ep Physics with Heavy Flavours

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Abstract: Recent results from H1 and ZEUS on heavy flavour production at HERA are reviewed.

1. Introduction

Heavy Flavour physics at HERA focuses on aspects related to production dynamics rather than weak decays and mixing angles. Heavy quarks – like jets – reflect the properties of hard subprocesses in ep interactions. Their mass provides the natural scale which allows the application of perturbative methods in QCD and also testing the theory in regions where no other hard scale (like high transverse energy) is present. Furthermore, when probing the structure of matter, heavy quarks single out the gluonic content.

For this talk topics from open charm and beauty production have been selected. There was no time to cover Onium production (for recent reviews, see [1]). There is no tau physics included, either, although τ candidates have been seen at HERA, and interesting limits on lepton-flavour violating lepto-quarks have been obtained [2].

At HERA, 820 GeV protons (defining the "forward" direction) collide head-on with 27 GeV electrons, yielding a centre-of-mass system (CMS) energy of $\sqrt{s} = 300$ GeV. The standard textbook notation will be used to describe the kinematics of deep inelastic scattering (DIS): Q^2 denotes the four-momentum transfer squared, x and y are scaling variables related to the momentum fraction of the struck parton and to the inelasticity of the collision, respectively. W denotes the photon-proton CMS energy. The kinematic regime where the exchanged photon becomes quasi-real ($Q^2 \rightarrow 0$) is called photo-production. Also in this region W can be large and attains values an order of magnitude higher than in fixed-target experiments.

2. Charm Production

In most of the studies presented here, open charm is detected in the "golden" decay channel $D^{*+} \rightarrow D^0\pi^+$ followed by $D^0 \rightarrow K^-\pi^+$.[1] ZEUS also uses the channel $D^{*+} \rightarrow (D^0 \rightarrow K^-\pi^-\pi^+\pi^-)\pi^-$, and this year for the first time they have shown results using $D_s+ \rightarrow (\phi \rightarrow K^+K^-)\pi^+$ [3].

2.1 Deep inelastic scattering

In QCD, c and b production in ep collisions proceed mainly via the boson gluon fusion diagram shown in figure 1.

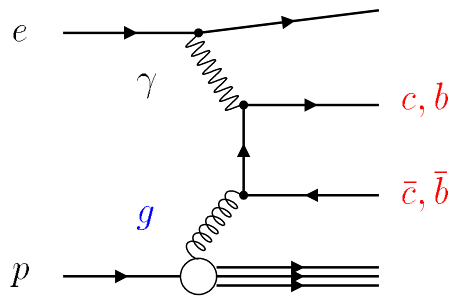

Figure 1: Boson gluon fusion.

Therefore, charm production has already in the past offered a way to determine the gluon density in the proton [4]. The process has been calculated in Next-to-Leading order (NLO) QCD in the so-called Three Flavour $\overline{MS}$ scheme for photo-production [5] and DIS [6]. In the HVQDIS program, the charm hadronization into D^* mesons is modeled using a Peterson fragmentation

[1] The charge conjugate is always implicitly included.

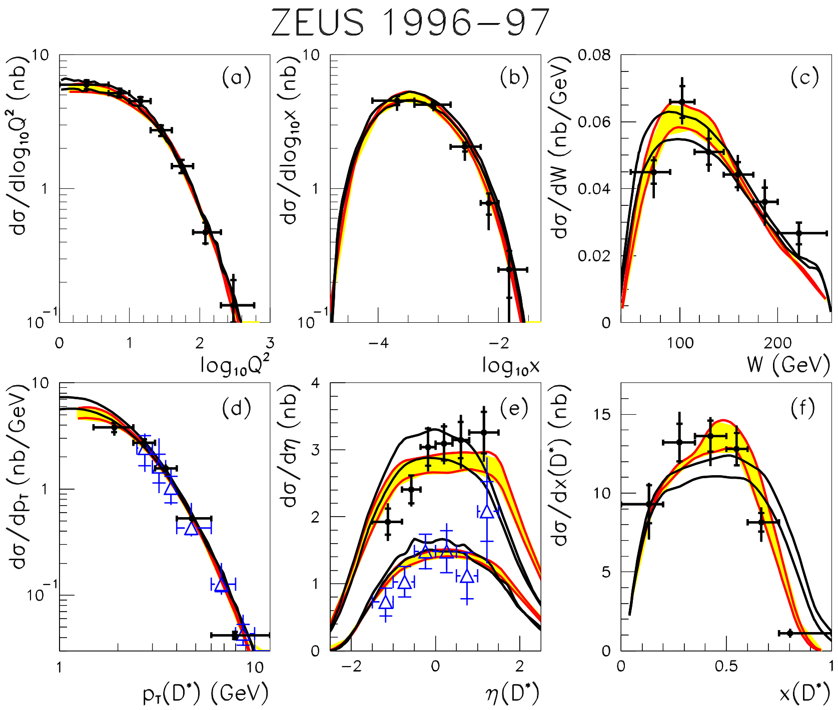

Figure 2: D^* cross sections in DIS, compared with NLO QCD, using for fragmentation a Peterson type (open band) or a LO MC model (shaded band). The widths of the bands correspond to a charm mass variation between 1.3 and 1.5 GeV.

function [7] with the parameter $\epsilon_c = 0.035$ as determined in e^+e^- annihilation [8].

Differential D^* cross sections in the experimentally accessible DIS range have been measured by H1 [9] and ZEUS [10]. The ZEUS data are shown in figure 2 and compared to the HVQDIS calculation. (The open points in (d) and (e) are results from the $K4\pi$ channel.) A Leading-Order Monte Carlo fragmentation approach based on the JETSET program also has been used by ZEUS. As can be seen from the figure, the pseudo-rapidity and the x_D distribution[2] are quite sensitive to details of the fragmentation modeling, whereas the distributions of other kinematic variables, like x and Q^2 are barely affected. The migration of the mesons towards positive pseudorapidities in the Monte Carlo, due to color interactions between the charm quark and the proton remnant, has been called the "beam drag" effect [11].

In general, there is good agreement with the NLO calculation. This gives the justification to the extrapolation to the full phase space, which is needed to extract F_2^c, the charm contribution to the proton structure function.

In the Quark-Parton Model, the structure function F_2 is given by the charge-weighted sum of the (anti-)quark densities, $F_2 = \sum_i e_i^2(q_i(x) + \bar{q}_i(x))$ and depends only on x. The presence of gluons introduces "scaling violations", i.e. a dependence of the structure function on Q^2. The gluons are also responsible for the observed steep rise of F_2 towards low values of x, where the quark sea is being probed.

The relative charm contribution to inclusive DIS, quoted as F_2^c/F_2, is not constant, but rises with Q^2 and towards low x, as can be seen in figure 3. Since the process under study is gluon-induced, F_2^c reflects the gluon content of the proton even more pronouncedly than F_2. The most salient feature is that in the HERA regime the charm contribution is very large, 20 - 30%, making the theoretical description of charm production an essential ingredient to the understanding of proton structure.

[2] $x_D \equiv 2p^*(D^*)/W$ is the fractional momentum of the meson in the γ^*p rest frame and strongly correlated with η.

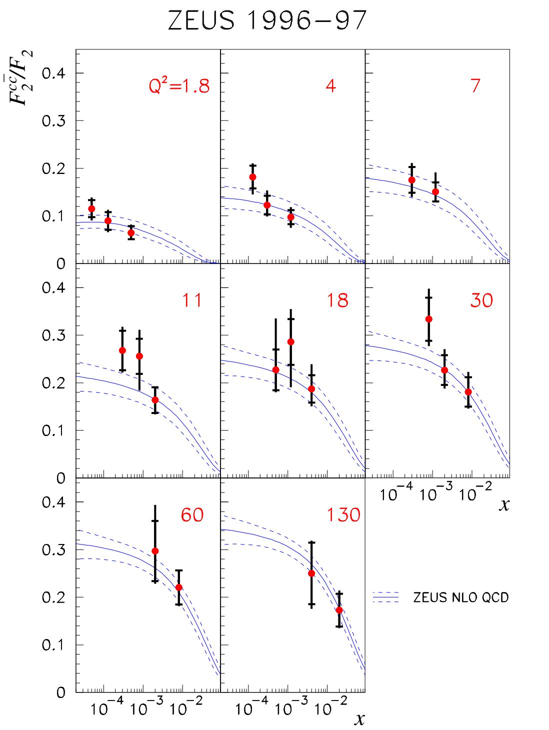

Figure 3: Relative charm contribution to inclusive DIS. (Extrapolation uncertainties of $\sim 20\%$ are not shown.)

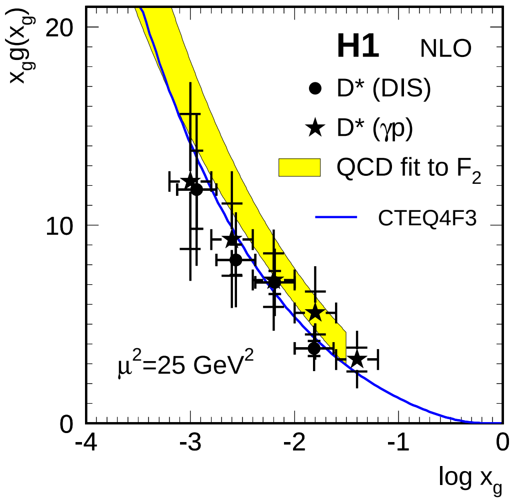

Figure 4: Gluon distribution.

H1 has performed a direct measurement of the gluon density in the proton from charm production in DIS and in photo-production. The kinematics of the reconstructed D^* meson and the scattered electron have been used to infer the incoming gluon momentum. The NLO programs have been used in order to correct for higher order processes and fragmentation by means of an unfolding procedure. The results, shown in figure 4, agree well with each other and with the gluon distribution determined indirectly through a QCD analysis of the scaling violations of inclusive structure function data. This demonstrates that the gluon density is universal, and indicates the success of the NLO QCD description.

2.2 Photo-production

In the case of photo-production of open charm, additional, so-called "resolved" photon contributions have to be taken into account. The photon may fluctuate into a hadronic state, and a parton from this state interacts with a parton from the proton, e.g. charm may be formed via gluon-gluon fusion. Since only a fraction of the photon's energy is available in the hard sub-process, in comparison with "direct" photon interactions, the outgoing charm is found at lower transverse momenta and at more forward rapidities. Resolved photo-production is therefore suppressed by experimental cuts, and in fact extra care was taken in the above-mentioned gluon analysis to minimize uncertainties related to such *a priori* unknown contributions.

There are two approaches in NLO QCD to describe charm photo-production. In the "massive" scheme [5], charm is produced only dynamically in the final state (like in the DIS case above). In the "massless" scheme [12], charm also plays an active role in the initial state as a parton of the proton and of the photon. While the first approach should be adequate near threshold where the transverse momenta are comparable to the charm quark mass, the second has been developed for the region of higher $p_\perp$.

D^* photoproduction cross sections as recently measured by ZEUS [3] in the region $80 < W < 120$ GeV are compared to NLO QCD calculations in the massive scheme in figure 5. Fair agreement can be seen in the low $p_\perp$ range, with however somewhat "stretched" parameter values. At higher $p_\perp$ the data tend to be above the prediction, in particular in the forward region. As in the DIS case, predictions in this region are seen to be sensitive to details of how the fragmenta-

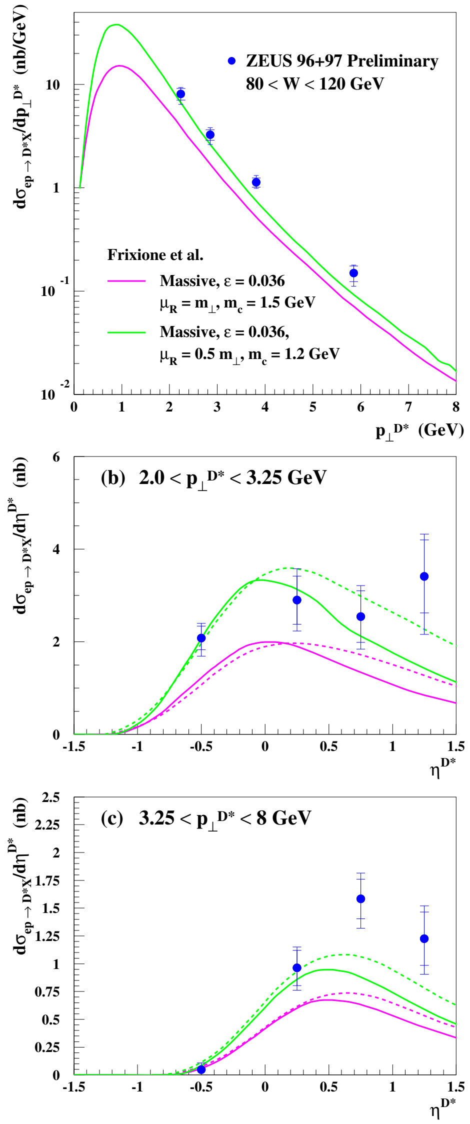

Figure 5: D^* photoproduction cross section, compared with NLO QCD in the "massive" scheme. (Dashed: Peterson, dotted: PYTHIA fragmentation).

tion process is being modeled. The same conclusions can be drawn from the ZEUS data obtained with D^* and D_s mesons at higher W [13]. H1, albeit with somewhat larger measurement errors, do not observe a discrepancy with respect to the "massive" calculations [9].

In the "massless" calculation, there is a large "resolved" contribution which is mostly due to diagrams where a charm quark from the photon interacts with a parton from the proton; an example is shown in figure 6. (Note that the assignment of "direct" and "resolved" is not unambiguous in NLO.) In this picture the cross sections are thus sensitive to the charm density in the *photon*, as indicated in figure 6, where different photon PDFs have been used in the calculation. H1 [9] and ZEUS data [13] (shown here) have been compared with NLO QCD in the "massless" scheme. As in the "massive" case, the agreement is not good everywhere.

2.3 Diffractive production

Pursuing these concepts further, charm production may also shed light on the dynamics of diffractive scattering. A fraction of about 10 % of the DIS events have a "rapidity gap": in contrast to the general case the region surrounding the outgoing proton beam is void of any particles. This distinctively "diffractive" topology leads to an interpretation of the events in terms of the exchange of a color-less object, which may be identified with the Pomeron ($I\!P$) in the framework of hadron-hadron interaction phenomenology. HERA offers the possibility to study these phenomena in a perturbative regime and to investigate the partonic structure of the exchange, where charm production again singles out the gluonic component.

Two different model predictions are considered here (figure 7). In the "resolved Pomeron" model [14], the structure of the exchanged object is described in terms of quark and gluon densities which have been obtained from a fit to inclusive diffractive DIS data [15]. In the "two gluon" model [16], the color-less exchange is realized in terms of two hard gluons, and cross sections are sensitive to the gluon density in the proton. The two approaches lead to remarkably different kinematic distributions. Both H1 [17] and ZEUS [18] have presented first measurements of differential cross sections this year.

$z_{I\!P}$ is an observable correlated with the fraction of momentum of the exchanged object which is carried by the parton interacting with the $c\bar{c}$ pair. In the "$2g$" model, $z_{I\!P} = 1$ would hold if the partons could be directly observed. The data [17] in figure 8 reveal that a sizeable fraction of charm is produced at low $z_{I\!P}^{obs}$ ("resolved Pomeron interaction"). The "resolved $I\!P$" approach however

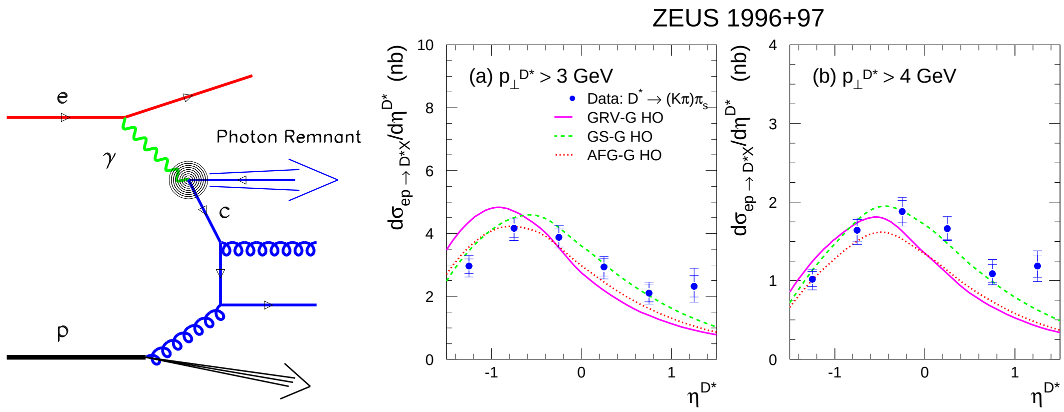

Figure 6: D^* photoproduction in the "massless" picture; D^* cross sections compared with NLO QCD in the "massless" scheme, where the curves correspond to different photon PDFs.

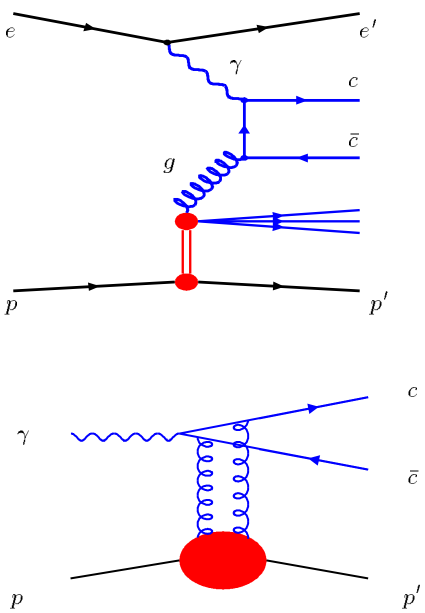

Figure 7: Diagrams of diffractive D^* production: "resolved Pomeron" (upper) and "2 gluon" model.

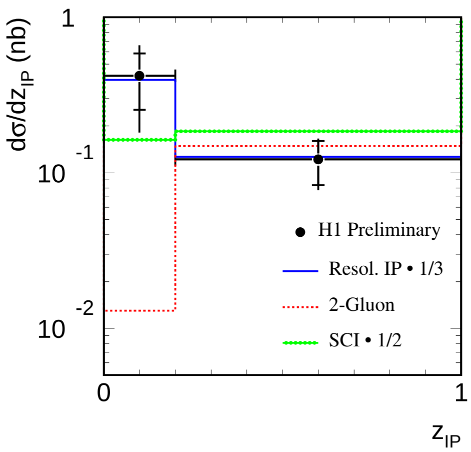

Figure 8: D^* cross section in diffractive DIS.

fails in reproducing the normalization of the H1 data. In the "two gluon" model, on the other hand, a lack of higher order, low $z_{I\!P}$ contributions is apparent. More general, models, where the hadronic system X predominantly consists of the $c\bar{c}$ system alone, are disfavored. The data still have large, mostly statistical, uncertainties, but they already provide valuable and rather distinctive indications for further refinement of the theoretical description.

3. Beauty Production

Finding beauty at HERA is not straightforward. Theory predicts total cross section ratios of about $\sigma_{\rm uds} : \sigma_{\rm charm} : \sigma_{\rm beauty} \sim 2000 : 200 : 1$ [5]. The measurements to date rely on the well established signature of semileptonic decays of b hadrons in jets. Due to the higher b mass, the leptons in b events have a higher transverse momentum p_T^{rel} with respect to the jet direction which approximates the flight direction of the decaying hadron (figure 9). The b cross section can thus be extracted by means of a fit to the p_T^{rel} distribution.

The preliminary H1 result released in 1998 has meanwhile been published [19]. The visible cross section, quoted for the range $Q^2 < 1\,{\rm GeV}^2$,

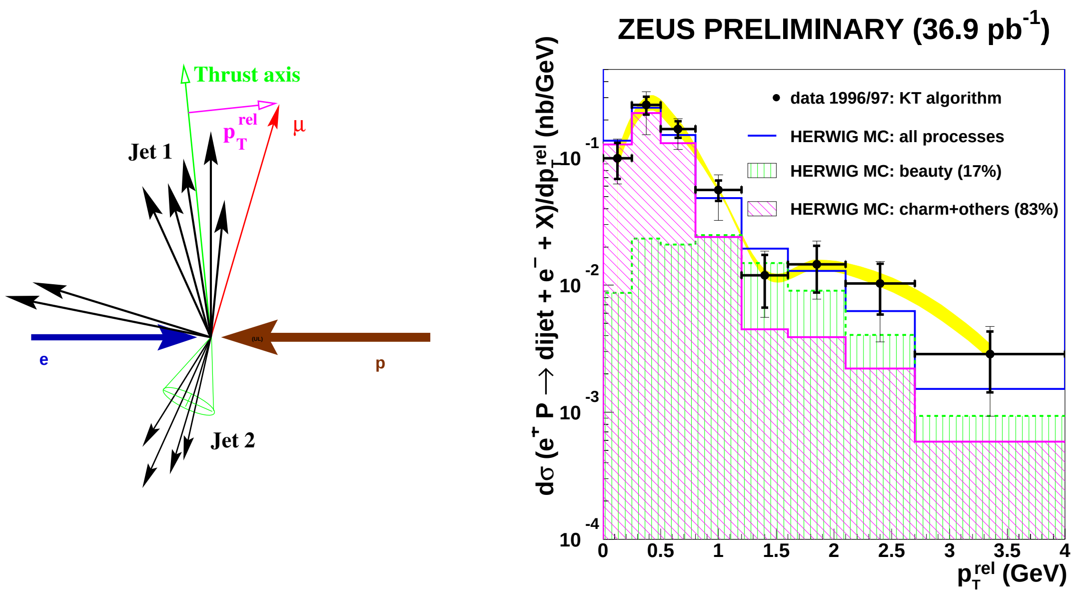

Figure 9: b production signature and p_T^{rel} spectrum.

$0.1 < y < 0.8$, $p_t^\mu > 2\,\mathrm{GeV}$, $35° < \theta^\mu < 130°$ of $\sigma_{b\bar{b}}^{vis} = 0.93 \pm 0.08^{+0.17}_{-0.07}\,\mathrm{nb}$ is found to be surprisingly high: the Monte Carlo prediction based on Leading Order QCD calculation is 4 to 5 times lower ($\sigma_{b\bar{b}}^{vis} = 0.191\,\mathrm{nb}$). NLO corrections are however non-negligible, as in the charm photoproduction case.

In figure 10 the result, extrapolated to the full phase space by means of a NLO program incorporating a Peterson type model of fragmentation, is confronted with the NLO prediction. Theory at NLO still undershoots the experimental result by about a factor of 2. This is in marked contrast to the expectation that predictions for beauty should be more reliable than for charm, due to the higher scale set by the b mass. On the other hand, the NLO approximation also has difficulties reproducing the normalization of open b cross section measurements at the Tevatron [20].

ZEUS has determined the beauty cross section in three independent analyses, using electrons, muons in the central region and muons in the forward detector region [21]. The p_T^{rel} distribution, obtained in the e channel, is displayed in figure 9. Overlayed is a Monte Carlo prediction obtained with the HERWIG generator, which already describes the shape of the data reasonably well. It should be noted that in HERWIG about half of the c and b photoproduction is due to resolved processes with a heavy quark in the initial state, mostly as an active parton in the photon. A fit of the different components yields a b fraction of 20%, which translates into a visible cross section of $\sigma_{vis}(e^+ \to 2\,\mathrm{jets} + e^- + X) = 39 \pm 11^{+23}_{-16}$ pb for events with 2 jets ($E_T^{1,2} > 7, 6$ GeV, $|\eta| < 2.4$) in the kinematic range $Q^2 < 1\mathrm{GeV}^2$, $0.2 < y < 0.8$, e: $P_T > 1.6\mathrm{GeV}$, $|\eta| < 1.6$.

Consistent results are obtained in the muon channels, with the same jet requirements and for the same kinematic range. For central muons ($-1.75 < \eta < 1.3$, $p > 3$ GeV) $\sigma_{vis}(e^+ \to 2\,\mathrm{jets} + \mu + X) = 36.4 \pm 5.2^{+10.4}_{-9.1}$ pb is quoted, and for forward muons ($1.4 < \eta < 2.4$, $p_\perp > 1.5$ GeV) $\sigma_{vis}(e^+ \to 2\,\mathrm{jets} + \mu + X) = 20.5 \pm 6.5^{+6.3}_{-5.7}$ pb.

Using the Monte Carlo to convert the measured hadronic cross section to a partonic cross section allows a comparison with NLO QCD calculations at parton level. This is done for the ZEUS result in the e channel in figure 10. Here, the result is found to be even a factor of 4 above theory, with somewhat larger errors.

The long lifetimes of c and b hadrons which can be measured with microvertex detectors provide an independent signature. With its Central

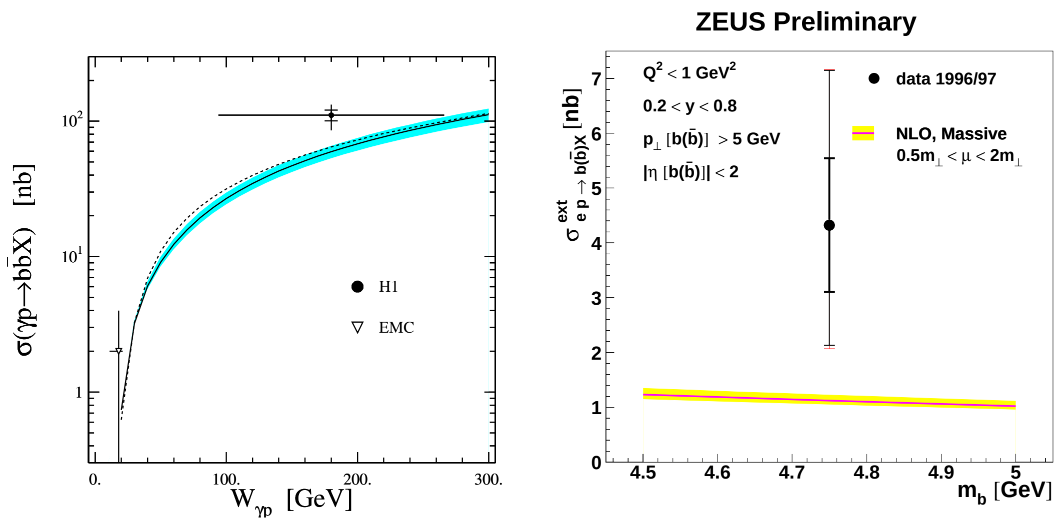

Figure 10: b production cross section, compared with NLO QCD.

Silicon Tracker (CST), H1 has for the first time at HERA attempted to exploit these features. An event with two jets and a penetrating track identified as a muon is shown on the left-hand side of figure 11. The muon has a relatively high transverse momentum of 3 GeV$/c$ with respect to the nearest jet, which is unlikely for muons from charm decays or mis-identified hadrons but is expected for decays of b flavoured hadrons. In the magnified view perpendicular to the beam (on the right-hand side) the tracks measured in the CST are represented as bands with widths corresponding to their $\pm 1\sigma$ measurement precision. The resolution provided by the CST reveals that the muon track originates from a well separated secondary vertex. This is now being integrated into ongoing physics analyses.

4. Summary and Outlook

Heavy quarks have become an increasingly interesting part of the physics field opened up by HERA. With the statistical power now reached in the data, charm quarks are a direct probe of the gluonic component of hadronic structure. In the case of the proton, the fact that about one quarter of the ep interactions in the HERA regime result in final states with charm makes it evident that understanding the charm contribution to the structure function F_2 is a *conditio sine qua non*. The agreement of the gluon density directly determined from charm with the result from the scaling violation analysis lends strong support to the underlying QCD picture.

New light has also been shed on the structure of the photon, where a charm content in the "resolved" photon may provide a viable route to understanding the HERA data. Finally, probing the structure of diffractive exchange with charm, differential cross section data have started to discriminate between different theoretical concepts.

Beauty production at HERA has now been measured by both H1 and ZEUS, and found to occur at a rate that is presenting NLO QCD with a challenge. Although experimental errors are still considerable, a re-evaluation of theoretical uncertainties might be appropriate.

Top pair production is kinematically excluded at HERA energies. It has however been speculated [22] recently that the events with isolated leptons and large missing $p_\perp$, of which the H1 collaboration [23] observes more than expected (and some with atypical kinematics), might be due to single top production mediated by a new, flavour-changing effective interaction. The top quark would decay via $t \to Wb$, $W \to \mu\nu$, giving rise to the observed signature. In fact, some of the observed outstanding events are kinematically not inconsistent with such a hypothesis. Lifetime-based tagging techniques will in the future be used to investigate such exciting possi-

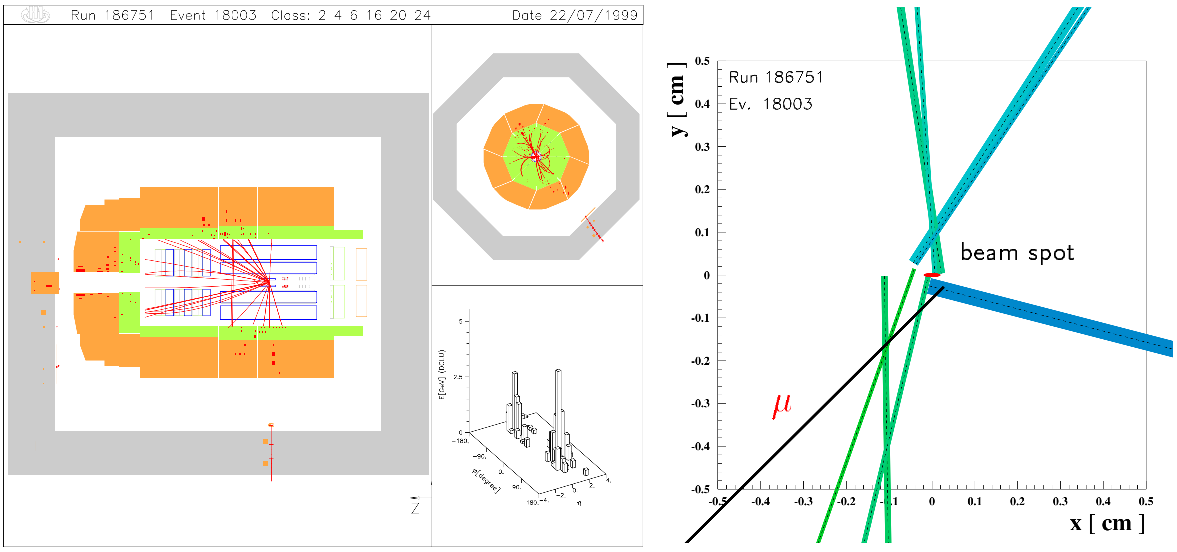

Figure 11: A b candidate in the H1 detector; right: vertex region.

bilities further. One more reason why H1 and ZEUS physicists look forward to the high luminosity running at the upgraded HERA machine in 2001.

Acknowledgments

I like to thank my colleagues in H1 and ZEUS for providing me with the results of their work for this presentation. And it is a pleasure to thank Paul Dauncey, Jonathan Flynn, and their crew for organizing a top meeting at a beautiful place in such a charming way.

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