary from 8% to 32%. It is worthwhile to try to reduce this background by relying on the details of the shower shapes in the calorimeters to distinguish single photons
from e.g. two close-by photons from $\pi^0$ decays.

(3) After subtracting background the FSR signal is between 149 and 326 events per experiment. This is not the true number of FSR events, but only the number of FSR events in the particular kinematic region surviving all the cuts of each experiment. The quoted errors include all statistical errors plus only those systematic errors necessary to extract the FSR signal in the particular kinematic region of each experiment. The additional systematic errors from extrapolations to the true FSR signal over all of phase space have been excluded from the quoted errors. All additional systematic errors in the Monte Carlo calculations or errors associated with determining a cross section have not been included in the quoted error.

(4) The ratio of FSR events to total hadronic events varies from $1.66 \times 10^{-3}$ to $1.89 \times 10^{-3}$, which is remarkably similar. It should be noted that these analysis are already at a statistics level which is better than two per mil.

(5) The JETSET 7.3 Monte Carlo, used by each LEP experiment, predicts between 132 and 279 FSR events in the particular kinematic regions surviving all the cuts of the various experiments.

(6) The ratio of FSR data to FSR predicted by Monte Carlo (Jetset 7.3) varies from 1.13 to 1.30 with errors as quoted in the last line of Table I. There is a consistent pattern of an underestimate of FSR by the Monte Carlo. This is most probably due to an inadequate description of FSR in the Monte Carlo rather than to an underestimate of the residual background after the cuts by the Monte Carlo. The basis for this statement is the fact that several LEP experiments have estimated backgrounds from the data themselves, with no reference to a Monte Carlo calculation. This can be done by repeating the isolated photon analysis, but for isolated charged particles. Assumptions have to be made about how to normalize the resulting distributions using e.g. approximate isospin invariance or known backgrounds in certain kinematic regions. Nevertheless, with some systematic errors, the backgrounds calculated in this way agree with the Monte Carlo estimates.

Understanding the origin if the observed FSR signal which is about 20% larger than expected is one of the challenges before this workshop.

6 Acknowledgments

Many thanks to all the people of the four LEP experiments.

References


