Radiative Corrections to Deep Inelastic Scattering on Heavy Nuclei at HERA

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Abstract: Radiative corrections to deep inelastic scattering on heavy nuclei at a possible future HERA experiment are calculated. We discuss the contributions from the elastic, quasielastic and inelastic radiative tails and their sensitivity to experimental cuts.

1 Introduction

The physical interpretation of the data of experiments on deep inelastic scattering requires the separation of the Born cross section from background contributions known as radiative corrections. Radiative corrections receive contributions from loop diagrams and from processes with the emission of additional photons. Some of the radiative events can be identified and removed from the event sample by experimental methods. However, a substantial contribution with soft or collinear photons can not be separated from non-radiative events. Thus, radiative effects have to be calculated theoretically and subtracted from measured cross sections. In this paper the FORTRAN codes HERACLES [1] and POLRAD [2] are applied for the calculation of radiative corrections to the scattering of leptons off heavy nuclei at a possible future modified HERA collider.

2 Physics of radiative corrections

There are three basic channels for the scattering of electrons on nuclei: elastic, quasielastic and inelastic processes. Their contribution depends on the kinematic region which we describe with the help of the four momentum transfer Q^2, the Bjorken scaling variable x_A and the invariant mass of the hadronic final state $W_A^2 = Q^2(1-x_A)/x_A + M_A^2$ (where M_A is the mass of the nucleus)[2]. For $W_A = M_A$, only elastic scattering is allowed. Quasielastic scattering,

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[2] We use kinematical variables defined in terms of both nuclear and nucleon masses and momenta. The former set (M_A, x_A, W_A) is used for elastic scattering; the latter set (M, x, W) is better suited for the description of the kinematics of quasielastic and inelastic processes.

corresponding to direct collisions with individual nucleons inside the nucleus, occurs at fixed $x_A \sim M/M_A$ where M is the mass of the hit nucleon. Inelastic scattering sets in when the pion threshold is reached ($W_A \geq M_A + m_\pi$, m_π is the pion mass).

At the Born level, both x_A and Q^2, and consequently W_A, are fixed completely by the measured momentum of the scattered lepton. Therefore it is also fixed which of the three basic processes contributes to the cross section. Including radiative corrections, however, a radiated photon may remain unobserved and the true values of x and Q^2 depend on the unknown momentum transported away by the photon. Then all processes contribute to the measured cross section. The total radiative corrections of order $O(\alpha)$ are obtained as the sum of these radiative contributions and, in addition, loop corrections. The latter are, first of all, due to the vacuum polarization, but also vertex and box graphs contribute, in particular at large Q^2. The former can conveniently be separated into initial state and final state radiation and the so-called Compton peak. Initial (final) state radiation is dominated by events which have a photon collinear to the incoming (scattered) lepton. The Compton peak is characterized by events with small true momentum transfer reached due to the emission of a hard photon although the scattered lepton mimics large Q^2.

The radiative corrections can be large and even exceed the Born cross section in the interesting region of small x. In a realistic experimental situation, part of the events with a radiated photon can be tagged in the calorimeter or be rejected by applying cuts on kinematic variables of the hadronic final state. An important example is the hadronic transverse momentum, $p_{T,had}$. Since $p_{T,had}$ is a measure of the true momentum transfer, a cut $p_{T,had} > p_{T,min}$ will remove the Compton peak almost completely. In particular, such a cut has a large influence on the tails from the elastic and quasielastic processes since these are dominated by the Compton peak. The effect of cuts on the inelastic radiative tail is more complicated and can, most easily, be analyzed with the help of Monte Carlo methods.

The FORTRAN codes HERACLES and POLRAD are used to obtain radiative corrections for HERA kinematics with lepton and nuclear beam momenta equal to 27.6 GeV and 410 GeV, resp. We will present results for beams composed of nuclei with $A = 2Z$ (D, ^{4}He, ^{12}C, ^{32}S and ^{208}Pb) which can be stored in the HERA ring with the same energy per nucleon at the same machine setup.

POLRAD is a program for radiative correction calculations in deep inelastic scattering of polarized leptons on polarized and unpolarized nuclei of spin 0, 1/2 and 1. The explicit formulae were introduced and discussed in [2]. The contributions to the total radiative corrections at lowest order were obtained on the basis of the covariant method for radiative correction calculations, offered by Bardin and Shumeiko in [3] and developed in [4]. Soft photonic higher-order effects are taken into account by the exponentiation prescription described in [5]. POLRAD includes routines for the calculation of the elastic and quasielastic radiative tails. Since the code is based on an analytic integration of bremsstrahlung contributions, it is restricted to the evaluation of inclusive cross sections.

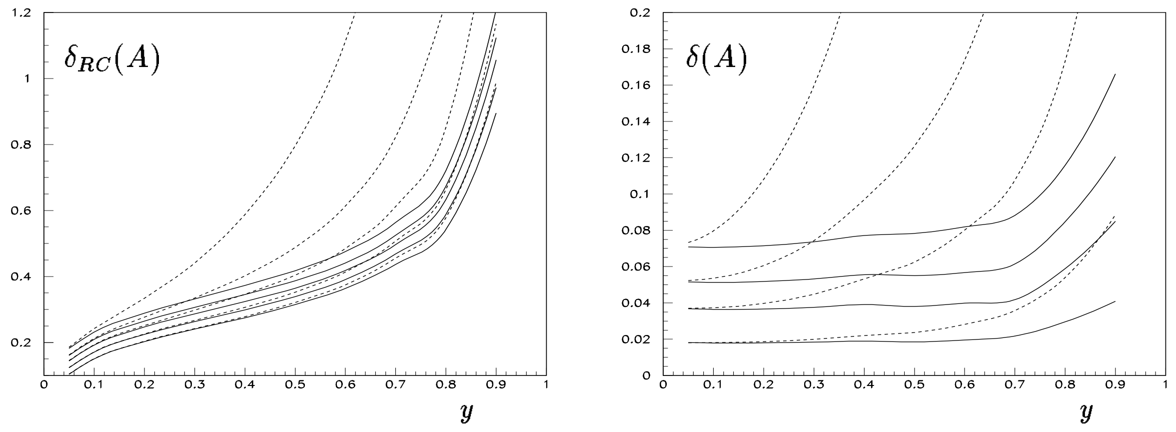
In contrast to this, HERACLES [1] is a Monte Carlo event generator and can therefore be used to obtain cross sections in almost arbitrary phase space regions. It includes the complete QED corrections of $O(\alpha)$ and, in addition, the complete standard model one-loop electroweak corrections. Some higher-order effects are included, but soft photon exponentiation is not performed. The program allows the use of either parton distribution functions or, for the purely leptonic QED corrections, of arbitrary structure functions. It therefore allows the inclusion of the longitudinal structure function, which is in our calculation obtained from the standard QCD expression.

3 Numerical results

The results of HERACLES and POLRAD are shown in Figs. 1 and 2. The investigated quantities are defined as

$$\delta_{RC}(A) = \frac{d\sigma^A/dy}{d\sigma_0^A/dy} - 1, \qquad \delta(A) = \frac{1+\delta_{RC}(A)}{1+\delta_{RC}(D)} - 1,$$

where $d\sigma^A/dy$ and $d\sigma_0^A/dy$ are the observed and the Born cross sections of deep inelastic scattering on the nucleus A, resp. The first quantity δ_{RC} describes the correction of the cross section itself, whereas the second one, $\delta(A)$, describes the correction of the ratio of cross sections $d\sigma^A/d\sigma^D$ which is expected to be accessible with better accuracy by the experiments. These correction factors are obtained from the cross sections after integrating x in the region $10^{-4} \le x \le 10^{-3}$. Results for larger values of x are discussed in the text below. For the explicit calculation, fits or models of inelastic and quasielastic structure functions and elastic formfactors for each nucleus are needed. A traditional model for parton distributions, MRS(A) [6], modified by shadowing effects as described in [7] is used for the deep inelastic structure functions. Quasielastic suppression factors and elastic nuclear formfactors were calculated in accordance with the models of Refs. [8][3] and [9], respectively.



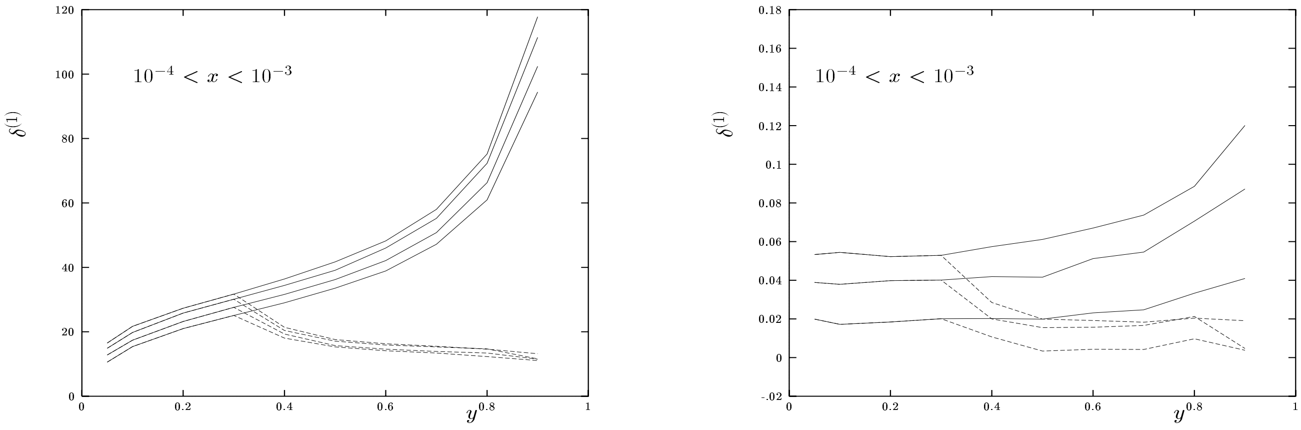
(a) (b)

Figure 1: *Radiative corrections $\delta_{RC}(A)$ and $\delta(A)$ for $10^{-4} \le x \le 10^{-3}$, as a function of y, with full lines showing the inelastic contribution, dashed lines showing the total inclusive radiative correction. The curves from bottom to top correspond to the nuclei D, He, C, S, Pb.*

The results for $\delta_{RC}(A)$ and $\delta(A)$ obtained from POLRAD are presented in Fig. 1. These quantities are shown with and without the contributions from the elastic and quasielastic tails. The radiative correction $\delta_{RC}(A)$ due to the inelastic tail grows rapidly with increasing y and reaches values of 100% for $y \sim 0.8$. Both the elastic and quasielastic tails give large additional contributions. The A-dependence of the inelastic cross section is contained only in the shadowing correction factor and is therefore weak. In contrast to this, the elastic tail depends much

[3]Stein's and Bernabeu's approaches for D and ^{4}He, and the Fermi-gas model for heavier nuclei.

stronger on the type of the nucleus since the correpsonding squared form factor is proportional to Z^2/A. At larger values of x the corrections are slightly smaller, reaching 100 % only at values of y above 0.9 for $10^{-3} \leq x \leq 10^{-2}$. Moreover, the cross section both at the Born level and including radiative corrections has a smaller A dependence at large x because the shadowing correction factor tends to 1 for large x and becomes larger than 1 for $x \sim 0.07$.



(a) (b)

Figure 2: *Inelastic contribution to the radiative corrections* $\delta_{RC}(A)$ *for* $10^{-4} \leq x \leq 10^{-3}$, *as a function of* y, *for the nuclei D, He, C, and S (corresponding to the lines from bottom to top) obtained from HERACLES. The full lines show the corrections without cuts, dashed lines are the results after cuts as explained in the text.*

Fig. 2 shows the results for the inelastic contribution as obtained from HERACLES. The full lines in this figure do not fully agree with the full lines of Fig. 1, since here we included the contribution from the longitudinal structure function F_L according to the standard QCD formula. The dashed lines exemplify the influence of experimental cuts on the radiative corrections. We did not attempt to apply the full set of cuts as are presently being used in the experimental analyses of H1 or ZEUS for structure function measurements since this would require a simulation and analysis of the full hadronic final state. Rather we simply rejected events which have a radiative photon of energy $E_\gamma \geq 10$GeV emitted in the cone of half-opening angle $\theta_{max} = 3°$ around the direction of the incoming electron beam. Most of these photons can not be observed directly. However, they reduce the amount of the total energy minus longitudinal momentum, $E - p_z$, which can be reconstructed from the observed final state. In addition, a cut on the transverse momentum $p_T^e + p_T^\gamma \geq 0.5$ GeV was applied which has little effect on the inelastic tail, but would remove most of the constributions from the elastic and quasielastic tails. The results in Fig. 2 demonstrate that a cut of this type reduces the corrections due to the inelastic radiative tail to the level of 15 to 30 %. In particular, the strong increase of corrections towards increasing y does not appear anymore. We also remark that the same cut eliminates the contribution from the elastic and quasielastic tails practically completely. Fig. 2b shows that the corrections of the cross section ratios are reduced as well.

In obtaining our results for the contributions of radiative tails to the measured cross section we used specific model assumptions for structure functions and form factors. In particular, we used the extrapolation of the fit from [7] for the shadowing corrections into the region of very small values of x. It is just this quantity (and parton densities, of course) whose measurement is aimed at with possible future experiments at HERA and an iterative procedure specifying fit parameters for shadowing corrections will be used to improve the precision of predictions for radiative corrections. However, not the complete required input for radiative correction calculations can be verified by the experiment and there will remain a residual uncertainty from tails extending into kinematical regions outside of what is experimentally accessible. The elastic and quasielastic tails are basically dominated by the values of form factors in the region of very small Q^2 (the Compton peak). Different models or fits of experimental data practically coincide in this region. Also, no marked effect coming from the resonance region fit of structure functions and the Fermi-motion term in the shadowing corrections was found. It was also checked that a modification of the low-Q^2 behaviour of the inelastic structure functions as proposed in [10] changes the results for the radiative corrections by a few per mille only.

In conclusion, our calculations have shown that radiative corrections to the cross section for scattering of leptons off heavy nuclei may be large and should be properly taken into account. Simple experimental cuts will, however, allow to reduce them considerably.

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