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# Heavy flavour production with leptons and hadrons

Matthew Wing
*Bristol University, ZEUS, DESY, Notkestrasse 85, 22607 Hamburg, Germany*

ABSTRACT

The production of charm and beauty quarks in $\gamma\gamma$ collisions at LEP, $ep$ collisions at HERA and $p\bar{p}$ collisions at the Tevatron is discussed. The comparison with predictions of next-to-leading-order QCD and the issues it raises are detailed. In particular, the strengths and weaknesses of the measurements and predictions are discussed.

## 1 Introduction

Measurements of the production of heavy quarks provide a wealth of information on high energy particle collisions. The mechanism for production of heavy quarks is governed by the strong force of nature which is described by Quantum Chromodynamics (QCD). Not only is QCD essential for understanding one of the four fundamental forces of nature, but many signatures of physics beyond the Standard Model (SM) are dependent on precise knowledge of the rate of QCD processes, which are expected to form the most significant background.

The importance of a precise understanding of QCD is apparent when considering current and future accelerators. Many of these accelerators will use protons and photons as the colliding particles, both of which have a hadronic structure and hence are described by QCD. Figure 1(a) shows a generic representation of the production of heavy quarks in a hadron-hadron collision. Knowledge accumulated at HERA, LEP and the Tevatron will directly benefit future programmes such as the LHC and a future linear collider where heavy quarks will be produced by the same mechanism. The produced partons then fragment into final-state hadrons which are measured in the detector as depicted in Figure 1(b). The fragmentation procedure is usually described by non-perturbative models and is again an uncertainty common to all experiments.

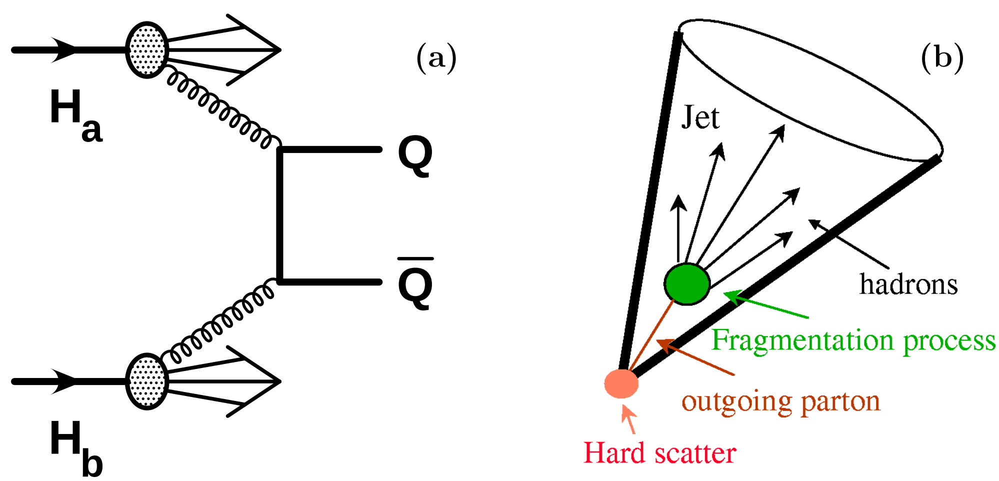



Figure 1: *Generic representation of (a) the production of heavy quarks in hadron-hadron collisions and (b) their subsequent hadronisation.*

Theoretically, heavy quarks provide ideal tools for probing QCD due to their relatively large mass, $m_Q >> \Lambda_{\text{QCD}}$, which entails a fast convergence of the perturbative expansion of the cross section. The production of heavy quarks is also *directly* sensitive to the gluon density in the colliding hadron (see Figure 1(a)). The gluon density is usually determined in the DGLAP-evolution fits to measurements of structure functions in inclusive deep-inelastic scattering. Direct measurements of the gluon density provide an important check of these methods and the factorisation of the cross section.

In these proceedings, results of open charm and beauty production from HERA, the Tevatron and $\gamma\gamma$ collisions at LEP are discussed. After a brief overview of theoretical and experimental aspects, emphasis is given to understanding hadronic structure and the dynamics of the hard scatter. Results on quarkonia and top production and measurements of $B$ fragmentation functions are discussed elsewhere [1].

## 2 Perturbative QCD

For the generic collision, shown in Figure 1, of two hadrons producing heavy quarks, $H_a + H_b \rightarrow Q\bar{Q} + X$, the cross section can be written as a convolution of the parton densities, $f_i^{H_a}$ and $f_j^{H_b}$, of the two hadrons and the short-distance cross section, $\sigma_{ij}$:

$$\sigma(S) = \sum_{i,j} \int dx_1 \int dx_2 \; \hat{\sigma}_{ij}(x_1 x_2 S, m^2, \mu^2) f_i^{H_a}(x_1, \mu) f_j^{H_b}(x_2, \mu) \qquad (1)$$

where $x_1$ and $x_2$ are the hadron's momentum fraction carried by the interacting parton and $\mu$ represents the renormalisation and factorisation scales. The short-distance cross section is a perturbative expansion in powers of $\alpha_s$ and the inverse mass of the heavy quark which implies faster convergence for larger masses. Two different schemes and their combination are used for predictions of heavy-quark production. In the "massive" scheme, there are no heavy quarks in the colliding hadron and the predictions should be more accurate for transverse momenta $p_T \sim m$. In contrast, heavy quarks in the "massless" scheme are active in the colliding hadrons and the predictions should be more accurate for $p_T > m$. The two schemes have recently been combined [2, 3] such that predictions should be appropriate for all $p_T$.

## 3 Experimental techniques

The reconstruction of heavy quark mesons is similar in all experiments. Signals for charm hadrons are generally observed by forming the invariant mass of the tracks identified with a specific decay channel, e.g. $D^0 \rightarrow K^-\pi^+$. If sufficiently accurate, a vertex detector can also be used to detect vertices displaced from the primary interaction point. An example of reconstructed $D^0$ mesons which uses both these techniques is shown in Figure 2(a) from the CDF experiment [4]. To detect beauty quarks, the invariant mass of the decay products is also formed for a specific decay channel such as $B^+ \to J/\psi K^+$. As the decay length of beauty is longer than that for charm quarks, a vertex detector is a powerful tool for distinguishing beauty from the lighter quarks. The transverse momentum of an electron or muon relative to the direction of the parent quark, $p_T^{\rm rel}$ also provides a clear signature. Due to its larger mass, $b$ quarks populate high values of $p_T^{\rm rel}$ as shown in Figure 2(b) [5].

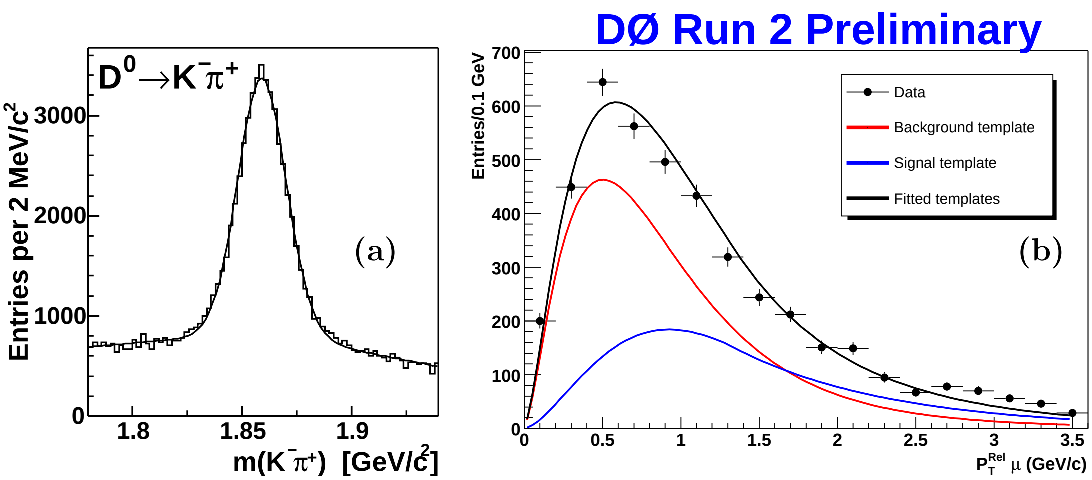



Figure 2: *Methods for tagging (a) charm quarks via the reconstruction of a $D^0$ meson and (b) beauty quarks using $p_T^{\rm rel}$.*

Due to limitations of the experimental apparatus, measurements are performed in a restricted kinematic region, usually defined by some momentum and angular restriction of the reconstructed heavy quark meson. Measurements performed in a restricted kinematic region are often extrapolated to the full phase space using either a next-to-leading order (NLO) calculation or Monte Carlo (MC) model. These extrapolations provide "measurements" of total cross sections or structure functions which are more intuitive and easy to compare between different experiments. They should, however, be treated with caution. The extrapolation is often performed to completely unmeasured regions, with factors as high as 20 and an uncertainty which is difficult to determine.

## 4 Latest results

Measurements of the beauty cross section using Tevatron Run I data [6], shown in Figure 3, provoked much of the current interest in the production rate of heavy quarks. Several decay channels were analysed. These results were then extrapolated to a cross section for some minimum transverse momentum of the $b$ quark, $p_T^{\min}$; the measurements are shown in Figure 3(a) compared with an NLO prediction [7]. The NLO prediction lies significantly below the data by a factor of 2–3 and is, therefore, one of the most significant failures of pQCD to describe high energy phenomena of the strong interaction. In order to remove unknowns associated with the extrapo-

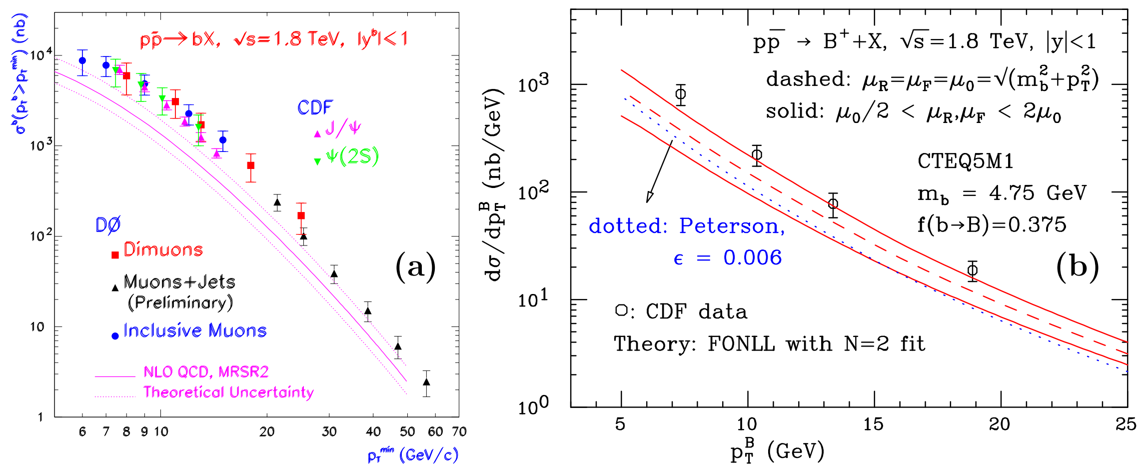



Figure 3: *Measurements of (a) the b quark cross section compared to NLO predictions and (b) the* $B^+$ *meson cross section compared with FONLL predictions from the Tevatron.*

lation procedure, measurements of $B$ mesons, which are directly reconstructed in the detector, were performed and compared with NLO QCD. As with the cross sections for the $b$ quark, the NLO prediction was significantly below the data. With the extra information provided by measuring the meson cross section, significant theoretical development was made [3] to try and describe these data. The improved theoretical calculations include the resummation of large logarithms in $p_T$ at the next-to-leading level (NLL) and their merging with the fixed order (FO) calculation which correctly accounts for mass effects. This new "FONLL" calculation also uses a new extraction of the fragmentation function of $b$ quarks to $B$ mesons as measured in an $e^+e^-$ experiment [8]. The result of this new calculation is shown compared to the data in Figure 3(b), where the difference between data and theory is reduced from a factor of 2.9 to 1.7 and consistency within the uncertainties is observed.

### 4.1 Structure functions

In deep inelastic scattering (DIS) at HERA, photons act as a pointlike probe of the proton and hence provides the unique opportunity to study the charm contribution, $F_2^{c\bar{c}}$, to the proton structure, $F_2$. Measurements of charm in DIS are directly sensitive to the gluon distribution in the proton and are therefore complementary to extractions of the gluon distribution in QCD fits. The largest sample of events for charm in DIS in both H1 and ZEUS [9] is tagged using the "golden" $D^*$ decay channel. Due to experimental limitations, the $D^*$ meson is restricted in to the central region of the detector with transverse momentum larger than 1.5 GeV. Cross sections are measured differentially in $Q^2$ and $x$ and compared with NLO QCD. The NLO QCD is then used to extract $F_2^{c\bar{c}}$:

$$F_{2,\mathrm{meas}}^{c\bar{c}} = \frac{\sigma(x,Q^2)_{\mathrm{meas}}}{\sigma(x,Q^2)_{\mathrm{theo}}} F_{2,theo}^{c\bar{c}} \tag{2}$$

The extrapolation factors to the full $D^*$ phase space vary between 4.7 at low $Q^2$ and 1.5 at high $Q^2$. The extracted $F_2^{c\bar{c}}$ values are shown compared with an NLO QCD prediction in Figure 4. The data show a steep rise to low $x$ indicative of a large

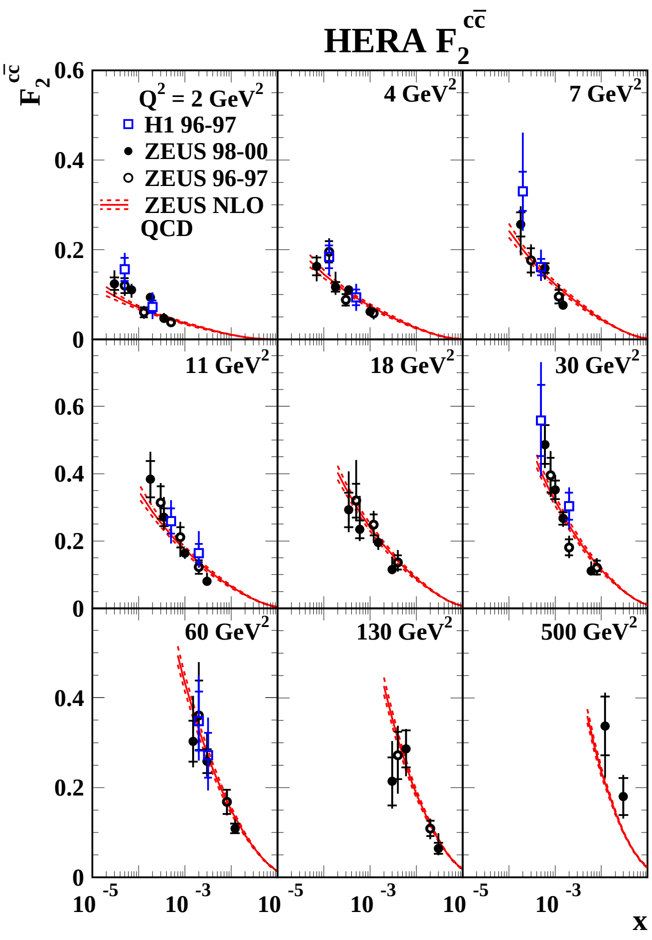
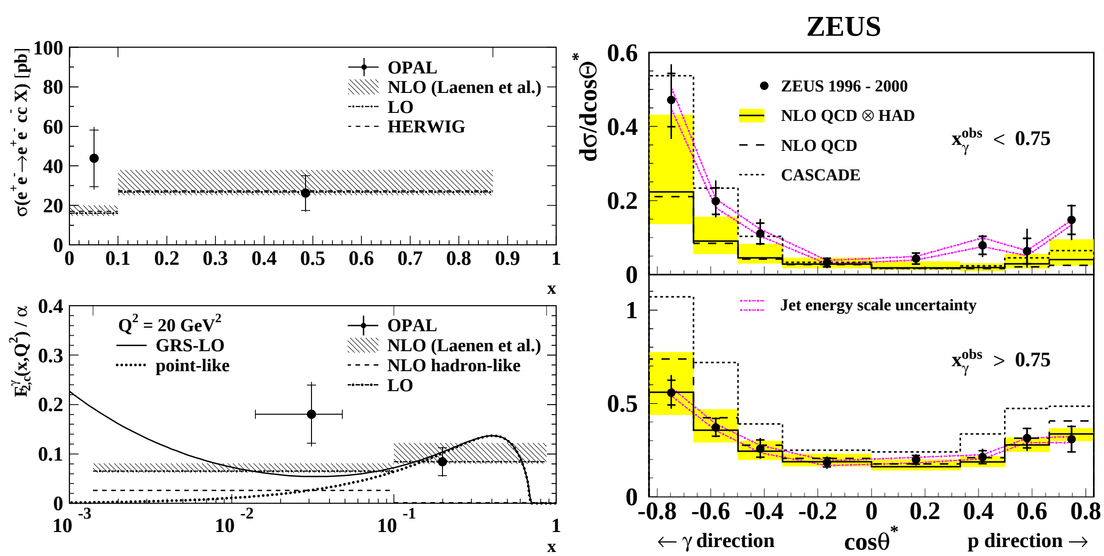



Figure 4: *Charm contribution, $F_2^{c\bar{c}}$, to the proton structure function for different $Q^2$.*

gluon density in the proton. The NLO QCD prediction is derived from fits [10] to measurements of $F_2$ and is largely independent of the data shown here. The data are well described by the NLO prediction demonstrating the consistency of the the gluon density extracted in PDF fits and "measured" more directly here. At low $Q^2$, the data, specifically the double differential cross sections, $\sigma(x, Q^2)_{\mathrm{meas}}$, measured within the acceptance of the detector, have reached sufficient precision such that the can be used to further constrain the gluon density in the proton.

In an analogous way, measurements of $D^*$ production in $e\gamma$ collisions at LEP allow extractions of the charm contribution, $F^{\gamma}_{2,c}$, to the photon structure function. The extraction of $F^{\gamma}_{2,c}$ is done as in Equation 2 except that the extrapolation of the $D^*$ to the full phase space is performed using MC models rather than a NLO calculation. Figure 5(a) shows the total charm cross section and the extracted $F^{\gamma}_{2,c}$ compared with predictions from NLO QCD. The measurements at high $x$, which are well described by NLO, are indicative of the scattering of two pointlike photons. At low $x$, the data is somewhat above the prediction in a region where it is expected that one of the photons exhibits some hadronic structure [11].




(a) (b)

Figure 5: *Measurement of (a) charm contribution to the photon structure function from LEP and (b) dijet angular distributions in charm photoproduction at HERA.*

Jet photoproduction at HERA is a complementary way of studying the structure of the photon. A recent measurement [12] of the dijet scattering angle, $\theta^*$, in $D^*$ production is shown in Figure 5(b). The distribution is sensitive to the propagator in the hard scatter and thereby sensitive to the nature of the sub-process. The tagged $D^*$ meson is associated with one of the jets and the scattering angle of this jet defined with respect to the proton direction. The angular distribution, enriched in direct photon processes ($x_\gamma^{\rm obs} > 0.75$), exhibits a symmetric distribution with a shallow rise to high values of $\cos\theta^*$. This is indicative of the exchange of a quark in the hard sub-process with the charm produced via the boson-gluon fusion process. At low $x_\gamma^{\rm obs}$, where the sample is enriched in resolved photon processes, the data are asymmetric, exhibiting a rapid rise to negative $\cos\theta^*$. This demonstrates that the charm comes from the photon and exchanges a gluon in the hard process. The prediction of NLO in which charm is produced in the hard sub-process and is not an active flavour in the structure function, lies below the data. The description of the data could be improved by including a charm component in a NLO fit of the photon PDF.

### 4.2 Measurements of charm cross sections

Cross sections measured within the acceptance of the detector, such as the angular distributions just discussed, do not rely on any model assumptions and provides "safe" data with which to compare any theoretical prediction. Measurements of $D^*$ cross sections are available in $\gamma\gamma$ processes at LEP, from the Tevatron and in both DIS and photoproduction at HERA. These have been compared with NLO calculations at fixed order, or with NLL calculations or the two "matched". These produce $c\bar{c}$ partons in the final state and incorporate a model of the fragmentation into $D^*$ mesons.

Measurements have been performed and compared at LEP by three collaborations, ALEPH, L3 and OPAL[13]. As a function of $p_T(D^*)$, the data are compatible with each other and with FO and NLL calculations. The data is not sufficiently precise to distinguish between the different calculations.

The HERA data which was used to extract $F_2^{c\bar{c}}$ in the previous section are shown in Figure 6. The data are shown for the same variable, $\eta(D^*)$, in a similar kinematic range compared to the calculation, HVQDIS [14]. The NLO calculation lies below the H1 data for large positive $\eta(D^*)$, whereas for the ZEUS data, the NLO calculation gives a good description. It should be noted that the ZEUS data is compared with the recent ZEUS NLO QCD fit as the proton PDF in the NLO calculation. This gives a a somewhat larger cross section at positive $\eta(D^*)$ and somewhat smaller cross section at negative $\eta(D^*)$. Whether the difference in conclusion arises from differences in data or differences in theory is not clear at present. The data are, however, consistent when extrapolated to measure $F_2^{c\bar{c}}$ as shown in Figure 4. A comparison of the cross sections in the same kinematic range should be made.

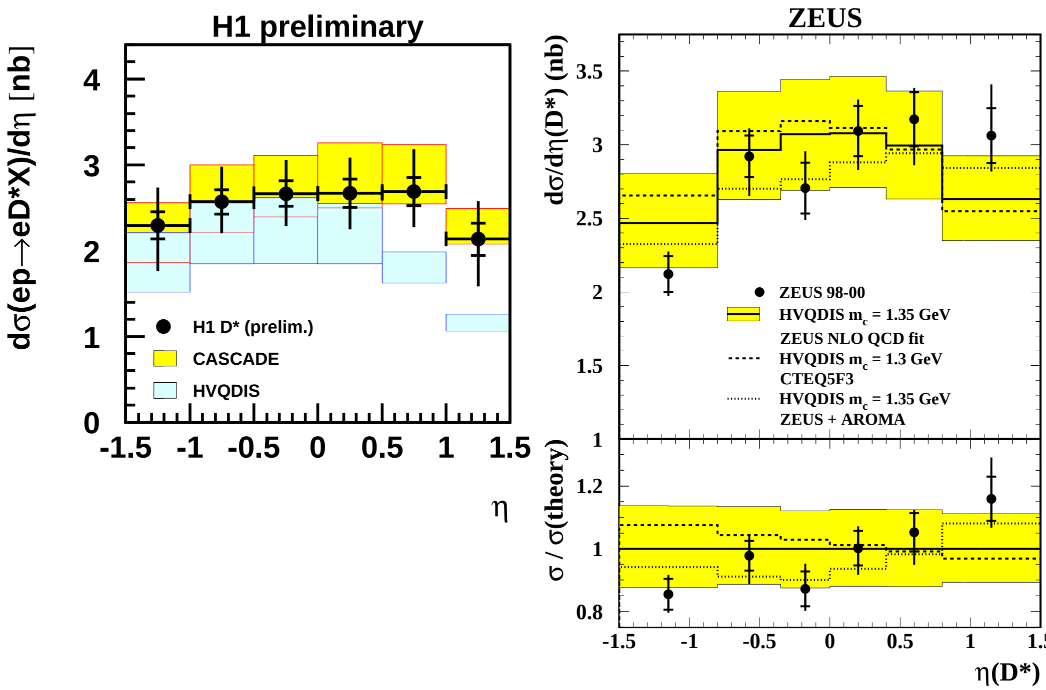



Figure 6: *Cross sections in DIS from both HERA experiments compared with predictions from NLO QCD (and CASCADE MC).*

Due to its larger cross section, charm photoproduction measurements are the most accurate from HERA. Theoretically, however, photoproduction has the additional uncertainty associated with the possibility of the photon resolving into a source of hadrons and the interactions behaving as a hadron-hadron collision (see Figure 1(a)). Example data are shown in Figure 7 compared with NLO QCD [15] and FONLL [16] predictions (and NLL [17] predictions not shown); none give a satisfactory representation of the data. Indeed the FONLL calculation which is meant to be more reliable at high $p_T(D^*)$ than the NLO QCD calculation gives a poorer description of the data. The precision of the calculations is also poor, with uncertainties as a functions of $\eta(D^*)$ between 30% and 80%, whilst the data has a precision of generally better than 10%. The precision of the data will improve in time with more data; it is hoped that higher precision for the predictions can also be achieved.

Using their upgraded (vertex) detector and Run II data from the Tevatron, the CDF collaboration have recently made measurements of charm meson cross sections [4]. The data are shown in Figure 8 compared with FONLL and NLL calculations. The FONLL calculation employs the same techniques as for the calculation of $B$ meson cross sections described previously. The comparison between

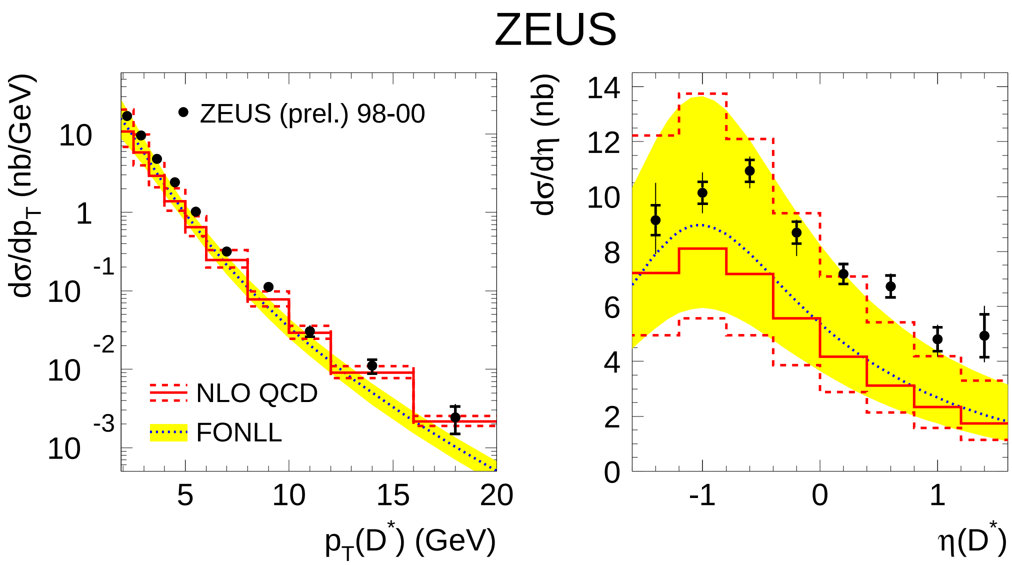



Figure 7: *Charm cross sections in photoproduction at HERA compared to QCD.*

data and prediction shown in Figure 8 is similar to the comparison for $B$ production shown in Figure 3(b). The data sample used here corresponds to an integrated luminosity of 6 $\mathrm{pb}^{-1}$ which represents a very small fraction of what CDF hope to collect during Run II. With the increased precision and greatly extended kinematic range expected, these measurements will provide detailed comparisons with predictions and a deeper understanding of the dynamics of charm production.

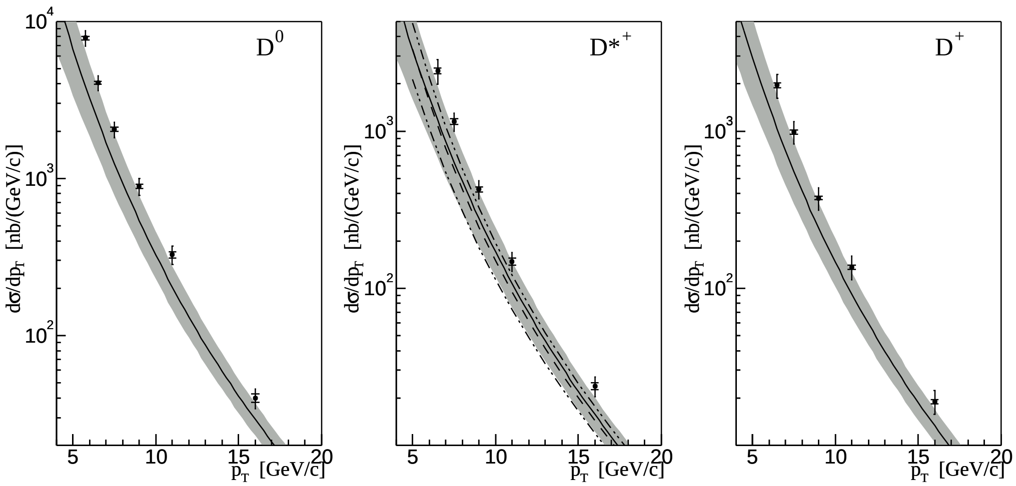



Figure 8: *Measurement of charm meson cross sections from CDF compared to FONLL theoretical predictions.*

In general, predictions of NLO QCD are below measurements of charm production, but compatible within the uncertainties. As the measured cross sections are a complicated convolution of (PDF $\otimes$ hard scatter $\otimes$ fragmentation) each with parameters which have associated uncertainties, e.g. scale, charm mass, etc., it is unclear how to improve the description of the data. Trying to minimise specific effects and uncertainties will help to qualify the situation. Examples of this are: measurements at high $p_T$ where the scale uncertainties are reduced; measurements of jet cross sections which are less sensitive to uncertainties in the fragmentation and independent measurements of the fragmentation in a hadron-hadron environment rather than using the parametrisations of LEP data.

### 4.3 Measurements of beauty cross sections

As with $D^*$ cross sections, beauty cross sections have been measured at HERA, LEP and the Tevatron. The measurements are, however, a complicated mix of different definitions both extrapolated and within the acceptance of the detectors.

Figure 9 shows the measurements of beauty (and charm) cross sections in $\gamma\gamma$ collisions at LEP [18]. All three beauty measurements lie above the prediction

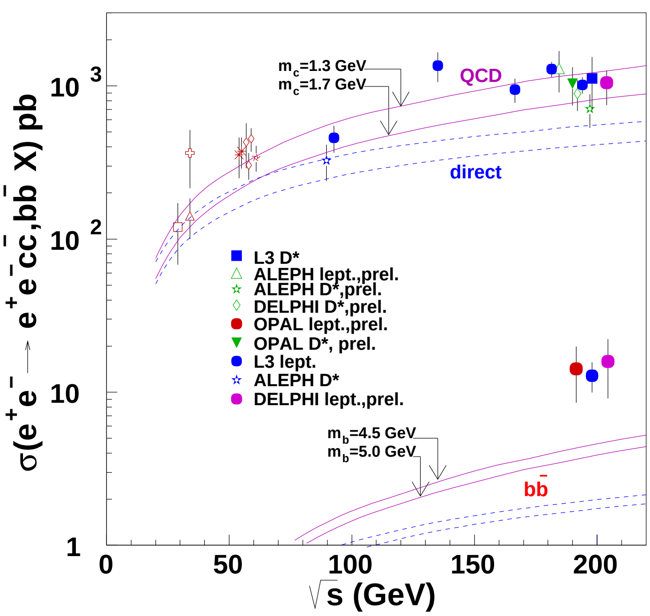



Figure 9: *Charm and beauty cross sections in $\gamma\gamma$ collisions at LEP.*

by about a factor of 3, whereas all the charm measurements are well described by the theory. The beauty results are similar to the first Tevatron results shown in Figure 3(a). It should be noted that the LEP data have large extrapolation factors to get from the cross section measured within the acceptance of the detector to the total cross section shown. As said earlier, whilst providing easy comparison between different experiments, extrapolations to completely unmeasured angular and $p_T$ regions should be treated with caution. In such cases, a cross section in a measured kinematic region should always be given and exact details of the extrapolation.

Measurements made at HERA [19] have also been a mixture of different styles of results. The latest and "purest" measurements made within the acceptance of the detector are shown compared to NLO QCD in Figure 10. In Figure 10(a) results from both experiments are shown and are consistent with each other. Predictions from NLO QCD are below the data, but not by a significant factor. This is in contrast to results which are extrapolated to the full phase space to all jet angles and momenta [20]. A similar measurement in DIS is shown compared with

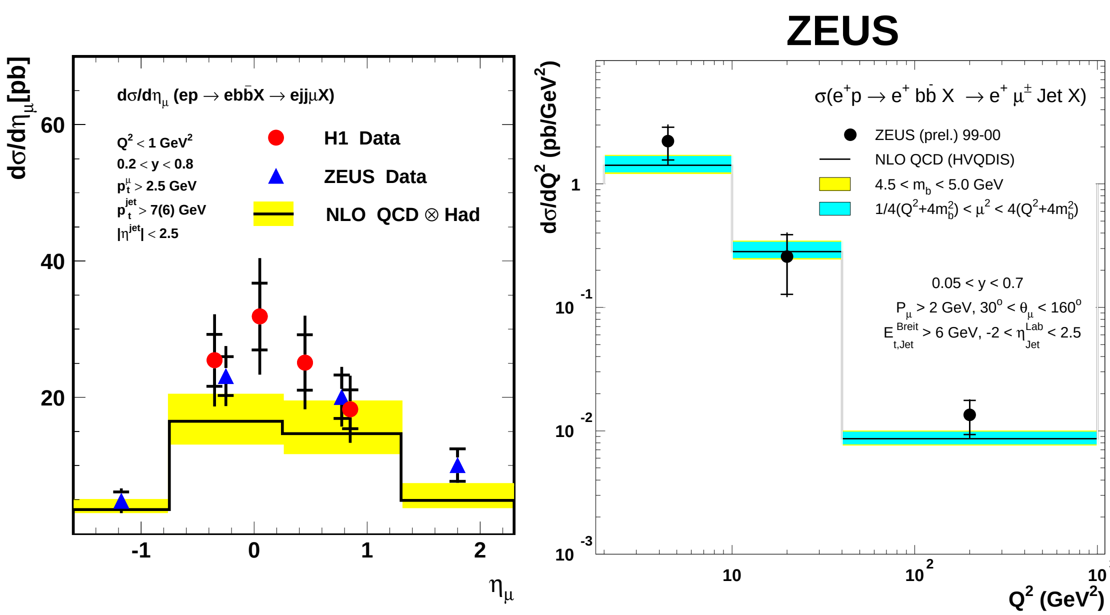



Figure 10: *Beauty cross sections in (a) photoproduction and (b) DIS at HERA compared with NLO QCD.*

NLO QCD predictions in Figure 10(b). The prediction is again below the data, but consistent within the uncertainties.

Understanding in the field of beauty production is progressing quickly and is currently one of the most interesting challenges in collider physics. Since the Physics in Collision conference, the results from H1 presented in Figure 10 are new and have shown consistency between experiments and highlighted problems in extrapolations. Further progress from all colliders is to expected soon. The LEP experiments should publish their measurements. The HERA experiments should finalise the HERA I data and should receive significantly more data from HERA II in the near future. The Tevatron experiments also have a wealth of data from Run II to analyse. All of these future measurements and publications should be careful to clearly define the cross section to be measured. Extrapolations to the full phase-space are not intrinsically incorrect, but the initial measured cross section should always be quoted and the exact method of extrapolation detailed.

## 5 Conclusions

The understanding of heavy-quark production is currently one of the most important challenges in QCD. In these proceedings, new results have been discussed both in terms of their quality and physics message. There are many technical and procedural issues involved in measuring heavy quarks which have to be mastered before the real physics can be seen. Most recent results, which provide sound measurements, show that although NLO QCD does a fair job in describing the data, it fails in the details which are now seen by the precision measurements being made. A deeper understanding of heavy-quark production is necessary for a more complete picture of QCD. It is also desirable, if not necessary, for future experiments such as those at the LHC where knowledge of the QCD background to a high precision is essential before physics beyond the SM can be seen. In the next few years, a combination of better data and improved theory should allow a detailed understanding of the production of heavy quarks to be achieved.

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