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Photoproduction of Open Charm at HERA

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Abstract. New results from the H1 and ZEUS experiments on photoproduction of open charm at HERA are presented. Final states containing charm events are identified by the reconstruction of charmed hadrons. These data are used to extract information on charm fragmentation ratios and fractions, to test QCD predictions on inclusive $D^{*\pm}$ meson production and to investigate di-jet angular distributions in photoproduction of charm.

1 Introduction

The description of charm photoproduction in *ep* scattering at HERA is based on perturbative QCD (*pQCD*). In leading order (*LO*) charm quarks are predominantly produced by the *photon gluon fusion (PGF)* process, i.e. $\gamma g \to c\overline{c}$, where a quasi-real photon emitted by the electron[1] interacts with a gluon in the proton producing a charm quark pair $c\overline{c}$. In addition to this *direct* process sizable contributions from *resolved* photon interactions, i.e. $g^{(\gamma)}g^{(p)} \to c\overline{c}$ and $c^{(\gamma)}g^{(p)} \to cg$ are expected in photoproduction due to the partonic structure of the photon. In next-to-leading order (*NLO*) or beyond, however, this distinction becomes inappropriate.

NLO calculations for charm production are performed in different schemes. All approaches assume a scale to be hard enough to apply pQCD and to guarantee the validity of the factorization theorem.

The *massive approach* assumes three active flavours in the proton. The densities of the three light quarks and the gluon in the proton and the photon are obtained by DGLAP evolution. Charm quarks are produced perturbatively [1] via PGF. These calculations are reliable for a renormalization scale $\mu_r^2 \approx m_c^2$, but break down for $\mu_r^2 \gg m_c^2$.

The *massless approach* [2,3] sets $m_c = 0$. Therefore charm is treated as an active flavour in the proton. Within this approach final state divergencies are absorbed into the fragmentation function. This scheme is indispensable for $p_\perp \gg m_c$ but breaks down for $p_\perp \leq m_c$.

In a third approach (*FONLL*) [4] the features of both methods are combined. This *matched scheme* adjusts the number of partons n_f in the proton according to the relevant scale. It applies the massive scheme at low scales and treats charm similarly to massless quarks for scales much above m_c.

Recent results on charm fragmentation parameters, on inclusive $D^{*\pm}$ meson production and on $D^{*\pm}$ with associated di-jet production presented in this paper are used to get further insight into charm photoproduction at HERA and to test the validity of theoretical calculations.

2 Fragmentation ratios

Experimentally heavy quark are not observed directly, but heavy flavoured hadrons are measured instead. This fragmentation process is a long distance effect, which can only be described by phenomenological models. These models are implemented into theoretical cross section calculations assuming fragmentation to be independent of the underlying production mechanism of the charm quarks. This universality can be tested by measuring the charm fragmentation properties in *ep* as well as in e^+e^- collisions.

In Fig. 1 recent results on the fragmentation ratios $R_{u/d}$, γ_s and P_V obtained from charmed hadron photoproduction at HERA [5] are compared with measurements in deep inelastic scattering(*DIS*) [7] and in e^+e^--annihilation [8]. The variable $R_{u/d} = c\overline{u}/c\overline{d}$, which measures the ratio of the neutral to charged D meson production, is expected to be close to unity because of the smallness of the bare u and d quark masses. The strangeness suppression factor $\gamma_s = 2 \cdot c\overline{s}/(c\overline{u} + c\overline{d})$ should be significantly smaller than unity because of the bare strange quark mass. Finally the ratio $P_V = V/(V+P)$ denoting the fraction of D masons produced in a vector state is expected to 3/4 from naive spin counting. From Fig.1 it can be concluded that all three fragmentation ratios are indeed universal quantities within the experimental accuracy. Furthermore, $R_{u/d}$ and γ_s are consistent with naive expectations while the ratio P_V deviates significantly from the value obtained by simple spin counting.

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[1] Hereafter, a reference to electrons implies a reference to either electrons or positrons.

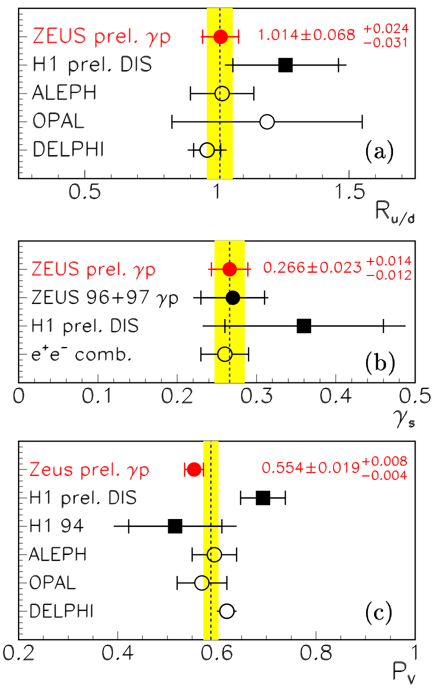

Fig. 1. The ratios (a) $R_{u/d}$, (b) γ_s and (c) P_V from γp at HERA in comparison with DIS and e^+e^- results. The vertical lines and the shaded bands correspond to the averages and their errors, respectively.

In addition to these ratios the fragmentation fractions of charm quarks into individual charmed hadrons measured in γp [5] are in agreement with the values obtained in DIS at HERA and e^+e^- annihilation at LEP. Furthermore it has been shown that the distribution of the fragmentation function of $D^{*\pm}$ mesons, as extracted in γp [6] is consistent with the results from similar measurements in e^+e^- at different energies. These observations give strong support for the assumption of the universality of charm fragmentation within the region of phase space currently accessible by the different charm production processes.

3 Inclusive $D^{*\pm}$ meson production

Inclusive $D^{*\pm}$ meson photoproduction serves as an important tool for testing QCD models of charm production. The experimental attractiveness of the $D^{*\pm}$ meson lies in the small energy release in the decay $D^{*+} \to D^0\pi^+$, which is very close to m_π and thereby leads to a good signal to background ratio. In addition the $D^{*\pm}$ meson fragmentation function is relatively well known which limits a part of the systematic uncertainties in theoretical calculations.

Fig.2 shows the inclusive $D^{*\pm}$ meson electro-production cross sections $d\sigma/dp_t$ and $d\sigma/d\eta$ in the photoproduction regime [9], where η denotes the pseudorapidity defined as $\eta = -\ln\tan\Theta/2$. The data are compared to NLO QCD calculations in the 3-flavour massive [1] and in the 4-flavour massless scheme [3]. The error bands on the theoretical predictions indicate the uncertainties due to variations of the renormalisation and factorisation scales. These

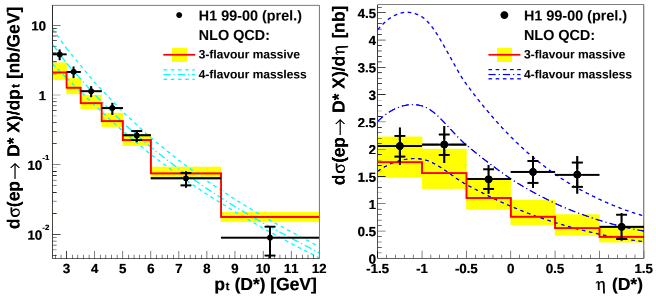

Fig. 2. Differential cross sections $d\sigma/dp_t$ and $d\sigma/d\eta$ compared with predictions from massive and massless NLO calculations.

uncertainties which are only part of the total uncertainties are large compared to the experimental errors. While the massless calculation is able to describe the data in $d\sigma/dp_t$, none of the calculations can reproduce the shape of $d\sigma/d\eta$.

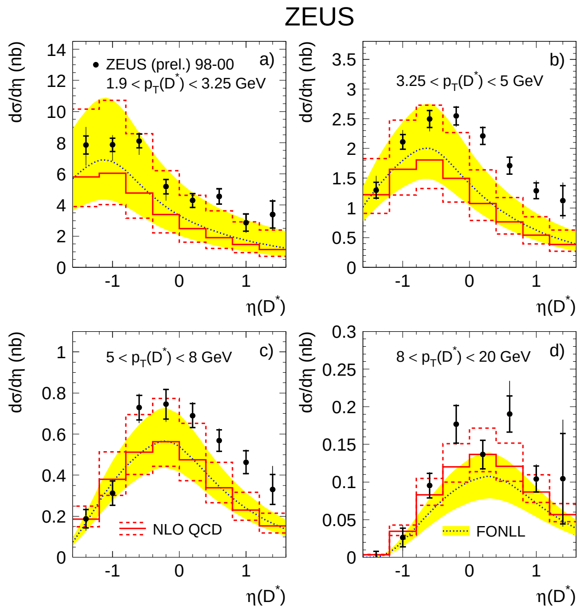

Fig. 3. Differential cross section $d\sigma/d\eta$ in bins of p_t compared with predictions from massive NLO and FONLL calculations.

The failure of the theory in describing the data at large η becomes more evident in Fig.3 which shows the cross section $d\sigma/d\eta$ in bins of p_t [10]. Here, the data are compared with predictions from the massive [1] and from the FONLL [4] approach. Despite of the large theoretical uncertainties significant deviations from the data are observed in the intermediate p_t region at $\eta > 1$.

4 Charm di-jet angular distributions

The study of charm events with associated di-jets has been proven to be an efficient tool for investigating details of the charm production mechanism [11]. Using the LO language the data may be divided into samples enriched in direct and resolved events by the variable x_γ^{obs}, which gives the momentum fraction of the photon carried by the two jets. The cross section $d\sigma/dx_\gamma^{obs}$ has been found to be larger at low x_γ^{obs} than predicted by NLO calculations [1], but agrees at large x_γ^{obs}. Agreement in shape between the measured cross section and LO Monte Carlo models including parton-showers is obtained if they include a resolved component of ≈40%. Furthermore this comparison predicts that most of the resolved contribution is due to $c^{(\gamma)}g^{(p)} \to cg$ rather than $g^{(\gamma)}g^{(p)} \to c\bar{c}$.

Direct information on the mechanisms of charm di-jet photoproduction in both the resolved and direct regimes is obtained from the analysis of the angular correlation between the direction of the jet associated with the reconstructed $D^{*\pm}$ meson and the proton direction in the the jet-jet rest frame [12]. For the processes $\gamma g \to c\bar{c}$ and $g^{(\gamma)}g^{(p)} \to c\bar{c}$ in which the propagator is a quark this angular distribution is expected to follow $d\sigma/d\cos\Theta^* \propto (1-|\cos\Theta^*|)^{-1}$. For $c^{(\gamma)}g^{(p)} \to cg$ the dependence on $\cos\Theta^*$ is more complicated. The dominant contribution is due to the gluon propagator yielding a $(1-|\cos\Theta^*|)^{-2}$ term for $\cos\Theta^* < 0$ while the smaller contribution from the quark propagator leads to a $(1-|\cos\Theta^*|)^{-1}$ dependence for $\cos\Theta^* > 0$.

In fig.4 the cross section $d\sigma/d\cos\Theta^*$ is shown in comparison with expectations from LO Monte Carlo models including parton showers. The data is divided into two samples: $x_\gamma^{obs} < 0.75$ which is dominated by resolved processes and $x_\gamma^{obs} > 0.75$ which is enriched in direct photoproduction. As expected in the region of large x_γ^{obs} only a small variation with $\cos\Theta^*$ is observed in the experimentally accessible $\cos\Theta^*$ range. The distribution shows a small asymmetry mainly due to contamination of resolved events. In the region of small x_γ^{obs} the data show a strong backward asymmetry due to the dominance of the process $c^{(\gamma)}g^{(p)} \to cg$ in resolved events. Both Monte Carlo models are not able to describe the absolute cross sections. When applying overall normalisation factors to the models, however, the PYTHIA program yields a good description of the data in both x_γ^{obs} regimes while HERWIG predicts a smaller backward asymmetry than experimentally observed for small x_γ^{obs}.

The prediction of NLO calculations in which charm is produced exclusively in the hard sub-process lies below the data for small x_γ^{obs}. The description of the data could be improved by including a charm component in a NLO fit to the photon structure function.

5 Conclusion

New results on open charm photoproduction from the H1 and ZEUS experiments at HERA have been presented. The measurements of the charm fragmentation ratios and fractions agree well with the results from other charm production processes and thus support the hypothesis of the universality of fragmentation. The inclusive $D^{*\pm}$ meson cross sections reveal the incapability of available NLO QCD calculations to describe the data in all aspects. The analysis of charm di-jet angular distributions has proven that charm as an active flavour in the photon is the major contribution to the resolved photon process in the LO framework.

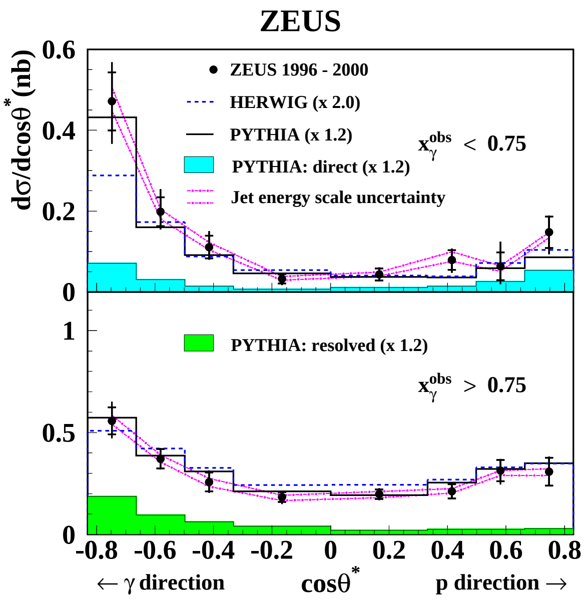

Fig. 4. Differential cross sections $d\sigma/d\cos\Theta^*$ compared with MC simulations PYTHIA and HERWIG for the resolved-enriched ($x_\gamma^{obs} < 0.75$) and the direct-enriched ($x_\gamma^{obs} > 0.75$) samples. The model predictions are normalized to the data.

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