Comparison of parton shower Monte Carlos to $q\bar{q}\gamma$ data from LEP

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Abstract
A comparison of $q\bar{q}\gamma$ data from the four LEP experiments to the expectations from
the JETSET and ARIADNE parton shower Monte Carlos is presented. Within the present
statistics, the properties of the photon and of the hadronic system are well described
by both models, but the overall normalisation of the JETSET prediction is too low by
about 15–30%.

1 Introduction: status of comparisons

Four parton shower Monte Carlos[1, 2, 3, 4] producing $q\bar{q}\gamma$ events have been discussed in
this workshop: JETSET, ARIADNE, HERWIG and SPLASH. Of the latter two, SPLASH is a new
model, which is still being tuned, and the version of HERWIG described by Michael Seymour is
not yet released, while the current ‘production’ version does not include final state radiation.
Full comparisons between these models and the LEP data are thus not yet available. This
summary will therefore consider only JETSET, the “standard” Monte Carlo for LEP hadronic
physics, and ARIADNE, comparisons with which have recently been published by the OPAL
experiment.

2 The experimental analyses

There are two basic approaches to the study of $q\bar{q}\gamma$ events. The first, which I will call cone
isolation, requires no significant activity in a cone of half-angle $\sim 20^\circ$ around the candidate
photon, with a cut on minimum photon energy and minimal additional criteria. This is the
L3 analyses[7]. Further details of all analyses may be found in the contributions of Alex
Firestone[9] and Patrice Perez[10].

The second approach is the use of the jet topology of the event. The hadronic system
(excluding the candidate photon) is subjected to a standard jet analysis, and the event is
accepted into the sample if $y_j > y_{cut}$ for all hadronic jets $j$, where $y$ is the jet distance
measure and $y_{cut}$ the experimental cut-off parameter. In the OPAL analysis[8], the only
published study using this technique, an isolation cone is still used to select photon candidates,
and the jet analysis applied is the standard JADE algorithm[11] (distance measure
defined by $y_{ij} = 2E_iE_j(1 - \cos\theta_{ij})/E_{vis}^2$. This matches the existing matrix element calculation by Kramer and Lampe[12]; however, the technique could also be used with alternative jet algorithms such as the Durham or $k_T$ algorithm[13].

These two approaches are in some senses complementary. The cone isolation method concentrates on the overall event rate and the properties of the photon and attempts to minimise the sensitivity of the analysis to details of the hadronisation. Unfortunately, the definition of the isolation cone necessarily introduces some sensitivity to such details (what is the chance of rejecting an event because a soft pion "accidentally" ends up in the region of the photon?), as do general considerations of experimental acceptance, background calculations and so forth.

Jet analyses deal with differential rates and with the properties of the whole event, including the hadronic system. From the point of view of comparisons with models, this approach clearly has more discriminating power; conversely, it also has more potential systematic effects arising from details of the jet analysis. An example of this can be seen in the discrepancy in the one-jet rate between the data and the matrix element calculation[14].

It should be noted that as $y_{ij}$ involves the energy of the photon and its angle to the nearest jet, cutting on this variable will bias the energy, $p_T$ and angular distributions of the photon. For this reason the results of cone isolation analyses and jet analyses are not directly comparable even after correction for experimental effects.

3 Results

3.1 Overall rates

As explained in Alex Firestone’s talk[9], all experiments observe an excess of $q\bar{q}\gamma$ events compared to expectations based on JETSET. Table 1 gives the ratio of data to JETSET prediction observed in each experiment; for more details see [9]. The individual excesses are of at best marginal significance ($\sim 1\sigma$ except for OPAL), but considering the four experiments together it is clear that a general consensus exists. OPAL's published results also include a comparison with ARIADNE, which produces 30–40% more photons than JETSET and thus agrees better with the OPAL data. This difference of ~30% between the two models seems to be consistent among experiments[15, 16], which may imply that ARIADNE will overestimate the yield for the other experiments which have smaller excesses over JETSET than OPAL; however, no other full comparison has yet been done.

<table>
<thead>
<tr>
<th>Exp’t</th>
<th>Ratio</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>ALEPH</td>
<td>1.17 ± 0.12</td>
<td>cone isolation</td>
</tr>
<tr>
<td>DELPHI</td>
<td>1.22 ± 0.17</td>
<td>cone isolation</td>
</tr>
<tr>
<td>L3</td>
<td>1.13 ± 0.18</td>
<td>cone isolation; prelim.</td>
</tr>
<tr>
<td>OPAL</td>
<td>1.30 ± 0.10</td>
<td>jet analysis; $y_{cut} = 0.005$</td>
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Table 1: Ratio of observed yield of $q\bar{q}\gamma$ events to JETSET expectations for each of the four LEP experiments.

When OPAL's overall event rate is plotted as a function of $y_{cut}$, it can be seen that the data fall off more steeply with increasing $y_{cut}$ than the JETSET and ARIADNE predictions, so
that the excess over JETSET is confined to low values of $y_{cut}$ only. This implies a discrepancy between data and models in the energy and/or angular distribution of the photon, but we shall see in a later section that no such discrepancy can be seen in the individual distributions, implying that any difference must be quite subtle.

![Graph of $q\bar{q}\gamma$ events per thousand multihadrons as a function of the JADE jet algorithm parameter $y_{cut}$](image)

Figure 1: Number of $q\bar{q}\gamma$ events per thousand multihadrons, as a function of the JADE jet algorithm parameter $y_{cut}$. (Data from OPAL.)

It is unexpected at first sight that a pure QED process like photon radiation should be so influenced by the details of the parton shower. As discussed elsewhere in this workshop[17, 2], the reason lies in the competition between photon and gluon bremsstrahlung. The experimental cuts requiring hard isolated photons lead to a data sample in which typically 80–90% of the photons have been radiated from the primary $q$ or $\bar{q}$. Fairly minor differences in the timing of gluon emission may therefore cause large differences in the observed rate. As an extreme example, ALEPH[5] took the $f\bar{f}(\gamma)$ generator DYMUS[18] and used it to generate a $q\bar{q}(\gamma)$ final state which was then hadronised using JETSET. This allows the photon radiation to take place without competition from gluon emission. The resulting ratio of data to MC was $0.62\pm 0.05$ (stat.), compared to $1.17\pm 0.12$ using the standard JETSET. Thus the absence of competition almost doubles the number of photons in the final sample.

### 3.2 Differential rates

OPAL's jet analysis allows the overall rate to be subdivided into one jet plus photon, two jets plus photon, etc. Figure 2 shows the data compared to JETSET and ARIADNE. It is clear that the proportion of 1-jet events is described better by ARIADNE than by JETSET, although the size of the effect is small (recall that points in $y_{cut}$ plots are highly correlated). A preliminary analysis by ALEPH[19] sees a similar effect. The matrix element calculation also has difficulty in describing the one-jet rate[14], which thus seems to be very sensitive to details of models, though it is unclear whether this sensitivity is meaningful in terms of the physics of the process or simply reflects a strong dependence on details of the analysis (e.g. technical features of the jet algorithm).
Figure 2: Number of events with \( n \) jets plus a photon, compared to expectations from JETSET (solid line) and ARIADNE (dashed line), as a function of \( y_{\text{cut}} \): (a) absolute rates; (b) relative rates. (Data from OPAL.)

3.3 Properties of the photon

All experiments have analysed their data in terms of the properties of the radiated photon. The most detailed published study is that of OPAL[8], which includes comparisons with both JETSET and ARIADNE. Apart from the overall normalisation, distributions such as photon energy, momentum transverse to the event thrust axis, etc., are well described by both models. The same is true of the comparisons with JETSET in ALEPH's and DELPHI's publications and L3's preliminary analysis.

The experimental cuts in photon energy range from 7.5 GeV for OPAL to 10 GeV for ALEPH. The data are well described apart from an excess of data over expectation for DELPHI's lowest energy point. This excess is not seen by the other experiments; it may be a statistical fluctuation or it may be due to poorly understood background, which is larger in DELPHI's analysis than in the others since no shower shape cuts are applied to reduce neutral hadron contamination.

In the OPAL analysis choosing a high \( y_{\text{cut}} \) biases the photon energy to high values. In this case it can be seen (see Figure 3) that the prediction from ARIADNE tends to be slightly harder than that from JETSET, although the experimental errors are as yet too large to discriminate between the predictions.

The photon momentum transverse to the event thrust axis illustrates the problems of comparing different analyses. In the ALEPH paper, the photon is required to be more than 30º from the nearest jet axis, which clearly biases the \( p_T \) distribution. DELPHI makes
Figure 3: Energy of the photon: (a) ALEPH, (b) DELPHI, (c) OPAL ($y_{\text{cut}} = 0.005$), (d) OPAL ($y_{\text{cut}} = 0.06$).

The ALEPH plot shown here is from a preliminary analysis and includes 1991 data; DELPHI and OPAL plots are from published analyses of the 1989 and 1990 data only.

no such cut, but the large background caused by the lack of shower shape cuts completely dominates the low $p_T$ region. Finally, OPAL includes the photon in the thrust determination, in contrast to ALEPH and DELPHI which use charged tracks only, so for large photon energies the thrust axis tends to align itself with the photon direction, leading to a spike in the distribution at near-zero $p_T$. However, considered individually, all experiments find good agreement between data and expectation.
Figure 4: Transverse momentum of the photon relative to the thrust axis of the event: (a) ALEPH, (b) DELPHI, (c) OPAL ($y_{cut} = 0.005$), (d) OPAL ($y_{cut} = 0.06$).

The ALEPH plot shown here is from a preliminary analysis and includes 1991 data; DELPHI and OPAL plots are from published analyses of the 1989 and 1990 data only.

4 Conclusions and Prospects

4.1 Event rates

It is clear that ARIADNE predicts about 30–40% more final state photons than does JETSET, at least within the present range of experimental cuts. At present the observed rate
seems definitely to be higher than the JETSET expectation, although perhaps not as high as ARIADNE. Analysis of the 1991 data sample, which represents almost double the integrated luminosity of the 1989+1990 data analysed so far, would put this comparison on a much sounder footing.

The analysis of n-jet rates by OPAL again favours ARIADNE over JETSET, though the statistical significance of this preference is low as yet. The properties of a $q\bar{q}\gamma$ event which determine its jet classification are many and varied and apparently subtle details of analysis can play an important role, so it may not be an easy task to discover exactly how the implementation differences between the two models relate to the resulting differences in n-jet rates.

A feature of "$q\bar{q}\gamma$" events which has been studied most intensively by L3[7] is the yield of isolated neutral hadrons, the principal background source for studies of final state radiation. Together with somewhat more indirect evidence from ALEPH[5], these data indicate that, at least in some regions of phase space, isolated neutral hadrons are considerably more common in the data than expected from either JETSET or HERWIG. This finding has obvious implications for the background estimation in $q\bar{q}\gamma$ analyses.

4.2 Properties of the radiated photon

In view of the large normalisation difference between JETSET and ARIADNE, the differences in the properties of the photons produced are surprisingly subtle. Photons from ARIADNE seem to have a slightly harder energy spectrum than those from JETSET, but even this distinction is rather small and quite beyond the discriminating power of the current experimental statistics.

Excluding the overall normalisation, all experiments find that the observed photon properties agree with expectations. Due to the different analyses, distributions from different experiments cannot be compared directly: in some cases (e.g. the difference between cone isolation and jet topology analyses) this will still be true even when all distributions have been corrected for experimental acceptance.

4.3 Future prospects

The results reported here use only the 1989 and 1990 LEP data samples. All experiments are presently analysing their 1991 data, which will increase the total data sample available by approximately a factor 3. This improvement in statistics will certainly enable many presently tentative conclusions to be put on a firm footing. The reliability of the results will also be improved by further cross-checks (for example, Monte Carlo predictions from HERWIG and jet topology analyses by other experiments). Minor refinements and improvements to the analyses can also be expected.

These developments will certainly improve our understanding of the $q\bar{q}\gamma$ process and its relevance to topics such as parton shower development, $\alpha_s$ and weak quark couplings. However, really significant changes to the present analyses — extending the acceptance to much lower energies or to photons close to jets, for example — will require an extremely good understanding of the systematics of background estimates and photon identification. The details of these tasks are very much dependent on the strengths and weaknesses of the individual experiments, but achieving the optimum photon yield is clearly a long-term job.
We must hope that the interest and enthusiasm shown in this workshop will continue through the years and inverse picobarns to come!

5 Acknowledgments

It is a pleasure to thank those members of the four LEP collaborations who have contributed their time and their data to this talk. Many thanks are also due to the LAPP staff who ensured the smooth running and pleasant environment of the workshop.

References

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[10] P. Perez, these proceedings.

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[17] T. Sjöstrand, these proceedings.
