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A MEASUREMENT OF WIDE ANGLE BREMSSTRAHLUNG IN A HIGH ENERGY
MUON SCATTERING EXPERIMENT AS A CHECK ON THE CONSISTENCY
OF RADIATIVE CORRECTION CALCULATIONS

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Abstract

The yield of wide angle bremsstrahlung photons produced by 120 GeV muons incident on a liquid hydrogen target has been measured in the kinematic range $0.3 < y < 0.8$ and $0.02 < x < 0.15$. These measurements have been compared with the predictions of the standard treatment of radiative corrections and no inconsistencies found in this kinematic range.

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1. INTRODUCTION

The counting rate observed in a deep-inelastic charged lepton scattering experiment is usually corrected for the possible radiation of real photons by the incident or the scattered lepton in order to extract the single-photon exchange cross-section. The radiation of such photons implies that the observed 4-momentum transfer derived from the kinematics of the leptons may be grossly different from the 4-momentum transfer to the target nucleon. A particularly significant contribution to the measured cross-section in the deep inelastic region comes from events where an elastic scatter from the nucleon is accompanied by the radiation of a real photon which carries almost all the measured energy loss, ν , of the lepton. This leads to the so-called elastic radiative tail and may account for a large fraction of the measured cross-section in certain kinematic regions, principally at high $y = \nu/E_{\text{beam}}$, and low $x = Q^2/2m\nu$. The procedure for obtaining the true, non-radiative, cross-section therefore involves significant corrections and it is essential that these are well understood if a measurement of the nucleon structure function is to be made with a precision of a few percent.

In principle the radiative corrections are calculable by standard perturbative QED methods; these necessarily involve the use of some approximations, for instance that the radiation of single photons is the dominant process. The data from most deep-inelastic charged lepton scattering experiments are corrected using the single photon emission formulae of Tsai [1]. Recently, however, calculations by Chahine [2] which include multiphoton emission have suggested that at high energies and in the extreme kinematic regions of high y and low x the standard radiative corrections may be in error by large factors. It is therefore important to verify the corrections which are applied. In this experiment it has been possible to measure the yield of hard photons and obtain a check on the method of calculation of radiative corrections. Wide-angle bremsstrahlung production by electrons has previously been measured in order to check the validity of QED for timelike virtual electrons [3,4,5] but these experiments were not sensitive to the phenomena postulated in ref. 2.

2. APPARATUS

The EMC Forward Spectrometer, which is situated in the M2 muon beam line of the CERN SPS, is described in some detail elsewhere [6]; for the analysis of the data presented here the most important component is the lead-scintillator calorimeter. It is sketched in fig. 1. This calorimeter is divided into two halves which are disposed symmetrically with respect to the transmitted muon beam. Each half consists of three modules, the two downstream modules being used for hadron detection. The upstream module is composed of lead sheets interleaved with blades of 1 cm thick plastic scintillator to a total depth of 20 radiation lengths, the effective radiation length of the composite being ~ 1.6 cm. The scintillator blades are 28 cm wide and 2.8 metres long; they are oriented alternately vertically and horizontally and the six blades of each view are coupled to a single photomultiplier. This interleaving samples an electromagnetic shower equally in the two views and allows the division of the active area into 100 square elements of 28 x 28 cm. The sampling equality enables the pattern recognition of multiple shower events to be attempted. The large element size prohibits the resolution of the individual photons from π^0 or η decays.

The calorimeter was situated downstream of the spectrometer magnet, approximately 13 m from the end of the 6 m liquid-hydrogen target and provided almost full coverage of the downstream aperture of the magnet. The principal insensitive region was defined by the 12.5 cm radius beam hole and a narrow vertical strip between the two halves. The relative calibrations of the scintillator elements and the correction factors for the attenuation of the scintillation light (which amount to about 10% per 28 cm) were obtained from a study of the pulse-heights recorded for muons in the beam halo. The overall energy scale was determined in-situ by a comparison of corrected pulse-height with the measured momentum of electrons in μ -e scattering events. The component of the energy resolution for a single electromagnetic shower due to shower fluctuations is $\sigma(E)/E \sim 0.40/\sqrt{E(\text{GeV})}$. In practice, however, this is worsened by the attenuation corrections and the pattern recognition procedure which can together produce systematic errors on the energy measurement of the order of a few percent, dependent upon the precise position at which a photon enters one of the elements.

3. DATA SELECTION

The data presented here were obtained from a flux of 1.74×10^{11} 120 GeV positive muons incident upon the hydrogen target. After reconstruction of the scattered muons in the wire-chambers of the Forward Spectrometer and the imposition of the kinematic cuts $Q^2 > 1.0 \text{ GeV}^2$ and $p'_\mu > 20 \text{ GeV}$ to remove backgrounds from μ -e scatters and meson decays there remained $\sim 98,000$ events with well-measured incident and scattered muons, and a reconstructed vertex.

Radiative correction calculations [1] predict that hard Bremsstrahlung photons will be emitted predominantly in the directions of the incoming muon, $\vec{p}_\mu$, and the apparent virtual photon, $\vec{q} = \vec{p}_\mu - \vec{p}'_\mu$, where $\vec{p}'_\mu$ is the scattered muon momentum vector - the so-called "s" and "t" peaks. Fig. 2 shows the predicted angular distribution of photons with $z = E_\gamma/\nu > 0.8$ in the region $0.6 < y < 0.7$ and $0.02 < x < 0.06$. The real photons are emitted within a few milliradians of the s- and t-directions. In this kinematic region the angle of the apparent virtual photon with respect to the incoming muon, $\theta_{\gamma*}$, is small, e.g. $\theta_{\gamma*} \sim 18 \text{ mr}$ for $y = 0.65$, $x = 0.04$ and a muon beam energy of 120 GeV. This angle decreases with increasing y and decreasing x , and for a fixed y and x decreases as the square root of the beam energy. Such an angle corresponds to a transverse distance of $\sim 28 \text{ cm}$ at the front face of the calorimeter; a measurement of the photon angular distribution is clearly not possible in this apparatus. It is therefore necessary to put further selections on the events to ensure a reliable measurement of the photon yield.

From the sample described above, events have been further selected where the apparent virtual photon vector, $\vec{q}$, projects onto the calorimeter at least 2 cm from any scintillator edge or dead region. This requirement then effectively defines the kinematic range in which there is a good chance that a hard photon will be measured by the calorimeter. Since the beam hole, defined by a cutout in the central scintillator blades, introduces a large uncertainty into the measurement of photon energies, only events where $\vec{q}$ projects onto the upper half of the calorimeter (the side closer to the photomultipliers) have been considered. With these further cuts on the incident and scattered muon $\sim 18,000$ events with $0.3 < y < 0.8$ and $0.02 < x < 0.15$ remain.

Any single photon signal, except at the highest z , will in practice be masked by a strong background of photons from the decays of neutral mesons produced by normal deep-inelastic scatters. This background falls steeply with z and an estimate of it would depend critically upon a correct knowledge of the resolution and linearity of the calorimeter. Since, however, neutral mesons are usually produced in association with charged mesons, this background can be strongly reduced by the requirement that no charged hadron track is observed in an event. This requirement reduces the signal of bremsstrahlung photons from the radiative tail of inelastic scatters but does not affect that from the elastic radiative tail; the photons from the latter process have $z \approx 1$.

4. RESULTS AND COMPARISON WITH PREDICTIONS

Fig. 3 shows the z -distribution of all electromagnetic showers for the kinematic region $y > 0.7$ and $x < 0.1$ for events selected according to the criteria described above, including the requirement that no charged hadron track was observed in the Forward Spectrometer. The clear peak of events at high z is ascribed to hard bremsstrahlung photons. The width and position of this peak are entirely consistent with the known instrumental uncertainties of the calorimeter. The emission of photons at $z = 1$ corresponds to an energy of ~ 90 GeV. Also shown on the figure is an estimate, normalized to the same number of scattered muons, of the residual yield of photons from neutral mesons, mainly π^0 and η , decaying electromagnetically. This background estimate was obtained from a Feynman-Field type Monte Carlo generation of meson jets [7] which were then followed through the apparatus; the same geometrical cuts on the virtual photon direction as used for the data were applied. The Monte Carlo model is consistent with measurements of neutral mesons made in the same apparatus in the same range of ν using a beam of 280 GeV incident muons [8].

In order to make a comparison with the predictions for the yield of hard photons the quantity:

$$f_{\gamma} = N_{\gamma}/N_{\mu}$$

is evaluated. N_γ is the number of events in which no hadron tracks and a $z > 0.8$ photon was observed and N_μ is the total number of events in a bin of y and x which satisfy the cuts described above. A small background due to neutral meson decays, estimated as previously described, is subtracted.

Figs 4a, 4b and 4c show the quantity f_γ plotted as a function of y for 3 bins of low x . Most of the photon yield is seen to be at high y and the lowest x . The size of the beam hole in the calorimeter prevents the measurements being extended reliably to higher y or smaller x values. Due to the structure of the angular distribution and the geometrical acceptance, the data represent the yield of photons in the region of the t -peak. The error bars shown on the data points are statistical only; the largest contribution to the systematic error is attributable to the estimate of the neutral meson background, which depends upon the precise energy calibration of the calorimeter, and leads to an overall absolute uncertainty of ~ 0.003 in f_γ . The curves plotted on fig. 4 represent the predictions of the exact 1-photon formulae of ref. [1] folded by a Monte Carlo calculation with the geometrical acceptance of the apparatus. This calculation included the energy resolution of the calorimeter and loss of photons by conversion in material upstream of the F.S. magnet. About one third of the observed photon yield is predicted to originate from the inelastic region. There is no conspicuous disagreement between the measurements and the predictions in the range of y and x covered.

5. CONCLUSIONS

The yield of wide-angle bremsstrahlung photons produced by 120 GeV muons from a proton target has been measured in the kinematic range $0.3 < y < 0.8$ and $0.02 < x < 0.15$ and is in good agreement with that predicted by the standard description of radiative corrections. This in itself is a necessary condition for the application of such corrections to deep-inelastic muon scattering data.

REFERENCES

- [1] Y.S. Tsai, SLAC Pub. 848 (1971);
L.W. Mo and Y.S. Tsai, Rev. Mod. Phys. 41 (1969) 205.
- [2] Charles Chahine, Phys. Rev. D 22 (1980) 2727;
Phys. Rev. D 22 (1980) 1062.
- [3] H.J. Behrend et al., Phys. Rev. Letters. 15 (1966) 900.
- [4] C. Bernardini et al., Lettere al Nuovo Cimento 1 (1969) 15.
- [5] R.H. Siemann et al., Phys. Rev. Letters 22 (1969) 421.
- [6] E.M.C. - O.C. Allkofer et al., Nuclear Instr. and Methods 179 (1981) 445.
- [7] T. Sjöstrand and B. Söderberg, Lund University preprint LU-TP 78-18 (1978).
- [8] E.M.C. - J.J. Aubert et al., CERN-EP/80-130 (1980),
Contribution to the XX Int. Conference on High Energy Physics,
Madison, Wisconsin, 1980.

FIGURE CAPTIONS

Fig. 1 Sketch of the EMC calorimeter.

Fig. 2 Predicted distribution of the angle ($\theta_{\gamma\gamma^*}$) between the direction of hard photons and the apparent virtual photon direction for the kinematic region $0.6 < y < 0.7$, $0.02 < x < 0.06$ and a 120 GeV muon beam.

Fig. 3 z-distribution of electromagnetic showers for events in the region $y > 0.7$, $x < 0.1$ and in which no hadron tracks were observed. The solid curve is an estimate of the residual background from the electromagnetic decays of mesons.

Fig. 4 The quantity $f_{\gamma} = N_{\gamma} / N_{\mu}$ plotted as a function of y for 3 bins of x :

a) $0.02 < x < 0.06$

b) $0.06 < x < 0.1$

c) $0.1 < x < 0.15$

The solid curves represent the exact 1-photon predictions of ref. [1] folded with the geometrical acceptance of the apparatus.

Fig. 1

Fig. 2

Fig. 3

Fig. 4