

Theory versus experiments in heavy flavour production

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ABSTRACT: I discuss the current status of the comparison between theoretical predictions and experimental data, relevant to the production of open charm and bottom quarks in photon-hadron and photon-photon collisions. I advocate the use of a formalism that matches fixed-order computations to resummed computations in order to make firm statements on heavy flavour production as described by perturbative QCD.

1. Introduction

Heavy flavour physics has been traditionally a challenging testing ground for the predictions of perturbative QCD. Loosely speaking, we like to define a quark as heavy when its mass m is much larger than Λ_{QCD} . This property entails the possibility of computing in perturbation theory the cross section for the production of an open heavy quark, which is not possible in the case of a light quark. It is customary, although not always accurate, to say that the mass of the quark sets the hard scale of the production process, and thus the relevant parameter to the perturbative expansion is $\alpha_S(m)$. Furthermore, the condition $m \gg \Lambda_{QCD}$ leads us to expect that the perturbative predictions are only marginally affected by power corrections and by contributions of non-perturbative origin, that we can not compute from first principles.

There is no doubt that the top quark is a heavy quark; in fact, perturbative QCD does a fairly good job in describing its production mechanism. There is also a consensus on the fact that the bottom can be consistently treated as a heavy flavour. The case of the charm is borderline; it is difficult to list it together with u, d, and s quarks; on the other hand, we expect non-perturbative physics to have a non-negligible impact in this case, and we know that perturbative corrections are huge, since $\alpha_S(1.5 \text{ GeV}) \simeq 0.3$.

In this paper, I shall not deal with top physics, and I shall concentrate on charm and bottom production in collider processes where at least one of the incoming particles is an on-shell photon. Thus, I shall not treat bottom production at hadronic colliders, nor charm and bottom production at fixed-target experiments. I shall only briefly remind the

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reader that Tevatron data for the production of B mesons lie above the QCD predictions obtained with “default” parameter choices; however, QCD can predict the shape of p_T spectrum, and does well for a few $b\bar{b}$ correlations. Also, the comparison between theory and data improves if b -jets are considered. As far as fixed-target charm hadroproduction is concerned, it appears that perturbative QCD cannot reproduce the data, unless non-perturbative effects, such as p_T -kick, are supplemented. Fortunately, these are moderate, and the agreement is, all in all, satisfactory. More details can be found in ref. [1]

2. Perturbative computations

Using the factorisation theorem, I write the cross section for the production of an inclusive open heavy quark Q in photon-hadron collisions as follows:

$$d\sigma_Q = \sum_j f_j^{(h)} \otimes d\hat{\sigma}_{\gamma j} + \sum_{ij} f_i^{(\gamma)} \otimes f_j^{(h)} \otimes d\hat{\sigma}_{ij}, \quad (2.1)$$

where $f_i^{(\gamma)}$ and $f_j^{(h)}$ are the parton densities in the photon and in the hadron respectively, and $d\hat{\sigma}_{\gamma i}$ and $d\hat{\sigma}_{ij}$ are the short-distance cross sections, computed in perturbation theory. At present, they have been computed to the next-to-leading order (NLO) accuracy in α_s , which means $\alpha_{em}\alpha_s^2$ and α_s^3 respectively. One has to keep in mind that $f_i^{(\gamma)}$ behaves asymptotically as α_{em}/α_s , and thus $d\sigma_Q$ in eq. (2.1) is a series in $\alpha_{em}\alpha_s^i$; the truncation of such a series at $i = 2$ will be denoted in what follows as fixed-order (FO) NLO result. As is well known, the two terms in the RHS of eq. (2.1) are separately defined in terms of Feynman diagrams, but have no physical meaning, and they must always be summed in order to obtain sensible physical predictions.

A similar factorisation formula holds in the case of photon-photon collisions:

$$d\sigma_Q = d\hat{\sigma}_{\gamma\gamma} + \sum_j f_j^{(\gamma)} \otimes (d\hat{\sigma}_{\gamma j} + d\hat{\sigma}_{j\gamma}) + \sum_{ij} f_i^{(\gamma)} \otimes f_j^{(\gamma)} \otimes d\hat{\sigma}_{ij}. \quad (2.2)$$

It is clear that the second and third terms in eq. (2.2) are analogous to the two terms in the RHS of eq. (2.1); on the other hand, the first term in the RHS of eq. (2.2) is peculiar of photon-photon collisions, and it corresponds to those events in which two pointlike photons initiate the hard scattering. Also in the case of eq. (2.2) all the terms in the RHS must be summed in order to obtain measurable quantities.

Although theoretically well defined, open heavy quark cross sections are not directly measurable; a description of the hadronization of the heavy quark into a heavy-flavoured hadron is necessary in order to compare theoretical predictions to data. This is done as prescribed by the factorisation theorem through the following equation:

$$\frac{d^3\sigma_H(k)}{d^3k} = \int D_{\text{NP}}(z) \frac{d^3\sigma_Q(\hat{k})}{d^3\hat{k}} \delta^3(\vec{k} - z\vec{\hat{k}}) d^3\hat{k} dz, \quad (2.3)$$

where H is the heavy-flavoured hadron with momentum k , and \hat{k} is the momentum of the heavy quark. $D_{\text{NP}}(z)$ is the non-perturbative fragmentation function, which is not

calculable but is universal; in what follows, I shall adopt Peterson form [2]. In eq. (2.3), it is assumed that fragmentation scales the 3-momentum of the incoming quark. Different prescriptions are possible, but in all cases \vec{k} remains parallel to $\vec{\tilde{k}}$; the mass shell condition can be either $k^2 = m^2$, or $k^2 = m_H^2$; and, finally, none of these prescriptions is boost invariant. However, all possible prescriptions coincide in the large- p_T limit. These ambiguities turn into uncertainties in the physical cross sections, which should be taken into proper account when comparing QCD predictions to data. A complete study on this issue will be presented elsewhere [3]; here, I just state the fact that these uncertainties are negligible with respect to the uncertainties due to the dependence upon other input parameters, such as mass and scales.

3. Charm production

In this section, I compare FO NLO predictions to data for D^* meson production at HERA (γp collisions) and at LEP ($\gamma\gamma$ collisions). The relevant computer codes have been developed in ref. [4] (for γp collisions) and in ref. [5] (for $\gamma\gamma$ collisions). I shall set $m=1.5$ GeV, and the renormalization scale equal to the transverse mass of the quark, $m_T = \sqrt{p_T^2 + m^2}$. The factorization scale will be set equal to m_T in γp collisions, and equal to $2m_T$ in $\gamma\gamma$ collisions, since in the latter case smaller values of p_T are probed. The parton densities in the proton are given by the CTEQ5M1 set. As far as the photon is concerned, I shall use the AFG set in the case of γp collisions, and the GRS set in the case of $\gamma\gamma$ collisions; AFG has been adopted since in photoproduction the formalism of ref. [6] is used, which requires densities defined in the $\overline{\text{MS}}$ subtraction scheme. I shall set $\Lambda_{QCD}^{(5)} = 226$ MeV, as constrained by the CTEQ5M1 set; this value is almost identical to the central value of the PDG global fit. The probability of a c quark fragmenting into a D^* meson is $P_{c \rightarrow D^*} = 23.5\%$. The on-shell photons at HERA and LEP are emitted quasi-collinearly by the incoming leptons. Their spectrum can thus be described by the Weizsäcker-Williams formula; here, I shall use the form of ref. [7].

In order to define their photoproduction events, H1 and ZEUS adopt different cuts on the fraction y of the electron momentum carried away by the photon, and on the virtuality Q^2 of the photon:

$$\text{ZEUS :} \quad 0.187 < y < 0.869, \quad Q^2 \leq 1 \text{ GeV}^2, \quad (3.1)$$

$$\text{H1 :} \quad 0.29 < y < 0.62, \quad Q^2 \leq 0.01 \text{ GeV}^2, \quad (3.2)$$

(in this paper, I shall only deal with data obtained by H1 with the ETAG33 electron tagger). In fig. 1 I present the ratio of the data relevant to D^* -meson p_T over FO theoretical predictions. The spectra have been measured by H1 [8] and ZEUS [9] experiments in different visible regions; apart from the differences already pointed out in eqs. (3.1) and (3.2), H1 impose a cut on rapidity ($|y| < 1.5$), whereas ZEUS impose a cut on pseudorapidity ($|\eta| < 1.5$). For each set of data, I compute FO predictions for two values of the ϵ parameter entering the Peterson function ($\epsilon = 0.02$ and $\epsilon = 0.036$), in order to give an estimate of the uncertainties due to the choice of this parameter, as constrained by recent fits [10].

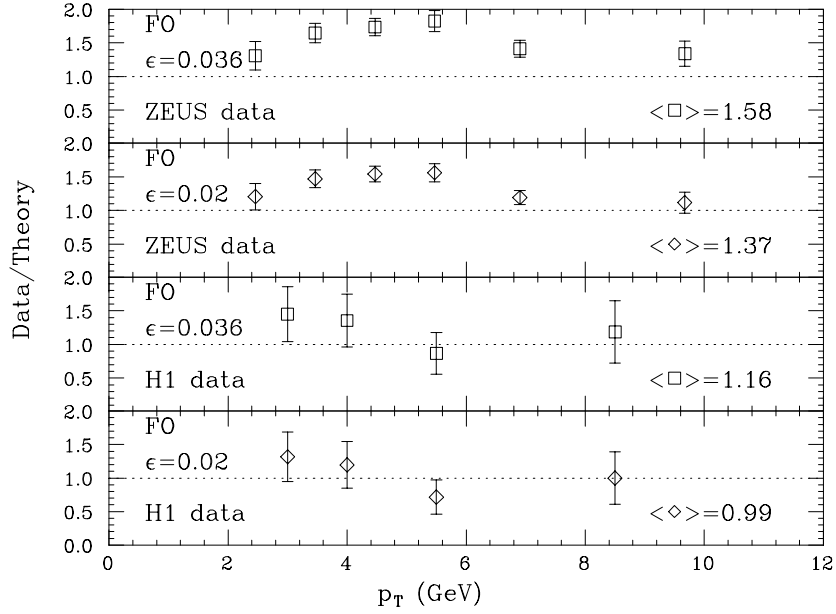


Figure 1: Ratio of data over theory (FO NLO) for the p_T spectrum of D^* mesons, in the visible regions of the ZEUS and H1 experiments. The weighted averages are also given.

Shape-wise, the theoretical cross section in the visible region appears to be only moderately sensitive to the choice of the ϵ parameter. The smaller ϵ value gives a slightly better description of the data, although $\epsilon = 0.036$ is theoretically preferred when used in the context of a FO computation (see ref. [10]). Regardless of the value of ϵ , H1 data appear to be in agreement with FO predictions, while ZEUS data display discrepancies. Taking the data at face value, the two data sets also indicate different p_T spectrum shapes. It has to be stressed that ZEUS data have smaller statistical errors. Given the different conclusions on QCD predictions that can be drawn by looking at the results of the two experiments, it is impossible to issue a unique statement on the comparison between theory and data. Should this problem persist when more data will be available, it will be necessary to define the same visible cross section within the two experiments.

The same pattern can be observed in the case of the rapidity/pseudorapidity spectra, presented in fig. 2 and fig. 3 for H1 and ZEUS data respectively. H1 data are in general statistically compatible with FO NLO predictions (obtained with $\epsilon = 0.036$), ZEUS data are not. Unfortunately, as in the case of the p_T spectrum, the cuts imposed in order to define the distributions are different. ZEUS data seem to suggest a shape different from that predicted by QCD, which fails to describe the data especially in the positive- η region. The last data point, however, is by far the one affected by the largest error. A similar trend can be possibly seen in H1 data, for the cuts $p_T > 2.5$ GeV and $3.5 < p_T < 5$ GeV, but in this case the discrepancy is not statistically significant.

I now turn to the production of D^* mesons in $\gamma\gamma$ collisions, which is measured by LEP experiments by applying a (possibly effective) anti-tag condition on the scattered electrons and positrons, $\theta < \theta_{max}$; this condition can be translated in a suitable form of

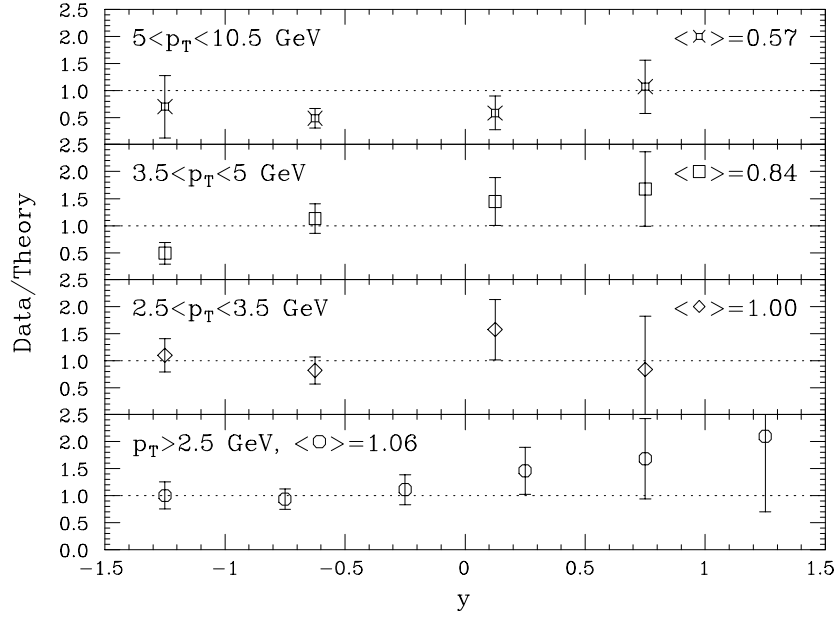


Figure 2: Ratio of H1 data over theory (FO NLO) for the y spectrum of D^* mesons, in the case of different p_T cuts.

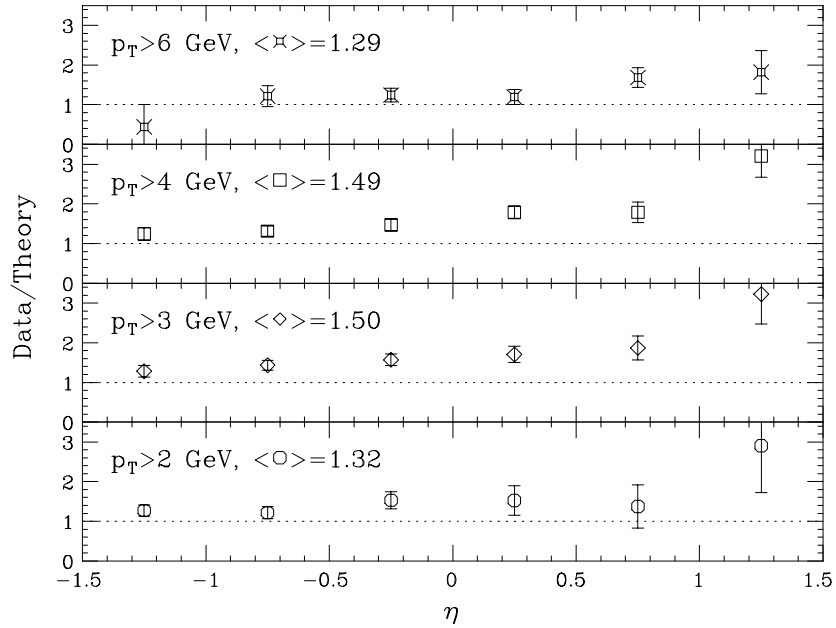


Figure 3: Ratio of ZEUS data over theory (FO NLO) for the η spectrum of D^* mesons, in the case of different p_T cuts.

the Weizsäcker-Williams function [7]. I shall compare here the FO NLO predictions to OPAL [11, 12] and L3 [13, 14] data; the two experiments have slightly different visible

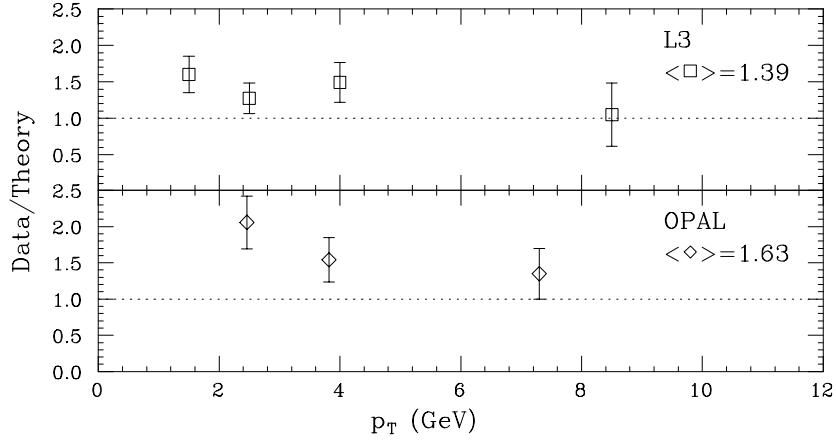


Figure 4: Ratio of data over theory (FO NLO) for the p_T spectrum of D^* mesons, in the visible regions of the OPAL and L3 experiments.

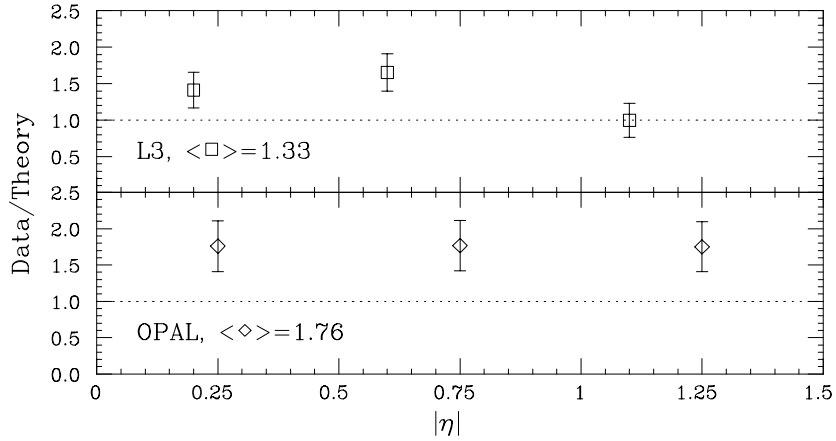


Figure 5: As in fig. 4, for the η spectrum.

regions:

$$\text{OPAL :} \quad \theta_{max} = 0.033, \quad 2 < p_T < 15 \text{ GeV}, \quad |\eta| < 1.5, \quad (3.3)$$

$$\text{L3 :} \quad \theta_{max} = 0.030, \quad 1 < p_T < 12 \text{ GeV}, \quad |\eta| < 1.4. \quad (3.4)$$

Also, the average center-of-mass energies relevant to the data of the two experiments are different: $\sqrt{s_{e^+e^-}} = 193 \text{ GeV}$ and $\sqrt{s_{e^+e^-}} = 198 \text{ GeV}$ for OPAL and L3 respectively.

The ratio of data over FO predictions is presented in fig. 4 and fig. 5 for p_T and η spectra respectively. In this case, only $\epsilon = 0.036$ has been considered. By taking the data at face value there is a weak indication of a p_T spectrum softer than the one predicted by QCD; as far as η spectrum is concerned, data seem to agree with QCD computations. All the data lie above the theoretical predictions; it can be shown that L3 data are within the band obtained by stretching the parameters entering the computation (mass and scales), while OPAL data lie just above the upper end of this band (see ref. [5]). In spite of this small discrepancy, it is fair to say that QCD gives a reasonable description of the current

data. A firmer conclusions will be drawn when more data will be available; also in this case, the comparison of theory and data would benefit if similar visible regions were defined by the different experiments.

4. Bottom production

Bottom rates are much smaller than charm rates (about three order of magnitude), and it is painful for experiments to collect the statistics sufficient to perform a measurement. In spite of this, recent years have witnessed a great progress in this field, and quite a few experimental results are now available. Different experiments use different techniques, and the measured observables are rather inhomogeneous: they can be visible cross sections, the visible region being defined by means of cuts applied to the bottom quark variables or to the variables of the μ produced in the decay, or they can be total rates, obtained by extrapolating the visible rates to the whole phase space. For this reason, at present the only way to obtain a coherent picture is that of comparing the data to a given theory, in this case NLO QCD. This is what is done in fig. 6, where FO predictions are compared to H1 [15], ZEUS [16], OPAL [17], and L3 [18] data.

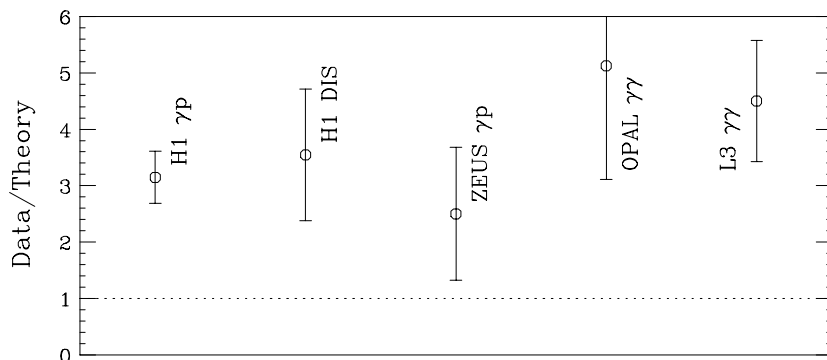


Figure 6: Ratio of data over theory (FO NLO) for total bottom rates, as measured in photoproduction, DIS, and $\gamma\gamma$ collisions.

It is striking that, for all the measurements except one, the ratio data/theory exceeds 3. Not only these values are much larger than those that we get at the Tevatron, they are also much larger than the corresponding results relevant to charm production, as measured by the same experiments. From the point of view of QCD, this is rather difficult to explain: as mentioned in the introduction, the mass of the quark sets the scale for the production process, and we would expect bottom cross sections to be predicted more accurately than charm cross sections. Thus, fig. 6 calls for an explanation; either a standard one (a better understanding of the fragmentation mechanism, or a more accurate description of semileptonic decays), or a more involved one (QCD processes may not be the only production mechanisms at work); and, of course, we need the statistics to be increased.

5. Beyond fixed-order computations

The fixed-order computations described in section 2 work fine as long as *all* the mass scales

relevant to the problem are of the same order of magnitude as the hard scale that is used to compute α_S . If this is not true, the coefficients of the expansion in α_S can be numerically large, since they depend upon $\log Q_1/Q_2$, where Q_1 and Q_2 are two of the mass scales. In other words, the expansion parameter is not α_S any longer, but rather $\alpha_S \log Q_1/Q_2$. In charm physics, this situation is easily encountered, when the p_T spectrum is measured; if $p_T \gg m$, terms such as $\log p_T/m$ grow large. Techniques exist that can take into account the dominant logarithmic terms to all orders in α_S ; the resulting cross sections are denoted as “resummed” (RS, also improperly called “massless”). In heavy flavour photoproduction, currently the resummation has been performed to the next-to-leading logarithmic level; that is, all the terms of order $\alpha_{em}\alpha_S(\alpha_S \log p_T/m)^k$ and $\alpha_{em}\alpha_S^2(\alpha_S \log p_T/m)^k$, $k = 1, \dots, \infty$, are included in the RS cross section.

As a rule of thumb, one would then compare data to FO predictions when $p_T \simeq m$, and to RS predictions when $p_T \gg m$. The problem is, the inequality $p_T \gg m$ cannot be turned into a quantitative statement. It is thus desirable to write the single-inclusive cross section in a form that is sensible in the whole p_T range, that is, which interpolates between the FO result, relevant to the small- and intermediate- p_T regions, and the RS result, relevant to the large- p_T region. This is the aim of ref. [19] and ref. [6], relevant to hadro- and photoproduction respectively. The main results of these papers read as follows:

$$\text{FONLL} = \text{FO} + (\text{RS} - \text{FOM0}) \times G(m, p_T), \quad (5.1)$$

where FONLL (for Fixed Order plus Next-to-Leading Logarithms) gives sensible predictions in the whole p_T range, and FOM0 is obtained from FO by letting to zero all the terms suppressed by powers of m/p_T . The subtraction of FOM0 from RS in eq. (5.1) is necessary to avoid double counting, since some of the logarithms appearing in RS are already present in FO. To be more precise, FONLL has the following features:

- All terms of order $\alpha_{em}\alpha_S$ and $\alpha_{em}\alpha_S^2$ are included exactly, including mass effects;
- All terms of order $\alpha_{em}\alpha_S(\alpha_S \log p_T/m)^k$ and $\alpha_{em}\alpha_S^2(\alpha_S \log p_T/m)^k$ are included, with the possible exception of terms that are suppressed by powers of m/p_T .

Finally, the function $G(m, p_T)$ is rather arbitrary, except that it must be a smooth function, and that it must approach one when $m/p_T \rightarrow 0$, up to terms suppressed by powers of m/p_T . In what follows, we shall use

$$G(m, p_T) = \frac{p_T^2}{p_T^2 + c^2 m^2}, \quad (5.2)$$

with $c = 5$. The practical implementation of eq. (5.1) is rather involved, especially in the photoproduction case; all the details can be found in ref. [6]. So far, no FONLL results are available for the case of $\gamma\gamma$ collisions.

A detailed study of the phenomenological consequences of eq. (5.1) relevant to charm production at HERA will be presented elsewhere [3]. Here, I shall only repeat the study performed in section 3, presenting the ratio of HERA data for the p_T spectrum over the FONLL results. For the latter, the Peterson parameter has been set equal to $\epsilon = 0.02$, consistently with the findings of ref. [10]. The results are presented in fig. 7, which has to

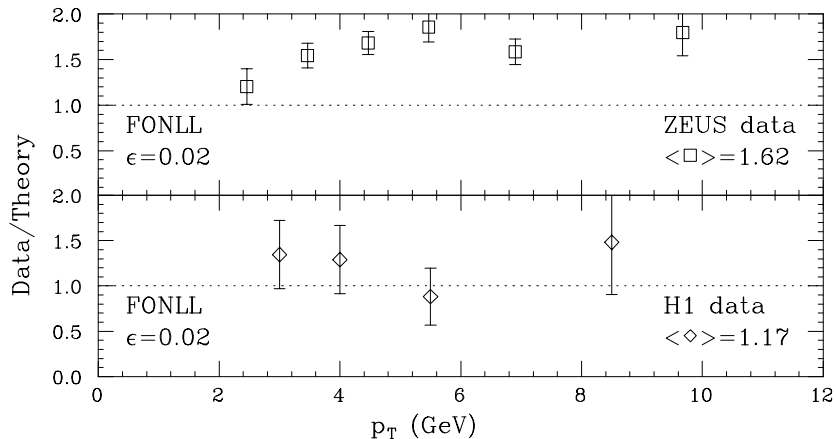


Figure 7: As in fig. 1, for FONLL predictions.

be compared to fig. 1. The plots are rather similar; the average of the values data/theory is only marginally larger in the case of FONLL computations, and this behaviour is basically driven by the large- p_T points. At a first glance, this seems to be counterintuitive, since FONLL is expected to perform better than FO at large p_T ; but actually, it means that, shape-wise, the p_T spectrum predicted by FONLL agrees better with data with respect to that predicted by FO. However, it has to be stressed that this is not yet statistically significant. It also becomes clear that, although FONLL improves over FO, FO predictions, and not RS predictions, were the right choice so far to compare to experimental data. It does not make much sense to compare these data to pure RS predictions; the p_T is simply not large enough. It is important to notice that any agreement between RS predictions and data in this p_T range must be regarded as accidental, and QCD is actually not tested at all.

6. Conclusions

It does not come as a surprise that NLO QCD undershoots charm data, or at least it does so for a “default” choice of parameters. However, the agreement with the experimental results is reasonable. Of all the data considered here, those of ZEUS are the only ones that can not be described even with an extreme choice of parameters. The p_T spectrum measured by ZEUS is harder than that of QCD, and the η spectrum grows faster than QCD predicts towards the positive η 's. LEP data only marginally favour a softer p_T spectrum than NLO QCD. The increase of the statistics and the extension of the measurements to larger p_T 's will shed further light on these issues. The whole p_T range in photoproduction can now be consistently treated within a single formalism, reducing the ambiguities in the comparison between theory and data. The use of similar visible regions by the different experiments working at the same machine will also help in performing more stringent tests of the theory.

The new results relevant to bottom production are quite puzzling; the rates are dramatically larger than QCD predictions, the disagreement with theory being much worse than the corresponding one in charm production. This is in contradiction with the picture

of the hard production process at work in QCD. However, more work has to be done in this field, both by theorists and experimentalists, before firm conclusions can be reached.

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