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Abstract

Using the recently measured photon fragmentation function, we make predictions for 'isolated' photon + 1 jet events using a cone type algorithm at LEP energies. For small cone half-angles, perturbation theory breaks down due to the presence of large logarithms. Furthermore, large hadronisation corrections are present. We suggest a definition of an 'isolated' photon which avoids these problems at small cone sizes and can be extrapolated to the reliably calculated large cone region.

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Recently there has been some interest in studying ‘isolated’ and non-isolated photon production in hadronic final states in e^+e^- annihilation at LEP energies, $\sqrt{s} \sim M_Z$ [1, 2, 3, 4, 5, 6, 7, 8]. An ‘isolated’ photon is accompanied by essentially no hadronic energy, while a non-isolated photon cluster is characterised by the fraction z of electromagnetic energy compared with the total energy of the cluster,

$$z = \frac{E_{EM}}{E_{EM} + E_{HAD}}. \quad (1)$$

The original motivation for making this distinction was to try to measure the electroweak couplings of the quarks using ‘isolated’ photons where the background from $\pi^0 \rightarrow \gamma\gamma$ was not severe [9]. It is difficult to resolve the two photons from an energetic π^0 and the pion can appear as a single electromagnetic shower in the calorimeter. Since a π^0 is usually accompanied by other hadronic debris, to reduce this background, it was required that few (or no) tracks occurred close to the electromagnetic shower. In non-isolated language, this corresponds to $z \sim 1$. From the theoretical standpoint, perfectly isolated photons are not infrared safe since the isolation is spoiled by the emission of soft gluons and consequently soft hadrons into the photon direction. Provided that the non-trivial experimental problems in removing π^0 background can be overcome², it makes more sense theoretically to study the production of non-isolated photons and subsequently define an ‘isolated’ photon cluster as having z larger than some cutoff, z_{iso} . However, in allowing some hadronic energy to accompany the photon, we admit the *perturbatively* divergent possibility that the photon was emitted from a collinear massless quark. In reality, this happens at large times, $c\tau \sim 1/\sqrt{s_{q\gamma}}$, so that in practice the quark has already hadronised and this final state collinear divergence can be factorised into a *non-perturbative* quark to photon fragmentation function at factorisation scale μ_F in much the same way that initial state collinear divergences are factorised into parton distributions [11]. The μ_F independent cross section then contains two components,

$$\sigma \sim \sigma(\gamma + \text{partons})(\mu_F) + \sum_{a=\text{quarks}} \sigma(\text{partons}) D_{a \rightarrow \gamma}(z, \mu_F), \quad (2)$$

often denoted ‘direct’ and ‘resolved’ respectively which individually depend on μ_F . It is important to note that in order to correctly absorb the infra-red divergence, each contribution should be evaluated at the same order in perturbation theory [12, 13], i.e. if $\sigma(\gamma + \text{partons})(\mu_F)$ is evaluated at $\mathcal{O}(\alpha\alpha_s^n)$, then $\sigma(\text{partons})$ should be evaluated at $\mathcal{O}(\alpha_s^n)$ since $D_{q \rightarrow \gamma}(z, \mu_F)$ is $\mathcal{O}(\alpha)$ in the presence of isolation [8] (and *not* $\mathcal{O}(\alpha/\alpha_s)$ as commonly quoted in the literature). Once measured, the parton to photon fragmentation function, $D_{parton \rightarrow \gamma}(z, \mu_F)$, can be applied to a wide range of processes just as the proton parton densities are extracted from deep inelastic scattering experiments and used in hadron hadron collisions.

In a recent paper [13], we described how the quark to photon fragmentation function could be measured in ‘photon’ + 1 jet events at LEP using a democratic algorithm to define the photon cluster: all particles (including the photon) are subjected to a clustering algorithm and the cluster containing the photon is designated the photon cluster provided

²The ALEPH collaboration claims to be able to remove the π^0 background for $z > 0.7$ [10] and it may prove possible to extend this to $z > 0.5$

that $z > z_{\text{cut}}$. This ‘photon’ + 1 jet rate is especially sensitive to the fragmentation function since the lowest order process, $e^+e^- \rightarrow \gamma + \text{parton}$, vanishes, while the next-to-leading order $\mathcal{O}(\alpha^3)$ ‘photon’ + 1 jet cross section, schematically given by,

$$\sigma \sim \sigma(q\bar{q}\gamma) + \sum_{a=q,\bar{q}} \sigma(q\bar{q}) D_{a \rightarrow \gamma}(z, \mu_F), \quad (3)$$

does depend on the fragmentation function.

The ALEPH collaboration has now measured this function using a democratic photon definition with the Durham clustering algorithm in the region $0.7 < z < 0.95$ [10] and finds that the ‘photon’ + 1 jet data (after subtraction of the rather large π^0 background) can be described by a fragmentation function of the form,

$$D_{q \rightarrow \gamma}(z, \mu_F^2) = \left(\frac{\alpha e_q^2}{2\pi} \right) \frac{1 + (1-z)^2}{z} \log \left(\frac{\mu_F^2}{\mu_0^2 (1-z)^2} \right) + A, \quad (4)$$

where $\mu_0 = 0.20 \pm 0.25$ GeV and $A = -12.40 \pm 2.95$. The particular form of the fitting function is motivated by requiring that (a) the cross section is independent of μ_F and (b) the cross section is well behaved as $z \rightarrow 1$. This latter point requires some further clarification: the ‘direct’ contribution acquires one factor of $(1-z)$ in the logarithm from using dimensional regularisation and the $\overline{\text{MS}}$ scheme to isolate the divergence as $s_{q\gamma} \rightarrow 0$. The second factor of $(1-z)$ comes from the boundary between the phase space regions where either the quark and antiquark combine to form the jet or the quark(antiquark) and photon combine to form the photon cluster. By explicitly removing these factors with this form of fragmentation function we ensure that the differential distribution is well behaved as $z \rightarrow 1$. In this letter, we wish to make predictions for the ‘photon’ + 1 jet rate using the cone type photon definition currently in use for ‘isolated’ photon studies at LEP. The fragmentation function as measured by ALEPH should enable this quantity to be reliably predicted.

The CONE algorithm for ‘isolated’ photon production [1, 2, 3, 4] can be straightforwardly carried over into the non-isolated case. First a cone of half angle δ is placed around the photon and all hadrons inside the cone are clustered with the photon to form the photon cluster such that $z > z_{\text{cut}}$. Second, all hadrons outside the cone are subjected to a jetfinding algorithm, typically the E0/JADE [16] or the Durham [17] algorithms, with a jet resolution parameter y_{cut} . Third, the photon cluster is resolved from the jets according to a resolution parameter y_{cut}^γ .

As discussed above, the first non trivial contribution to the ‘photon’ + 1 jet rate comes from $e^+e^- \rightarrow q\bar{q}\gamma$ and $e^+e^- \rightarrow q\bar{q}$ where one of the quarks fragments into a photon. The Dalitz plot for the $q\bar{q}\gamma$ final state is shown in Figure 1 for the Durham and E0 jet algorithms with $\delta = 60^\circ$, $y_{\text{cut}} = y_{\text{cut}}^\gamma = 0.1$ and $z_{\text{cut}} = 0.8$ in terms of the quark and antiquark energy fractions,

$$x = \frac{2E_q}{\sqrt{s}} = 1 - y_{\bar{q}\gamma}, \quad x' = \frac{2E_{\bar{q}}}{\sqrt{s}} = 1 - y_{q\gamma}, \quad (5)$$

where $y_{ij} = s_{ij}/s = (p_i + p_j)^2/s$ and $x_\gamma = 2E_\gamma/\sqrt{s} = 2 - x - x'$. In region 1, the quark and antiquark coalesce to form the jet and the photon cluster has $z = 1$, while in region 2 (3), the

Figure 1: Dalitz plot for the $q\bar{q} + \gamma$ final state in terms of the quark and antiquark energy fractions x and x' . The dotted (dash-dotted) line shows the ‘photon’ + one and two jet regions for $\delta = 60^\circ$, $y_{\text{cut}} = y_{\text{cut}}^\gamma = 0.1$ in the Durham (E0) scheme. The regions where the quark-antiquark combine to form a jet are separated from the region where the quark (antiquark) combines with the photon by a dashed line. The boundary in z for $z_{\text{cut}} = 0.8$ curtailing regions 2 and 3 is shown solid.

quark (antiquark) combines with the photon to form a mixed cluster with $z < 1$. The dashed line separating regions 1 and 2, shows the effect of the cone size in determining whether the quark combines with the photon or the antiquark. The collinear divergence occurs at $x' = 1$ and $x = 1$ respectively and lies along the edge of regions 2 and 3. This singularity can be absorbed into the ‘resolved’ photon contribution from $q\bar{q}$ final states where one of the quarks fragments into a photon. The 1 jet + ‘photon’ cross section (for massless quarks of charge e_q) as a function of z in scheme $S = E0, D$ is then given by,

$$\begin{aligned} \frac{1}{\sigma_0} \frac{d\sigma^S(1 \text{ jet} + “\gamma”)}{dz} &= 2 D_{q \rightarrow \gamma}(z, \mu_F) + \left(\frac{\alpha e_q^2}{\pi} \right) \left[\frac{(1 + (1 - z)^2)}{z} \log \left(\frac{s}{\mu_F^2} \right) \right] \\ &+ \frac{1}{\sigma_0} \frac{d\hat{\sigma}(1 \text{ jet} + “\gamma”)}{dz} + R_\Delta^S \delta(1 - z). \end{aligned} \quad (6)$$

Here the dependence on the scale μ_F has been made explicit, while the quantity R_Δ^S represents the jet algorithm dependent contribution to the cross section where quark and antiquark combine, thus leaving the photon completely isolated. In this case, the photon cluster has $z = 1$. Unlike the democratic algorithms, R_Δ is the only scheme dependent contribution. The factorisation scale independent (but cone size dependent) contribution is given by,

$$\begin{aligned} \frac{1}{\sigma_0} \frac{d\hat{\sigma}(1 \text{ jet} + “\gamma”)}{dz} &= \left(\frac{\alpha e_q^2}{\pi} \right) \left[\frac{(1 + (1 - z)^2)}{z} \log(yz(1 - z)) + z \right. \\ &- \frac{1 + (1 - z)^2}{1 - z} \left(\frac{zy}{1 - z} + \frac{y(y - 2)}{2} + \frac{(1 - 2z)^2}{z(1 - z)^2} \log \left(\frac{z(1 + y) - y}{z} \right) \right) \\ &- \left. 4(1 - z)y - 4 \log \left(\frac{z(1 + y) - y}{z} \right) \right]. \end{aligned} \quad (7)$$

Here y is the maximum value of $y_{q\gamma}$ allowed when the photon and quark combine,

$$y = \frac{1}{v} \left(1 - \sqrt{1 - 2v} \right) - 1 \quad \text{where} \quad v = z(1 - z)(1 - \cos \delta). \quad (8)$$

In the limit $z \rightarrow 1$ this boundary is given by,

$$y \rightarrow \frac{1}{2} (1 - z)(1 - \cos \delta), \quad (9)$$

which is to be compared with the analogous large z boundaries in the democratic Durham and E0 schemes of $y = (1 - z)/(1 + z)$ [13]. We see that in both cases, the boundary contains the same $(1 - z)$ factor, so that with the choice of fragmentation function given in eq. 4, the cross section should in principle be well behaved as $z \rightarrow 1$. Furthermore, for $\delta = 90^\circ$, the large z limits for the cone and democratic algorithms are identical.

There is a slight subtlety since there is a discontinuity in z across this boundary - for $y_{q\gamma} > y$, $z = 1$, while for $y_{q\gamma} < y$, $z < 1$. This causes a problem when hadronisation effects are taken into account - the process of going from the parton level to the hadron level can cause a sizeable shift in z . Although this mismatch exists in both democratic and cone algorithms, the problem is most severe when the matrix elements are largest - i.e. when y is small. In the democratic case, analysed by ALEPH [10], this problem is visible in the data as a spillover from the $z = 1$ bin to the adjoining $z = 0.95$ bin. To get round this problem and to make a sensible comparison with the parton level predictions, ALEPH have defined an ‘isolated’ photon as having $z > z_{\text{iso}} = 0.95$ and compared that with the parton level prediction for $z > z_{\text{iso}}$. Since the $z \neq 1$ contribution (all the terms in eq. 6 apart from R_Δ) tends to zero at high z in the democratic Durham scheme, the result is dominated by R_Δ . By doing this, the uncertainty in z due to hadronisation effects is reduced where the cross section is largest. Hadronisation corrections can still move events from $z = 1$ to values of $z < z_{\text{iso}}$, however, this occurs at larger values of $y_{q\gamma}$ where the cross section is smaller. With this procedure, ALEPH find good agreement between the theoretical predictions for the democratically ‘isolated’ photon + 1,2 and 3 jet rates [10]. In the cone algorithm, because y is somewhat smaller than in the democratic scheme, we expect that the mismatch between the z measured at the parton and hadron levels where the cross section is significant will extend over a larger range of z and that the corresponding value of z_{iso} should be smaller.

The differential cross section $1/\sigma_0 d\sigma/dz$ for the appropriate combination of light quarks at LEP energies is shown in Fig. 2 for the CONE algorithm (this contribution is independent of the choice of hadron clustering algorithm) with $y_{\text{cut}} = y_{\text{cut}}^\gamma = 0.1$ and $\delta = 90^\circ, 60^\circ, 30^\circ$ and 15° . As noted earlier, for $\delta = 90^\circ$, the cone and democratic algorithms merge at large z so that it is no surprise that the z distribution for $\delta = 90^\circ$ is well behaved as $z \rightarrow 1$. However, for smaller cone sizes, the distribution is negative for z close to 1. This is balanced by the rapid increase of R_Δ with decreasing cone size.

Based on the previous discussion, we expect that after hadronisation corrections the R_Δ contribution is partially smeared to lower z values, thereby filling in the negative region and creating a physically sensible positive definite distribution. To make a sensible comparison with experiment, it is necessary to introduce a suitable (δ dependent) choice of z_{iso} . Clearly,

Figure 2: The differential cross section $1/\sigma_0 d\sigma/dz$, in the CONE type schemes and $y_{\text{cut}} = y_{\text{cut}}^\gamma = 0.1$ for the appropriate combination of light quarks at LEP energies with the ALEPH determination of the fragmentation function. The cone size is $\delta = 90^\circ$ (solid), $\delta = 60^\circ$ (dotted), $\delta = 30^\circ$ (dashed) and $\delta = 15^\circ$ (dashdotted).

for $\delta = 90^\circ$, the ALEPH choice for the democratic algorithm would be appropriate, $z_{\text{iso}} = 0.95$. However, we see that as δ becomes smaller, the negative region rapidly extends to much smaller values of z so that a much smaller value of z_{iso} is required. We can understand this by looking at the small δ limit,

$$R_\Delta^S \rightarrow \left(\frac{\alpha e_q^2}{\pi} \right) \frac{(1 + (1-z)^2)}{z} \log \left(\frac{1}{\delta^2} \right),$$

$$\frac{1}{\sigma_0} \frac{d\sigma^S(1 \text{ jet} + \gamma)}{dz} \rightarrow \left(\frac{\alpha e_q^2}{\pi} \right) \frac{(1 + (1-z)^2)}{z} \log(\delta^2). \quad (10)$$

The $z = 1$ contribution (R_Δ) grows logarithmically as $\delta \rightarrow 0$ at the expense of the $z < 1$ fragmentation contribution. This is precisely the region in which perturbation theory breaks down because we try to resolve the collinear region where the fragmentation contribution is important. At small cone angles, the R_Δ contribution alone becomes meaningless. Note that in many studies of ‘isolated’ photons, the cone size is chosen to be $10^\circ - 20^\circ$ so that it is important to attempt to make a sensible prediction for ‘isolated’ photon + 1 jet production with small cone angles at LEP energies.

To estimate the cross section in the small δ limit it is vital to include the fragmentation contribution. This can be done in a well defined way, that avoids the large logarithms of the cone angle while simultaneously reducing the hadronisation corrections, by extending the boundary between the ‘photon’ + two jet region and region 1 (the dotted and dotdashed lines in Fig. 1) onto the $x = 1$ or $x' = 1$ axes such that,

$$\begin{aligned} z_{\text{iso}}^D &= 1 - \sqrt{y_{\text{cut}}}, \\ z_{\text{iso}}^{E0} &= 1 - y_{\text{cut}}. \end{aligned} \quad (11)$$

Figure 3: The ‘isolated’ photon + 1 jet cross section R_Δ (solid) and $\int_{z_{\text{iso}}}^1 1/\sigma_0 d\sigma/dz dz$ (dotted) for (a) $\delta = 20^\circ$ in the E0 scheme and (b) $\delta = 15^\circ$ in both Durham and E0 schemes as a function of the jet resolution parameter y_{cut} . z_{iso} is given by eq. 11 while the data is taken from refs. [1, 2]

With this choice, the $\log(1/\delta)$ from R_Δ precisely cancels with a similar logarithm from the fragmentation region so that the cross section is almost independent of the cone size. This is exactly what we would expect; varying the cone size within the fragmentation region should not affect the cross section since we are unable to resolve any structure within this region. Furthermore, hadronisation corrections which slightly change x (x') and move events from region 1 to region 2(3) or vice versa, do not change the cross section. As a consequence, we expect that the cross section for $z > z_{\text{iso}}^S$ (where $S = D, E0$) is a reliable estimate of the ‘isolated’ photon + 1 jet rate at small cone angles.

Figure 3 shows the ‘isolated’ photon + 1 jet cross section normalised to the total hadronic cross section as a function of the jet resolution parameter y_{cut} . In Fig. 3a, the cone size is 20° and the data is taken from ref. [2], while in Fig. 3b, $\delta = 15^\circ$ and the data is taken from ref. [1]. In both cases, the solid lines show the lowest order R_Δ contribution. As discussed in [6, 7, ?], the $\mathcal{O}(\alpha_s)$ corrections to R_Δ are large and negative ($\sim -45\%$), so that reasonable agreement with the data can be made for $\alpha_s \sim 0.12$ [1, 2]. These large corrections reflect the confusion over the precise definition of an isolated photon. On the other hand, the δ independent ‘isolated’ photon + 1 jet cross section for $z > z_{\text{iso}}$ defined by eq. 11 (dotted line) is significantly closer to the data which suggests that (a) the hadronisation effects are modelled better and (b) that the higher order corrections to *both* R_Δ and the fragmentation region are of a more reasonable size.

It is interesting to ask how the ‘isolated’ photon + 1 jet cross section varies as a function of the cone angle. At large angles, $\delta \sim 90^\circ$, the prediction merges with that for the democratic algorithm used to extract the fragmentation function while at small angles, we see from Fig. 3 that the prescription described by eq. 11 is reasonable. By measuring the cross section as a function of δ , we can hope to extract further information about the fragmentation region.

Figure 4: The ‘isolated’ photon + 1 jet cross section R_Δ (solid) and $\int_{z_{\text{iso}}}^1 1/\sigma_0 d\sigma/dz dz$ (dotted) for z_{iso} given by eq. 14 in the Durham and E0 schemes as a function of the cone angle δ for $y_{\text{cut}} = y_{\text{cut}}^\gamma = 0.1$. The data is taken from refs. [1, 2] and [10]

To make a rough estimate of how the cross section varies for intermediate δ , we can adapt the phenomenological ALEPH approach to solving the hadronisation problem and choose the value of z separating ‘isolated’ from non-isolated photons to be the value of z where the boundary between the fragmentation and quark-antiquark combination region takes the value $y = y_0$ such that for $\delta > \delta_0$,

$$z_0 = \frac{1}{2} \left(1 + \sqrt{1 - \frac{(1 - \cos \delta_0)}{(1 - \cos \delta)}} \right), \quad (12)$$

where,

$$\cos \delta_0 = 1 - \frac{8y_0}{(1 + y_0)^2}. \quad (13)$$

For $y > y_0$ ($z < z_0$) we can in principle use perturbation theory to examine the fragmentation region, however for $y < y_0$ ($z > z_0$), we cannot reliably resolve the photon from the accompanying hadronic debris and therefore assign the event to the ‘isolated’ photon category. In the democratic scheme, ALEPH find $z_{\text{iso}} = 0.95$ corresponding to $y_0 = 0.025$ to be a suitable choice [10] which corresponds to a cone size of $\delta_0 = 35.9^\circ$. Therefore, as a first estimate of the cone size dependence of the cross section, we define the value of z separating ‘isolated’ from non-isolated photons to be,

$$z_{\text{iso}} = \max(z_{\text{iso}}^S, z_0). \quad (14)$$

This is shown in Fig. 4 for both the Durham and E0 schemes with $y_{\text{cut}} = y_{\text{cut}}^\gamma = 0.1$ and $y_0 = 0.025$. The solid lines show the logarithmically increasing R_Δ contribution while the dotted lines represent this approximation. At large values of δ , $z_{\text{iso}} \rightarrow 0.95$, while for small values of δ ($\delta < 39^\circ$ in the Durham scheme and $\delta < 61^\circ$ in the E0 scheme), $z_{\text{iso}} \rightarrow 0.68$ and 0.9 respectively. As expected from fig. 2, at large cone angles, the cross section integrated above z_{iso} and R_Δ are rather close; perturbation theory is working well and the hadronisation

corrections are small. The z distribution tends to zero as $z \rightarrow 1$ and the contribution from $1 > z > z_{\text{iso}}$ is small. On the other hand, for smaller values of δ this is no longer the case and the rapid growth of R_Δ is counterbalanced by the increasingly negative contribution from $1 > z > z_{\text{iso}}$. Around $\delta \sim 40^\circ$ in the Durham scheme, the overall contribution from $1 > z > z_{\text{iso}}$ is slightly positive resulting in a cross section slightly larger than R_Δ . The available data from OPAL [1] and ALEPH [2] are also shown. For comparison, we also show the $y_{\text{cut}} = 0.1$ point from the democratic ALEPH analysis [10] at $\delta = 90^\circ$.

In this letter we have attempted to utilise the recent ALEPH measurement of the photon fragmentation function to predict the ‘photon’ + 1 jet rate using the cone algorithm. However, at small angles there are large hadronisation corrections and large logarithms of the cone size. To avoid these problems, we have defined an ‘isolated’ photon as having $z > z_{\text{iso}}$ where z_{iso} is given in eq. 14. At small angles, we find rough agreement between our lowest order prediction and the available data. This is quite remarkable since previously large negative $\mathcal{O}(\alpha_s)$ corrections to the ‘perfectly’ isolated photon event rate (R_Δ alone) were necessary to describe the data. We expect that the $\mathcal{O}(\alpha_s)$ corrections to the ‘isolated’ photon + 1 jet rate using our definition will be small.

At large cone sizes, the cone algorithm is very close to the democratic algorithm used to extract the photon fragmentation function. Accordingly, we expect the prediction of the large δ cross section to be reliable. Motivated by the ALEPH data, we have also provided an estimate of how the ‘isolated’ photon + 1 jet rate depends on the cone size. A measurement of this dependence should provide yet another probe of the fragmentation region.

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