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HEAVY QUARK PHYSICS AT HERA

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A brief overview of the anticipated heavy quark physics at HERA is given. The topics discussed include heavy quark photo- and leptoproduction cross sections at HERA calculated in the context of perturbative QCD, various mechanisms of J/ψ-leptoproduction and their rates, determination of the gluon density of the proton using open and bound charmed hadrons, and rare D^0-meson decays. Some selected aspects of B-Physics at HERA are also discussed.

1. Introduction

Heavy quark physics at HERA has been studied at some length in the context of two HERA workshops at DESY [1]-[6], and elsewhere [7]. In the workshop proceedings published in 1988 [1] a lot of emphasis was put on the potential of HERA in the discovery of the top quark. In the meanwhile, stringent lower bounds on m_t from the CDF collaboration giving $m_t > 91 GeV$ [8] and indirect estimates from the precision electroweak data pitching m_t in the range $m_t = 140 \pm 40$ GeV [9] have pushed away the top frontier. This statement can be quantified by noting that at HERA (with $\sqrt{s} = 314$ GeV), the inclusive top quark production cross section is estimated to be $\sigma(ep \rightarrow tX) \leq 0.02\ pb$ for $m_t \geq 100$ GeV. In view of this we shall not entertain top quark physics at HERA in this paper. Cross sections and top quark search strategies at the LEP + LHC ep collider can be seen in [10].

The cross sections $\sigma(ep \rightarrow QX)$ for $Q = c, b$ at HERA, using improved QCD perturbation theory, have been estimated as [11,12]:

$$\sigma(ep \rightarrow cX) \simeq O(1\ \mu b)$$
$$\sigma(ep \rightarrow bX) = O(10\ nb) \qquad (1)$$

The reliability of these estimates is discussed in section 2.

With a luminosity of 100 pb^{-1}/year, one expects an annual crop of $O(10^8)$ charmed hadrons and $O(10^6)$ beauty hadrons at HERA. These rates make HERA a powerful charm factory (though, unfortunately, not a Tau-factory!), providing new and unique oppurtunities to test perturbative QCD, measure the structure functions of the proton as well as of the photon, and search for new physics beyond the standard model in the flavour changing neutral current (FCNC) sector. It has been argued in [4] that experiments at HERA would provide an order of magnitude improved sensitivity over the existing bounds for a number of FCNC processes involving charmed hadrons. This is discussed in section 3.

Concerning B physics, the inclusive b-cross section in ep collisions at HERA is comparable to that of LEP at the Z^0 resonance. At both LEP and HERA B hadrons are produced in the continuum, hence higher mass B-states, such as Λ_b-baryons and B_s and B_c mesons, can be detected and their properties studied. While on B physics, we mention here the possibilty of using the HERA proton beam to do a fixed target experiment. The cross section for

$pA \to bX$ with the HERA proton energy is estimated to be $O(15)$ nb/nucleon, giving $O(10^9)$ B hadrons/year with a high-A target, such as Tungsten [13]. While a fixed target experimental facility provides an attractive addition to the present research programme at HERA, we shall concentrate here on B physics that could be studied in ep collisions. We assume that an integrated luminosity of $O(1)fb^{-1}$ will be accumulated over a decade, making a number of FCNC processes involving B hadron decays amenable to experiments at HERA. These issues are taken up in section 4.

2. Heavy Quark Production Cross sections at HERA

Experiments at HERA will allow to measure the proton structure functions, $F_2(x, Q^2)$ and $F_L(x, Q^2)$ over a wide range in (x, Q^2) [14]. Studies of final states involving heavy quarks will allow to measure the charm and bottom quark content of these structure functions. Estimates based on next-to-leading order QCD calculations are available in literature [15]. It is, however, well known that the cross sections for $ep \to QX$ for $Q = c, b$, are dominated by photoproduction processes, with the photon being almost real ($Q^2 \simeq 0$). Hence we shall mainly concentrate on the process

$$\gamma + g \to Q + \bar{Q}. \quad (2)$$

In the next to leading order in α_s, the following processes also contribute

$$\begin{aligned} \gamma + g &\to Q + \bar{Q} + g, \\ \gamma + q(\bar{q}) &\to Q + \bar{Q} + q(\bar{q}). \end{aligned} \quad (3)$$

In addition, one has also to include the so-called resolved-photon processes

$$\begin{aligned} q + \bar{q} &\to Q + \bar{Q}, \\ g + g &\to Q + \bar{Q}, \end{aligned} \quad (4)$$

where one of the incoming partons ($q/\bar{q}$ or g) originates from the proton and the other from the photon. The parton densities in the photon, very much like the parton densities in hadrons, are described by Q^2-dependent distribution functions $f_i^\gamma(x, Q^2)$. In the case of electroproduction, one needs additionally the probability functions $f_i^e(x, Q^2)$ of finding a parton i with fractional momentum x in the electron These can be obtained by convoluting the Weizsäcker-Williams (WW) function $f_\gamma^e(x)$ with the corresponding partonic densities $f_i^\gamma(x, Q^2)$, for which there are several parametrizations available [16,17]. A separation of the direct and resolved-photon components is possible if one uses the topology of the heavy quark events. One of the first goals of HERA experiments indeed is to measure these densities. We summarize here attempts to determine the gluon density of the proton $G(x, Q^2)$. A comparable effort for the determination of the parton densities of the photon in the context of heavy quark production at HERA is desirable and should be carried out.

Heavy quark cross sections at HERA depend, apart from the input partonic densities, also upon the usual QCD-specific parameters such as the quark mass, m_Q, the QCD scale Λ, and the mass factorization scale, μ. Using the values $\Lambda_{\overline{MS}}(n_f = 4) = 260 \pm 100$ MeV, the subtraction scale μ in the range $m_b/2 < \mu < 2m_b$, the b quark in the mass range 4.5 $GeV < m_b < 5.0$ GeV, and the Eichten et al. parametrization of the structure functions of the proton [18], one gets $\sigma(ep \to b\bar{b}X) = (6.0 \pm 1.1)nb$ at $\sqrt{s} = 314$ GeV [11]. The contribution of the hadronic component of the photon (the so-called resolved-photon contribution) to the bottom quark cross section has been estimated to be less than 30 % at HERA energies [11,19], using the photon densities from [16]. The corresponding cross section for the electroproduction of charmed quarks is predicted to be $\sigma(ep \rightarrow c\bar{c}X) = (0.68^{+0.26}_{-0.18})\mu b$ at HERA for $m_c = 1.5\ GeV$ [11]. The parameters used in this evaluation adequately explain the charm photoproduction cross section and differential distributions in lower energy fixed target experiments. It remains an interesting and open question if the same perturbative QCD framework also describes quantitatively the characteristics of heavy quark electroproduction at HERA.

The order $(\alpha\alpha_s^2)$ calculations for the photoproduction of heavy quarks by Ellis and Nason[11] have been checked recently by Smith and van Neerven [12]. The results for the cross section $\sigma(ep \rightarrow eb\bar{b}X)$ at HERA ($\sqrt{s} = 314\ GeV$) in the DIS and $\overline{MS}$ renormalization schemes, assuming $m_b = 4.75\ GeV$ and $\Lambda(n_f = 4) = 0.212\ GeV$, from this investigation are [12]:

$$\begin{aligned}
\sigma(ep \rightarrow b + \bar{b} + X)(\mathcal{O}(\alpha)) &= 4.60^{+0.34}_{-0.24}\ nb \\
\sigma(ep \rightarrow b + \bar{b} + X)(\mathcal{O}(\alpha^2); \mathrm{DIS}) &= 7.13^{+1.64}_{-0.62}\ nb \\
\sigma(ep \rightarrow b + \bar{b} + X)(\mathcal{O}(\alpha^2); \overline{MS}) &= 6.59^{+1.28}_{-0.47}\ nb
\end{aligned} \quad (5)$$

where the central values correspond to the factorization scale set equal to $\mu = m_b$, and the upper and lower numbers represent the shift in $\sigma(ep \rightarrow b + \bar{b} + X)$ if one sets $\mu = m_b/2$ and $\mu = 2m_b$, respectively.

The cross sections quoted above have been obtained in the next-to-leading order pertrbative QCD and they should be quite adequate at not-too-high energies, $s > M^2 \gg \Lambda^2$, where M is the generic heavy quark mass. It is, however, known that at high energies (multiple) gluon exchanges give rise to large factors $\ln^n \rho$ (with $\rho \equiv 4M^2/s$) in the cross sections of interest. In the limit $\rho \rightarrow 0$, the leading logarithms can be summed to all orders by using the transverse-momentum factorization of the short- and long-distance physics (i.e. the hard-vertex and the structure function terms) [20–22]:

$$4M^2\sigma_{\gamma g}\left(\rho, M^2; Q_0^2\right) = \int d^2k_\perp \int_0^1 \frac{dz}{z} z\hat{\sigma}\left(\rho/z, k_\perp^2/M^2\right) \mathcal{F}\left(z, k_\perp, Q_0^2\right).$$

where $\hat{\sigma}$ is the cross section for $\gamma + g(k) \rightarrow Q\bar{Q}$ involving an off-shell gluon. The function $\mathcal{F}\left(z, k_\perp, Q^2\right)$ is defined as the (unintegrated) structure function of a gluon with longitudinal fractional momentum z, and transverse momentum $k_\perp$, at the scale Q^2. The usual gluon structure function follows after the $k_\perp$-integration

$$G(z, M^2, Q^2) \equiv \int_0^{M^2} d^2k_\perp \mathcal{F}(z, k_\perp, Q^2) \quad (6)$$

The resummed results for the photo- and leptoproduction of heavy quarks are being discussed by Hautmann in these proceedings [23]. We note here that the cross sections in this approach depend essentially on the so-called FKL anomalous dimensions [24], which are energy-dependent. As $s \rightarrow \infty$, the anomalous dimension γ asymptotes to its maximum value $\gamma = 1/2$, giving

$$\frac{4M^2\sigma_{\gamma g}(\rho, M^2; Q^2)}{G(M^2, Q^2)} \simeq h(1/2) = \frac{27}{56}\pi^2 h(0) \quad (7)$$

which is a factor (~ 5) larger than the lowest order result obtained by neglecting the resummation effects, $h(0)$,

$$h(0) = \frac{28\pi}{9}\alpha\alpha_s e_Q^2. \quad (8)$$

Fixed-order perturbation theory results can be matched with the $k_\perp$ factorization (resummed) ones for large ρ; at very high energies ($\rho \rightarrow 0$), however, fixed order theory underestimates the

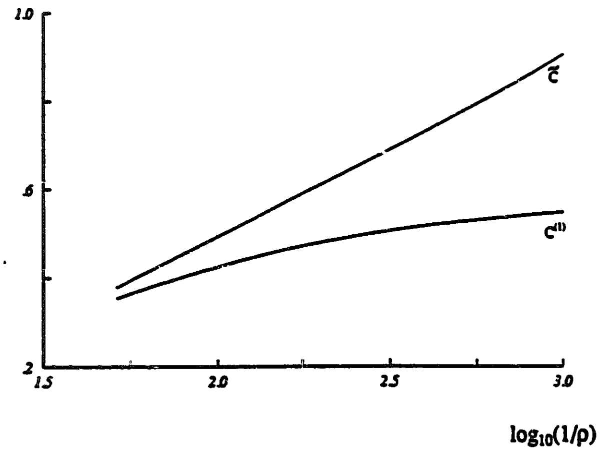

Fig. 1. Resummed ($\tilde{C}$) and one-loop ($C^{(1)}$) coefficient functions for bottom quark electroproduction as functions of $\ln(1/\rho)$, assuming $m_b = 5$ GeV and $\Lambda = 260$ MeV (from ref. [3]).

heavy quark production cross section. This is shown in Fig. 1 in terms of the coefficient functions $\tilde{C}$ (resummed) and $C^{(1)}$ (one-loop) entering the definition of the cross section $\sigma_{\gamma g}(\rho, M^2; Q^2)$ [3]. The rise of $\tilde{C}$ with increasing $1/\rho$ (hence energy) reflects, in essence, the rise of the FKL anomalous dimension [24], leading to the result in Eq. (7). The actual enhancement in the charm and bottom quark cross sections due to resummation is expected to be rather modest at HERA energies. Catani et al. [3] estimate that the total cross section for b-quark production at HERA will be $O(20\%)$ larger than predicted by the one-loop calculations [11,12]. Very similar conclusions have been reached in the detailed Monte Carlo simulation by Webber [25], based on similar considerations.

3. Charm Physics at HERA

Apart from providing quantitative tests of perturbative QCD through the production processes, charm physics at HERA also offers the following possibilities:

- Determination of the gluon density through the process $ep \to ec\bar{c}X$, which is dominated by the fusion process $\gamma + g \to c + \bar{c}$.
- An understanding of the dynamics of leptoproduction of heavy quark bound states, leading eventually to a determination of the gluon density through J/ψ-production in the process $ep \to J/\psi X$.
- Search for the rare decays of charmed mesons.

We summarize the main conclusions of a recent HERA study concerning these points [4–6].

3.1. Determination of the gluon density using charmed hadron events at HERA

The determination of the gluon density from (open) charmed hadron events at HERA ($ep \to ec\bar{c}X$) has been studied by Woudenberg et al. [5] by using the traditional methods for charmed hadron tagging, namely $D^{*\pm}$ reconstruction from the process $D^{*\pm} \to D^0\pi^\pm \to (K^\mp\pi^\pm)\pi^\pm$, and inclusive dileptons from the decays $c\bar{c} \to l^+l^-X$. The inclusive cross section for $D^{*\pm}$ events, taking into account detector simulation and trigger efficiency, has been estimated to be $O(10^3\ pb)$ giving $O(10^5)$ reconstructed $D^{*\pm}/100\ pb^{-1}$ at HERA. The cross section for the process $ep \to c\bar{c}X \to e^+e^-X$, with a beam pipe cut of 0.1 rad. and the transverse momentum of the prompt (decay) electron satisfying $p_\perp(e^\pm) > 0.8\ GeV$, is estimated to be $O(60\ pb)$ giving 6×10^3 dielectrons/ 100 pb^{-1} from $c\bar{c} \to e^+e^-X$ events; summing over both electrons and muons one gets a factor 4 higher cross-section.

We now describe the reconstruction technique for the variable x_g, the fractional momentum carried by the gluon. Writing the momenta of the particles explicitly for the process of interest

$$e(\ell) + p(p) \to e(\ell') + c(p_c) + X(p_X) \tag{9}$$

the usual DIS kinematic variables are defined as,

$$s = (p+l)^2, \quad y = \frac{p \cdot q}{p \cdot l}, \quad Q^2 = -q^2, \tag{10}$$

where $q = l - l'$ is the four-momentum of the exchanged photon. In the case of D^*-tag, the variable x_g can be determined using the relation

$$x_g = \frac{\hat{s} + Q^2}{ys} \simeq \frac{\hat{s}}{ys} \tag{11}$$

with $\hat{s} = M^2_{c\bar{c}} = M^2_{\gamma g}$. To a good approximation, one could equate

$$\hat{s} = \frac{p_\perp^2 + m_c^2}{z(1-z)} \tag{12}$$

where $p_\perp \equiv p_\perp(D^*)$ and $z = p.p_c/y(p.l)$. With this method x_g can be determined at HERA in the range $5 \times 10^{-4} \leq x_g \leq 10^{-1}$. Alternatively, one could estimate x_g using the rapidity $\hat{y}_{cc}$ of the partonic system, giving (since $Q^2 \simeq 0$)

$$x_g = \frac{yE_e}{E_p} \exp\left(2\hat{y}_{cc}\right) \tag{13}$$

This method, according to the analysis in [5], can be used to determine x_g in the range $6 \times 10^{-4} \leq x_g \leq 10^{-1}$. For the inclusive dilepton events, the reconstruction of $\hat{y}(c\bar{c})$ can be well approximated by the rapidity of the lepton pair. In this way, x_g-values in the range $3 \times 10^{-4} \leq x_g \lesssim 3 \times 10^{-2}$ can be measured.

Having constructed the variable x_g, one could study the dependence of the charm cross section on x_g to measure the gluon density $G(x_g)$ in the proton at HERA, providing a much more direct and theoretically dependable extraction of this function. For the time being, one could show the sensitivity of the cross section on currently available parametrizations. To illustrate this, one would be able to distinguish the gluon densities due to Morfin and Tung (sets B1 and B2) [26] with a rather modest HERA luminosity. This is shown in Fig. 2, where the product

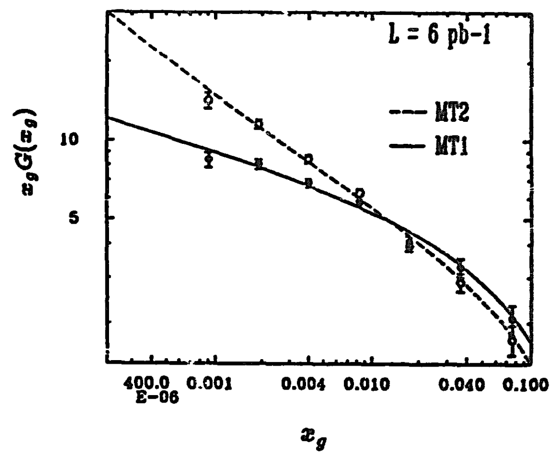

Fig. 2. The gluon density $x_gG(x_g)$ reconstructed from the Monte Carlo simulation of the process $ep \to D^{*+}X$ at HERA, using the Morfin-Tung parametrizations. The statistical error corresponds to an integrated luminosity of 6 pb^{-1}. (from ref. [5].

$x_gG(x_g)$, reconstructed from the inclusive production $ep \to D^{*+}X$ at HERA, is shown as a function of x_g. The error bars indicated correspond to the statistical error in a Monte Carlo simulation assuming an integrated luminosity of 6 pb^{-1}. However, a detailed analysis will be necessary to reduce the uncertainty due to the partonic structure function of the photon since the resolved photon contribution to $\sigma(ep \to c + X)$ is both model dependent and large at HERA. In view of the fact that no bound state wave function is required to determine the cross section (as opposed to the J/ψ leptoproduction discussed below), and the underlying QCD framework in the next-to-leading order (NLO) is at hand, final states having charmed hadrons are well suited to measure the gluon density at HERA.

3.2. *Determination of gluon density using J/ψ production at HERA*

HERA collisions are expected to produce J/ψ copiously. We denote the generic process as:

$$e(\ell) + p(p) \to e(\ell') + J/\psi(p_{J/\psi}) + X(p_X). \quad (14)$$

In the WW approximation ep cross sections are obtained from the corresponding γp cross sections by the usual convolution of $f_\gamma^e(y, Q^2)$ with $\sigma_{\gamma^* p}(W^2, Q^2)$:

$$\sigma_{ep}(s) = \frac{\alpha}{2\pi}\int \frac{dy}{y}\int \frac{dQ^2}{Q^2}\left\{\left[1+(1-y)^2\right]\sigma_{\gamma^* p}(W^2, Q^2)\right\}$$

with the Q^2 integration limits being

$$m_e^2 \frac{y^2}{1-y} \le Q^2 \le ys - W_{\min}^2 \quad (15)$$

and $W^2 = s_{\gamma p} = (q+p)^2$. Concentrating on the photoproduction of J/ψ, the following processes have been studied in the context of HERA by Jung et al. [6]:

(i) Elastic J/ψ production: $\gamma + p \to J/\psi + p$.
(ii) Diffractive inelastic J/ψ production:
$\gamma + p \to (J/\psi + X) + p$.
(iii) Diffractive dissociation:
$\gamma + p \to J/\psi|\text{diff.} + X$.
(iv) Inelastic J/ψ production:
$\gamma + p \to J/\psi + X$.
(v) Direct J/ψ production in the resolved-photon processes:
$g + g \to J/\psi + g$; and
$g + g \to J/\psi + \gamma$.
(vi) J/ψ via χ-production in the resolved-photon processes:

$$\begin{aligned} g+g &\to \chi_{0,2} \to J/\psi + \gamma \\ \{g+g, q+\bar{q}\} &\to \chi(\to J/\psi + \gamma) + g \\ g+q &\to \chi(\to J\psi + \gamma) + q \end{aligned}$$

(vii) J/ψ-production via $\gamma\gamma$ collision:
$\gamma + \gamma \to \chi_{0,2} \to J/\psi + \gamma$
(viii) J/ψ-production via b-production:
$\gamma + g \to b\bar{b} \to J/\psi + X$.
(ix) J/ψ in double charm pair production:
$(\gamma, g) + g \to J/\psi + c\bar{c}$.

It is obvious from the outset that a satisfactory description of the processes listed above requires detailed model building. Also, concerning QCD tests and determination of the gluon density, it should be stressed that the NLO corrections in the electroproduction of (J/ψ) have yet to be calculated; in view of these remarks it is difficult to be quantitatively predictive about J/ψ physics at HERA. We summarize the rates from whatever is known theoretically and experimentally and then take up the point of x_g-determination from J/ψ-producion at HERA.

The dominant contribution to J/ψ-production is through the inelastic process $\gamma + p \to J/\psi + X$ (reaction (iv) listed above). In the Colour-Singlet (CS) model [27,28], γg-fusion leads to a colour-singlet state

$$\gamma + g \to J/\psi + g. \quad (16)$$

A comparison of the CS model predictions compared with data from fixed target experiments (FTPS [29], NA14 [30], EMC [31], and NMC [32]) in the differential distribution $d\sigma/dz$ (here z is the scaled J/ψ-energy, $z = E_{J/\psi}/E_\gamma$) reveals that the shapes are well accounted for by the model only for $z < 0.8$. However, a K-factor between 1.8 [29] and 4.9 [32] is needed to explain the rates, if one uses the lowest order J/ψ-decay width $\Gamma_{l\bar{l}}$ [6]. Using instead the QCD corrected width $\Gamma_{l\bar{l}}$, the respective K-factors are decreased by a factor ~ 2. There are several mechanisms available in the above list that contribute to the large-z region. In the same context, it has also been argued in [33] that the shape $d\sigma/dz$ from the CS model is sensitive to the relativistic corrections, which are significant and enhance the large-z part of the distribution. It remains an interesting and open question to quantitatively understand the fixed target results on J/ψ production. Experiments at HERA will also provide important input here. With the parameters

$m_c = 1.5\ GeV, K = 2.8$ and the Morfin-Tung parametrization (set B1) [26], the inelastic cross section for $ep \rightarrow J/\psi + X$ at HERA is estimated to be 8.5 nb in the CS model.

Taking up now the elastic J/ψ production $\gamma p \rightarrow J/\psi p$, it is usually assumed that its cross section is determined by the single-pomeron exchange in the Regge picture. This involves the proton-pomeron-proton (p-IP-p) vertex, which can be taken from analogous studies in proton-proton collisions [34–36], as well as, the photon-pomeron-J/ψ (γ-IP-J/ψ) vertex, which is less well known and hence more model dependent. In the vector meson dominance (VMD) model the vertex γ-IP-J/ψ is related to the hadronic vertex J/ψ-IP-J/ψ, which in turn can be related to the proton form factor [34]. Normalizing this model by the elastic J/ψ cross section measured by the FTPS collaboration [29] and using an energy dependent pomeron density, gives a cross section $\sigma(ep \rightarrow eJ/\psi p) \simeq 4.5\ nb$ at HERA [6]. An alternative approach is to determine the γ-IP-J/ψ vertex by modelling it on open $c\bar{c}$ production instead of VMD [33], giving $\sigma(ep \rightarrow eJ/\psi p) = 2.2\ nb$ at HERA energy.

For the diffractive dissociation process $\gamma + p \rightarrow J/\psi|_{\text{diff.}} + X$, one could generalize the single-pomeron exchange model for the elastic $\gamma + p \rightarrow J/\psi + p$ scattering by replacing the elastic form factor of the proton by a suitable integral over the inelastic structure function of the proton $\bar{F}_2$, a parametrization of which is given in ref. [34]. This model predicts $\sigma(\gamma p \rightarrow J/\psi|_{\text{diff.}} + X) = 2.6\ nb$, compared to the FTPS data for the diffractive dissociation, $\sigma(\gamma p \rightarrow J/\psi|_{\text{diff.}} + X) = (4.4 \pm 0.9(\text{stat.}) \pm 1.1(\text{syst.}))\ nb$. Extrapolating to HERA energies, a cross section $\sigma(e + p \rightarrow e + J/\psi|_{\text{diff.}} + X) = 1.55\ nb$ has been obtained in ref. [6]. The cross section for the diffractive inelastic J/ψ production (reaction Γ50ii) above) is estimated to be $\sigma(e + p \rightarrow e + (J/\psi + X) + p) \simeq 0.35\ nb$.

Finally, the resolved-photon and two-photon production of J/ψ (reactions (v)-(ix) above) have been evaluated using the photon densities of ref. [16]. In the estimates presented below a cut on the transverse momentum of the J/ψ, $p_\perp^{J/\psi} > 1\ GeV$, has been applied to render finite cross sections for some of these processes. The rates are: $\sigma(gg \rightarrow J/\psi g) = 0.09\ nb$, $\sigma(gg \rightarrow J/\psi \gamma) = 0.023\ nb$, $\sigma(J/\psi X; \text{via } \chi \text{ decays}) = 0.11\ nb$, $\sigma(\gamma\gamma \rightarrow \chi_{\ell,2} \rightarrow J/\psi + \gamma) = 0.001\ nb$, $\sigma(J/\psi X; b\text{-decays}) = 0.07\ nb$, and $\sigma(J/\psi + c\bar{c}) = 0.16\ nb$. They should be compared with the corresponding inelastic J/ψ-production cross section, $\sigma(ep \rightarrow J/\psi X; p_\perp^{J/\psi} > 1\ GeV) = 1.05\ nb$ (1.32 nb), obtained by using the Morfin-Tung parametrization B1(B2). Summing up the contributions of all these processes, the inclusive J/ψ cross section at HERA is estimated to be:

$$\sigma(ep \rightarrow J/\psi X) = O(20)\ nb. \tag{17}$$

This rate would allow to undertake quantitative studies of the various competing processes in J/ψ-leptoproduction at HERA.

We now briefly review the determination of x_g in the process $ep \rightarrow J/\psi X$. The photon-parton CM energy $\sqrt{\hat{s}}$ for $e + p \rightarrow J/\psi X$ events can be determined via the relation

$$\hat{s} = \frac{p_\perp^2 + (1-z)m_{J/\psi}^2 + z s_2}{z(1-z)} \tag{18}$$

where $\sqrt{s_2}$ is the invariant mass of the partonic final state excluding the J/ψ. With Q^2 and s_2 set to 0, the determination of x_g requires the measurement of $p_\perp^{J/\psi}$, z, and y. The partonic CM energy can be well measured via the leptonic decay $J/\psi \rightarrow l^+l^-$, with $p_\perp(l^+l^-) = p_\perp^{J/\psi}$ and $z(l^+l^-) = z(J/\psi)$. The energy fraction carried by the photon y is reconstructed using the Jacquet-Blondel method

$$y_{\text{rec}} = \sum_h \frac{(E + P_L)h}{2E_e} \tag{19}$$

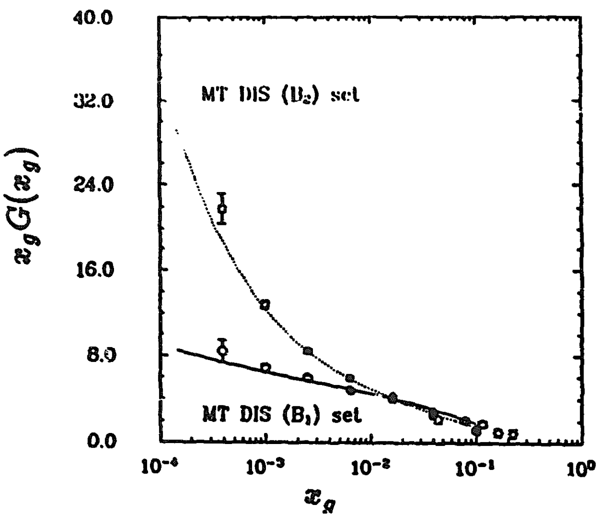

Fig. 3. The gluon density $x_g G(x_g, \mu^2)$ reconstructed from the Monte Carlo simulation of the inelastic J/ψ electroproduction at HERA, using the Morfin-Tung parametrizations. The statistical error corresponds to an integrated luminosity of 50 pb^{-1} for set B_1 and 20 pb^{-1} for set B_2. The $\diamond$ represent the recent NMC data (from ref. [6].

where the sum runs over all the particles in the calorimeter except the scattered electron. The scaled J/ψ energy, z, can be determined in terms of y_{rec}

$$z_{rec} = \frac{p \cdot p_{J/\psi}}{y\,(p \cdot l)} = \frac{(E + P_L)_{J/\psi}}{2 y_{rec}\, E_e} \tag{20}$$

The study in ref. [6] shows that x_g can be measured in the range $3 \times 10^{-4} \leq x_g \leq 1 \times 10^{-1}$ at $< \mu^2 >= \hat{s}$ with about 10% accuracy at the statistical level assuming an integrated luminosity of 20 pb^{-1}. Thus, already the first generation experiments at HERA would be able to discriminate among the various gluon densities. For the previous example of the sets B_1 and B_2 of Morfin-Tung parametrizations this can be seen in Fig. 3. However, we emphasize that extracting the gluon density from the J/ψ data would require a firmer theoretical framework than what is currently available.

3.3. Rare D-meson decays

The possibility of observing the decays $D^0 \to \mu^+\mu^-$, e^+e^-, $\mu^\pm e^\mp$ at HERA has been studied by Egli et al. [4]. Note that the last of the decays, being lepton flavour violating, is not allowed in the Standard Model. If SM provides the dominant contribution to the FCNC processes, then the anticipated branching ratios $BR(D^0 \to \mu^+\mu^-) \simeq 10^{-19}$ and $BR(D^0 \to e^+e^-) \sim 10^{-24}$ are unreachable at HERA–and for that matter anywhere else. However, these branching ratios could be dramatically enhanced if new physics effects are present, such as leptoquarks in the TeV mass-range, causing the decays $D \to \bar{l}_1 l_2$ at a measurable rate. In the MC simulation undertaken in ref. [4], the D^*-tagging technique discussed earlier, $D^* \to D^0\pi$ with the subsequent decay $D^0 \to l_1\bar{l}_2$, has been used to estimate the sensitivity to the leptonic branching ratio of D^0. With $\sigma(ep \to c\bar{c}X) \simeq 0.5\ \mu b$ and an integrated luminosity of 100 pb^{-1}, a sensitivity of $1.5 \times 10^{-6}, 5 \times 10^{-7}$ and 1×10^{-6}, for $BR(D^0 \to \mu^+\mu^-)$, $BR(D^0 \to e^+e^-)$ and $BR(D^0 \to \mu^+e^-)$, respectively, can be reached at HERA. This is one to two orders of magnitude better than the present experimental limits [40]. Likewise, the sensitivity in the FCNC semileptonic decays $D^0 \to (\bar{K}^0, \pi^0, \rho^0)l^+l^-$ and $D^+ \to (K^+, \pi^+, \rho^+)l^+l^-$, which at present is typically $(1-2) \times 10^{-3}$, could be substantially improved at HERA. The sensitivity to such semileptonic decays, as well as, $D^0 - \bar{D}^0$ mixing and doubly Cabibbo suppressed decays $D^0 \to K^+\pi^-$ depends crucially on the ability to measure the charges of the $K^\pm, \pi^\pm$, etc.

In summary, there is a good case for HERA in doing consolidation work in charm physics (charmed hadrons and J/ψ production cross sections, gluon density measurements). Also, improved sensitivity in rare charmed hadron decays is expected.

4. B-Physics at HERA

The energy-momentum profile of B-hadrons and their decay products at HERA , as well as the photoproduction background, have been worked out in ref. [1]. We shall assume that the background for B-physics at HERA is manageable and discuss briefly the physics that one could study with $O(10^6)$ B-events per 100 pb^{-1} at HERA.

4.1. Prospects of detecting the mesons B_s and B_c and the beauty baryons at HERA

A number of higher mass beauty hadrons, both mesons and baryons, remains to be discovered. In the mesonic sector there are two which deserve special attention, namely B_s and B_c. Their masses have been estimated to lie in the range $M(B_s) = 5345 - 5388$ MeV and $M(B_c) = 6194 - 6292$ MeV, while their spin-1 partners are expected to have the masses $M(B_s^*) = 5410 \pm 10$ MeV and $M(B_c^*) = 6340 \pm 20$ MeV [37–39]. Since the anticipated mass difference $M(1^-) - M(0^-) \simeq 50(80)$ MeV for the $B_s(B_c)$ mesons is smaller than the pion mass, the heavier 1^--mesons will decay to the lighter 0^--mesons radiatively. For the B_s-mesons the cross section at HERA can be estimated assuming a value for P_s, the probability of the fragmentation $b \to B_s X$. With $P_s = 15\%$, one obtains:

$$\sigma(e + p \to B_s + X) =$$
$$2\ P_s\ \sigma(e + p \to b\bar{b} + X) = O(2\ nb).$$

This would yield some 200,000 $B_s/\bar{B}_s$ mesons per 100 pb^{-1}. The dominant semileptonic decays, $B_s \to (D_s^+, D_s^{*+})\ \ell^- \nu_\ell$ and non-leptonic decays $B_s \to J/\psi(\phi, \eta, K^+K^-, ...)$ and $B_s \to D_s^{*+}D_s^{*-}, D_s^{*+}D_s^-, ...$ are measurable at HERA. The branching ratios for the B_s-decays in a good number of modes can be estimated from the corresponding known decays and branching ratios for the B_d-mesons. Using this analogy, the inclusive semileptonic branching ratio for $B_s \to D_s + X + \ell + \nu_\ell$ should be $O(10\%)$, for $\ell = e, \mu$, each. Assuming a detection efficiency of 10% for the D_s meson by summing over the known decay modes, one gets a cross section of $O(40\ pb)$ for the tagged B_s semileptonic decays at HERA. For the determination of the B_s-mass a non-leptonic decay is needed. The decay mode $B_s \to J/\psi\phi$ should have a branching ratio comparable to the decay mode $B_d \to J/\psi K^*$, which is put at $(3.7 \pm 1.3) \times 10^{-3}$ in the PDG tables [40]. With 14% branching ratio for $J/\psi \to \ell^+\ell^-$, one gets $\sigma(e + p \to B_s X \to J/\psi\ \phi \to \ell^+\ell^-\phi) = O(1\ pb)$, providing $O(100)$ tagged B_s-mesons in the indicated decay mode. Thus, experiments at HERA (likewise LEP) should be able to determine the mass and decay characteristics of the yet undiscovered B_s meson.

Next, we discuss the more massive and less copious B_c-mesons with characteristic decay signatures $B_c^+ \to J/\psi\ell^+\nu_\ell$ (semileptonic) and $B_c^+ \to J/\psi D_s^{*+}$, $J/\psi\rho^+$ etc. (nonleptonic). The cross sections for B_c production at HERA and LEP are both small and model dependent. The quantitity $F(B_c)$ defined as:

$$F(B_c) \equiv \frac{\sigma(B_c^+ X) + \sigma(B_c^- X)}{\sigma(b\bar{b}X)} \tag{21}$$

has been estimated by Lusignoli et al. to be $F(B_c) = (2.0 \pm 0.2) \times 10^{-3}$ and $(1.0 \pm 0.2) \times 10^{-3}$ for HERA and LEP, respectively [41]. This gives a cross section $\sigma(e + p \to B_c X) = O(10\ pb)$, yielding $O(10^3)$ B_c mesons per 100 pb^{-1} at HERA. The cleanest experimental signature for the B_c^+-meson is through the semileptonic decay $B_c^+ \to J/\psi \ell^+ \nu_\ell$, with the subsequent decay $J/\psi \to \ell^+\ell^-$, giving rise to three charged leptons in a jet with a branching ratio around 1% [41]. With this cross section for the B_c-meson, one expects $O(10)$ three-lepton states in a jet for an integrated luminosity of 100 pb^{-1} at HERA. This will establish the B_c-signal. However, measuring its mass would require the detection in a non-leptonic mode, which may or may not be accessible with $O(10^6)$ B-decays at HERA. Since heavy quarks in ep collisions are dominantly produced with low energy, the probability of the fusion $b\bar{c} \to B_c + X$ at HERA in the process $e+p \to c\bar{c}+b\bar{b}+X$ may not be as suppressed as the above estimates of $F(B_c)$ indicate. A more reliable calculation is needed here.

Concerning b-baryons, there exist indications in the UA1 data [42] for the presence of the lightest of them, Λ_b, which has been reconstructed in the exclusive decay mode $\Lambda_b \to J/\psi\Lambda$, with the mass $m(\Lambda_b) = (5640 \pm 50 \pm 30)$ MeV and the product branching ratio

$$P_{\Lambda_b} Br(\Lambda_b \to J/\psi\Lambda) = (1.8 \pm 1.0) \times 10^{-3}. \quad (22)$$

Likewise, the ALEPH collaboration has measured the yields of both $\Lambda\ell^-$ and $\Lambda\ell^+$ combinations in Z^0-decays, and posted a product branching ratio [43]:

$$P_{\Lambda_b} Br(\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell) Br(\Lambda_c \to \Lambda X) = [0.95 \pm 0.22(stat.) \pm 0.21(syst.)]\%$$

This, on using $P_{\Lambda_b} = 0.1$ and $Br(\Lambda_c \to \Lambda X) = 0.27 \pm 0.09$ from the PDG tables [40], gives $Br(\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell) = O(30\%)$. Measurements along these lines are also feasible at HERA, given that $O(10^5)$ b-baryons will be produced per 100 pb^{-1} luminosity.

The b-baryon spectrum is very rich. Apart from the isosinglet $\Lambda_b = udb$, which we have just discussed, there are the isotriplet b-baryons $\Sigma_b^+ = uub$, $\Sigma_b^0 = udb$, $\Sigma_b^- = ddb$, the strange b-baryons $\Xi_b^0 = usb$, $\Xi_b^- = dsb$, and the $S = -2, B = -1$ baryon $\Omega_b^- = ssb$. There are yet other (and heavier) b-baryons, with charmed quark(s), and double and triple beauty quarks. All of them await discovery! We note parenthetically that the Σ_b and Σ_b^* baryons (the lowest spin-3/2 state of a b-quark consisting of a b-quark and two non-strange light quarks) are expected to be heavy enough to allow them to decay into $\Lambda_b + \pi$. They should be looked for in the experiments where Λ_b's are seen. There exist predictions for the mass splitting based on quark models. A typical range for the mass difference $M(\Sigma_b) - M(\Lambda_b)$ is between 180 and 210 MeV [37]. The mass difference between Σ_b^* and Σ_b is expected to be: $M(\Sigma_b^*) - M(\Sigma_b) \simeq 20$ MeV.

4.2. Prospects of measuring the mixing parameter χ_s and the mass difference $x_s = (\Delta M/\Gamma)_s$ at HERA

A number of experiments in e^+e^--annihilation and $p\bar{p}$ collisions has measured the mixing parameter χ characterizing mass mixing in the neutral B-meson sector. The present world average is $\chi = 0.148 \pm 0.018$, based on the UA1, CDF, and LEP experiments [44], where the quantity χ is defined as $\chi = P_d\chi_d + P_s\chi_s$, with $\chi_d(\chi_s)$ being the mixing parameter in the $B_d^0 - \bar{B}_d^0$ ($B_s^0 - \bar{B}_s^0$) sector and $P_d(P_s)$ the production probability for the $B_d(B_s)$ meson. With $\chi_d = 0.155 \pm 0.031$ from the ARGUS and CLEO data [44], a model dependent determination of χ_s is possible. For example, using $P_d = 0.375$ and $P_s = 0.15$ one gets $\chi_s = 0.60 \pm 0.14$ to be compared with the SM expectations, $\chi_s \simeq 0.5$.

In the HERA study [1], the statistical accuracy attainable for $\Delta\chi/\chi$ has been estimated to be 7% with an integrated luminosity of 200 pb^{-1} using the dilepton modes $e+p \to b+\bar{b}+X \to l^\pm l^\pm + X$

and $e + p \to b + \bar{b} + X \to l^{\pm} l^{\mp} + X$. Flavour correlations are important in disentangling χ_s and χ_d in continuum b-production experiments and we refer to [46] for a detailed discussion on this point.

The ratio involving the mass difference and lifetime for the $B_s^0 - \bar{B}_s^0$ system, $x_s = (\frac{\Delta M}{\Gamma})_s$, is an important quantity to calibrate the strength of the $|\Delta B| = 2, \Delta Q = 0$ transitions. Since x_d, the mixing ratio for the $B_d^0 - \bar{B}_d^0$ system, is known, a measurement of x_s could be reliably used to determine the Cabibbo-Kobayashi-Maskawa (CKM) matrix element ratio $|V_{ts}/V_{td}|$ via the relation $\frac{x_s}{x_d} = |\frac{V_{ts}}{V_{td}}|^2 (1 + \Delta)$ [45], where $\Delta \sim O(SU(3)$ breaking$) \sim 0.2 - 0.3$. The above measurement can be combined with the unitarity constraint $|V_{ts}| = |V_{bc}| \simeq 0.045$ to provide a good determination of the (otherwise difficult to measure) CKM matrix element, V_{td}. Present CKM phenomenology gives $x_s \simeq 15$ [46]. Such a large value will make it mandatory to undertake time-dependent measurements to determine x_s. A case to case study of various experimental facilities in carrying out x_s-measurement has been done in [46], where also the HERA case is discussed. One estimates that for a proper time resolution $\sigma_t/\tau \leq 0.1$ and the B_s-tagging efficiency of $O(10^{-3})$ at least $O(10^7)$ B hadrons will be required to measure $x_s \leq 10$. This, according to the quoted b-quark cross section at HERA, would require an integrated luminosity of 1000 pb^{-1} – a long term goal for HERA ep experiments.

4.3. Prospects of measuring rare B-decays at HERA

Rare B decays also provide fertile grounds for testing the Standard Model in flavour changing neutral current (FCNC) processes. Since the short distance contributions are dominated by the top quark, rare B-decays provide an alternative means to bound the top quark mass and constrain the CKM matrix elements V_{td}, V_{ts}, and V_{tb}. In this context, radiative decay of the b-quark $b \to s + \gamma$ have received special attention, for which one obtains an inclusive branching ratio $Br(b \to s + \gamma) = (3 - 4) \times 10^{-4}$ for the top quark mass in the range 100 – 200 GeV [47]. Theoretical estimates for $B \to K^* + \gamma$ are less certain, with the predictions dispersed over an order of magnitude giving a range $Br(B \to K^* + \gamma) = (1.5 - 15) \times 10^{-5}$. The present most stringent (though still preliminary) experimental upper limit on an exclusive radiative B-decay is: $Br(B \to K^* + \gamma) \leq 0.92 \times 10^{-4}$ (90 % C.L.) [48]. It is important to measure the decay rate $B \to X_s + \gamma$ inclusively (here X_s denotes hadrons with total strangeness S=-1), for example via the inclusive photon energy spectrum as has been advocated in ref. [49]. Theoretical uncertainties in this case are expected to be relatively small though from an experimental point of view such measurements are quite challenging.

In Fig. 4, we show the inclusive photon energy spectrum in the process $B \to X_s + \gamma$, which is based on a QCD-corrected effective Hamiltonian and a simple model for the wave function of the B-hadron. The photon spectrum peaks around $\simeq 2.55$ GeV in the rest frame of the B-meson, though in the model being used the shape is somewhat dependent on $p_F = O(\Lambda)$, which represents the average momentum of the b-quark inside the B-hadron. The principal background from the charged current b-decays has also been estimated and shown in Fig. 4. This background, though large in overall rate, is below the $B \to X_s + \gamma$ signal beyond $E_\gamma \geq 2.0$ GeV. Thus, a good signal for the inclusive radiative rare B-decays at HERA is to search for energetic photons with $(E_\gamma)_\perp \geq 2.0$ GeV (measured w.r.t. the b-jet axis), recoiling against the hadron(s) X_s, with the γX_s having the B-invariant mass.

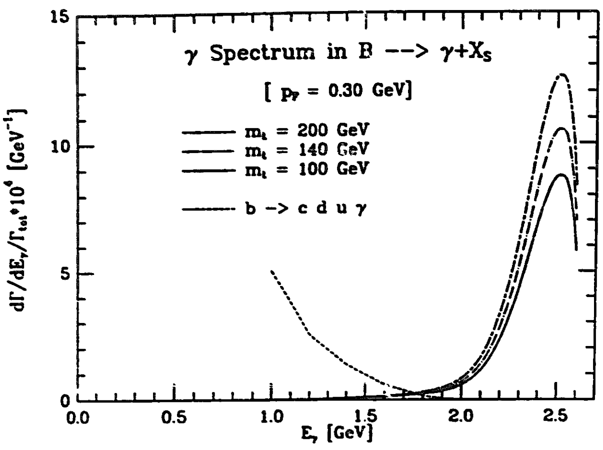

Fig. 4. Inclusive photon energy spectrum for the process $B \to X_s + \gamma$ using perturbative QCD and a B-meson wave function model described in the text, with the parameter p_F set to 0.3 GeV and three representative values of the top quark mass, as indicated. The dashed curve corresponds to the photon energy spectrum from the background process $B \to X_c + \gamma$ (from ref. [47]).

With $O(10^6)$ B-hadrons, and a functional microvertex detector which could be used to suppress the large photoproduction background, the γ-spectrum from the rare B-decays may indeed be reconstructed at HERA.

Likewise, B-decays involving a charged dilepton pair, $B \to X_s + \ell^+\ell^-$, provide precision tests of the Standard Model. The SM estimates for the short-distance (m_t-dominated) contributions are: $Br((B_d, B_u) \to X_s + \mu^+\mu^-) = 7.0 \times 10^{-6}$ and $Br((B_d, B_u) \to X_s + e^+e^-) = 1.2 \times 10^{-5}$, for $m_t = 150\ GeV$ [47]. Based on model calculations, one expects that the low lying states such as $(K, K^*, K^{**}, ..)$ will contribute a significant fraction to the inclusive rare decays involving dileptons [47].

Even more interesting from a theoretical point of view are the CKM-suppressed radiative decays, $B \to X_d + \gamma$ (likewise $B \to \rho + \gamma, ...$), as well as the FCNC semileptonic decays $B \to X_d + (\ell^+\ell^-)$ (likewise $B \to (\pi, \rho, A_1, ...)(\ell^+\ell^-)$), since they measure the CKM matrix element $|V_{td}|$. A branching ratio of $(1-2) \times 10^{-5}$ for the inclusive decay $B \to X_d + \gamma$, and $(1-2) \times 10^{-6}$ for the exclusive decay $B \to \rho + \gamma$ have been estimated in ref. [49]. These rates would be very challenging to measure in HERA ep collisions. The branching ratios for a number of CKM-allowed rare B-decays, estimated in the Standard Model, together with the present experimental limits are given in [47].

Summarizing the discussion on rare B-decays, we note that they can be searched for more successfully in a high luminosity experiment at $\Upsilon(4S)$ and in high energy hadronic collisions such as at the Fermilab $p\bar{p}$ collider, or perhaps in a fixed target experiment using the HERA proton beam. Since the present experimental limits on rare B-decays are already very stringent, the sensitivity in the ep mode at HERA is limited to the CKM-allowed decays like $B \to X_s + \gamma$ and $B \to X_s + \ell^+\ell^-$, if $O(10^7)$ B-decays could be analyzed. Searches for rare B decays would certainly be an additional motivation for the high luminosity version of HERA (ep). Likewise, there is a good physics case for a fixed target dedicated B-experiment at HERA provided it is technically feasible.

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