Recent developments are reviewed in the field of two photon physics at LEP and their contribution to testing QCD.

1 Introduction

Two photon physics is performed at $e^+e^-$ colliders such as LEP via the interaction of two virtual photons, as shown in Fig. 1. The energy spectrum of the virtual photons is sharply peaked at low energy, so that the final states produced are predominantly at low energy. However, the cross section for the process rises logarithmically with the $e^+e^-$ centre of mass energy, so that at LEP II, with no $Z^0$ resonance to compete with, it is the dominant process.

The following standard variables are defined.

- $Q^2 = -(4$ momentum transfer$)^2$ of photon 1
- $P^2 = -(4$ momentum transfer$)^2$ of photon 2
- $Q^2 > P^2$ by definition
- $W = $ Invariant mass of final state
- $x = \frac{Q^2}{Q^2 + W^2}$

A number of facts make the experimental measurements in two photon physics difficult. The first of these is that one does not have a monoenergetic beam of photons. Instead, all measurements must be extracted from a measured $e^+e^-$ process. Secondly, in general the observed invariant mass $W_{\text{vis}}$ is less than the true one $W_{\text{true}}$. This is due to the tendency for much of the final state energy either to be deposited in the forward luminosity spectrometers, which are poor at measuring hadronic energy, or even be lost along the beam pipe.

From the theoretical point of view, the photon, as a fundamental particle of the Standard Model, should allow precise calculations to be performed. This is indeed the case, provided it is probed with sufficiently large a scale that perturbative QCD calculations can be performed. However, many of the photons in two photon collisions have small four momentum, which cannot be described by perturbative QCD. In these cases, we are forced to adopt a phenomenological model, Vector Meson Dominance, where the photon is
assumed to behave like a vector meson. This means that, in order for measurement made at LEP to test QCD, they have to be limited to processes which include at least one large scale. The scales available are

- Four momentum of photon(s)
- Transverse momentum of final state
- Mass of produced quark
- Mass of produced hadron pair.

The following sections discuss recent advances in measurements using the first three of these. Most of these results were reported at the PHOTON 2000 conference, the proceedings of which will be published by AIP in 2001. Prior to publication, they can be seen at http://www.photon2000.lancs.ac.uk/proceedings/.

2 The Photon Structure Function

The photon structure function $F_2^\gamma(x, Q^2)$ is measured directly in so-called single tagged events, in which one of the electrons is scattered sufficiently to be detected. This results in the $Q^2$ of the associated photon being significantly different from zero. In this arrangement, it is then acceptable to distinguish this photon as a probe of the properties of the other photon, whose four momentum transfer will be close to zero, and which is treated as the target. This in turn means that the full machinery of deep inelastic scattering can
be adopted. The cross section for the process is expressed in terms of two structure functions $F_1^\gamma(x,Q^2)$ and $F_2^\gamma(x,Q^2)$,

$$\frac{d\sigma}{dx dy} = \frac{4\pi\alpha^2 s(e^\gamma)}{Q^4} \left[(1-y)F_2^\gamma(x,Q^2) + xy^2F_1^\gamma(x,Q^2)\right],$$

where

$$y = 1 - \frac{E_{\text{tag}}}{E} \cos^2\left(\frac{\theta_{\text{tag}}}{2}\right).$$

However, as $y$ is very much less than one in any practical measurement, only $F_2^\gamma$ is experimentally accessible.

When $F_2^\gamma(x,Q^2)$ is calculated, it falls naturally into two parts, one part known as the point-like part is calculable exactly in QCD and depends only on $\lambda_{\text{QCD}}$. The second, so-called hadronic part is not calculable and has to be approximated by some flavour of VDM. A number of different authors have attempted to calculate $F_2^\gamma(x,Q^2)$, resulting in sets of parton distribution functions (PDFs) which can be compared to data.

While measurements of the Photon Structure Function have been made since the late 1970’s, there continue to be improvements at LEP II. In addition to much larger data sets, higher $Q^2$ and lower $x$ than ever before, there has been progress in two areas aimed at reducing the large systematic errors that plague the measurement. These arise from the problem of unfolding the true final state invariant mass distribution from the observed one. This requires a good model of the final state, which has been lacking for many years, resulting in large model dependance of the result. Two approaches have been taken to attack this. The first is the improvement of the Monte Carlo models by the production of standardized hadron level distributions by three of the four LEP experiments. This is intended to make it easier for program authors to tune their programs. The other new approach is the use of two-dimensional unfolding techniques to reduce the model dependance of the result by using additional information that is available in the data. This approach has been adopted by ALEPH and OPAL.

3 High $p_t$

In the production of high transverse momentum jets, or particles, it is the transverse momentum scale which ‘probes’ the structure of a photon. Calculations are performed by convoluting matrix elements for the hard scattering process with flux factors of photons produced by electrons, and photon PDFs. Photons are classified as ‘Direct’ if the photon enters the hard scattering process itself or ‘Resolved’ if it is a parton from the photon which is involved.
Events are classified as Direct, Single Resolved or Double Resolved, depending on how many photons in the event are resolved. Apart from kinematical effects, these three processes are all of the same order of magnitude in cross section.

Very recently, two authors\textsuperscript{5, 6} have provided code to allow NLO QCD calculations to be performed in a Monte Carlo manner which allows experimental cuts to be applied to the calculation. This greatly improves the possibilities of comparing data and theory, though it should be noted that such comparison is still between theory calculated with massless quarks, and data corrected to the hadron level.

Recent experimental results include the first measurement of jet production in tagged events by a LEP experiment\textsuperscript{7} allowing access in principle to the virtual photon structure function. They agree well with the NLO predictions in $p_t$ distributions. A new approach from OPAL\textsuperscript{8} is an attempt to get a more direct probe of differences between the various photon PDFs. These show greatest difference at low $x$, however these differences are largely lost when measuring $p_t$ distributions. Instead, OPAL have plotted $x_\gamma$ which is defined as

$$x_\gamma^\pm = \frac{\sum_{\text{jets}} (E^\pm p_z)}{\sum_{\text{hadrons}} (E^\pm p_z)}$$

both entries ($x_\gamma^+$ and $x_\gamma^-$) are included in distributions. Comparing to the equivalent distributions in Monte Carlo shows some direct sensitivity to the PDF at low $x$, however comparing to NLO calculations emphasizes the difference between calculations done with partons and hadron level measurements, as very poor agreement is found. The NLO calculation produces far too large a spike at $x = 1$ with correspondingly too low a cross section at lower $x$ values.

4 Heavy Flavours

From the theoretical point of view, the measurement of heavy flavour production in two photon physics has much to recommend it. The only processes that contribute significantly are the direct and single resolved ones.\textsuperscript{9} The contribution of the latter is dominated by processes including initial state gluons and thus directly probes the gluonic part of the photon PDFs, which is not directly measured in photon structure function measurements. The scale of the process is set by the heavy quark mass. In tagged measurements the situation is even more favourable, as the direct and resolved components do not mix and are scheme independent up to NLO. For $x > 0.2$, the pointlike part dominates and is exactly calculable in QCD. Below this, the hadronic part, and hence the gluon part of the photon, is probed.\textsuperscript{10}

Performing the measurement is made difficult by the lack of a good high
statistics tag for charm or beauty in two photon physics. The lifetime tagging techniques which have been so successful in $e^+e^-$ annihilation events have not turned out to be useful. Two heavy flavour tags have been used, the ‘$D^*$ mass trick’, which has the advantage of being a clear unambiguous charm tag, but with low statistics, and lepton tagging, which suffers from large poorly understood backgrounds. Early measurements of charm production were presented as total cross sections. These suffer from large errors, when extrapolating from the observed visible cross section to the total cross section. The results are consistent with NLO QCD predictions, but these predictions have large mass and scale dependancies. Recently, more differential calculations have become available, and it turns out that these also have smaller theoretical uncertainties. As a result, LEP measurements are now presented in limited $p_t$ and rapidity corresponding to experimental acceptances. Current measurements from L3 and OPAL agree well with each other and with a massless calculation, while ALEPH preliminary measurements show a flatter $p_t$ dependence, and agree better with the massive calculation. L3 also show the charm cross section as a function of invariant mass and find a NLO calculation reproduces the slope of their data, but not the normalisation which is a factor of two above the calculation.

In lepton tagged data, both L3 and OPAL observe an excess at high $p_t$ which they ascribe to b-quark production. The rate observed by each experiment is consistent but 2σ above the theoretical expectation.

A first measurement of tagged charm production has been presented by OPAL. There are two bins in $x$. The high $x$ bin is consistent with the NLO calculation, but the low $x$ point suffers from too large errors to make any meaningful comparisons.

5 Double Tagged Measurements

Until recently, the lack of statistics has meant that little attention has been paid to double tagged events. However, the large amount of data available at LEP means that this is now a feasible area of study and allows to test the observation that for events with $W^2_{\gamma\gamma} >> (Q_1^2, Q_2^2)$ the BFKL calculations are considerably larger in certain areas of phase space than those using the DGLAP approach. This was seen as a clean way to distinguish the two. Early results from L3 were clearly above the predictions of models such as PHOJET although not as large as the LO BFKL prediction. Recently, it has become clear that NLO corrections to BFKL are large reducing the difference between them and DGLAP calculations. In addition, OPAL have shown that there is a possibility of large radiative corrections being required.
when calculating the final invariant mass from the tagged electrons. The corrections go in the direction of reducing the cross section just in the kinematical region where large deviations from DGLAP were apparently observed by L3. It would seem premature at this stage to say whether BFKL calculations can really be tested in the LEP double tagged data.

6 Conclusions

The great success of the LEP machine at CERN has provided us with an unrivalled sample of two photon physics events to study. The analysis of these events remains challenging, but in recent years the greater collaboration between the experiments and theorists has led to much improvement in the detail to which the data can be used to probe QCD. It is to be hoped that the end of LEP does not lead to too rapid an end to this effort as there is still much to be learned.

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