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Experimental Aspects of Heavy Quark Physics at HERA [1]

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1. Introduction

HERA is the $e-p$ collider now under construction at DESY, Hamburg. It will provide collisions between 30 GeV electrons and 820 GeV protons and is expected to become operational by 1990. Two detectors have been approved for data taking at HERA, H1 and ZEUS. A schematic layout of ZEUS is shown if Fig. 1.1. This figure illustrates the angular coverage of the high resolution calorimeter in the (w.r.t. the incoming p direction) forward (FCAL), central (BCAL) and rear (RCAL) directions. It also shows the position of the vertex detector (VXD), the central tracking device (CTD) as well as the forward and rear tracking chambers (FTD and RTD). The forward, barrel and rear calorimeters are planned to be instrumented with two planes of Si pads for improved electron/hadron separation. Muons are detected in the forward direction in a spectrometer using drift and limited streamer tube chambers plus scintillator counters interspersed between the magnetized iron yoke and toroid. The barrel and rear muon detectors are based on limited streamer tube chambers before, in between and behind the backing calorimeter and behind the concrete shield.

With the purpose of sharpening our thinking on the physics potential offered by HERA, DESY devoted the 1987 annual Theory Workshop to the topic "Physics at HERA". Twelve study groups were formed to cover the various aspects under this title. We are going to present in this report some of the most important results obtained in the study group "Heavy Quark Physics at HERA". Particular attention is paid to the problem of reconstructing the original quark direction of flight as well as to the importance of quantitatively assessing the amount of gluon radiation. Procedures for tagging charm, bottom and top hadron events are discussed as well as the implications for experimentation at HERA. A more comprehensive review can be found in [1]. See also the lectures given at this Meeting by A. Ali [2] and G. Schuler [3].

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[1] Based on lectures given by F.B. at the VI ELOISATRON Workshop on Heavy Flavours, Erice, Italy

[2] Alexander von Humboldt Fellow, now at DESY.

[3] Supported by CICYT, Spain.

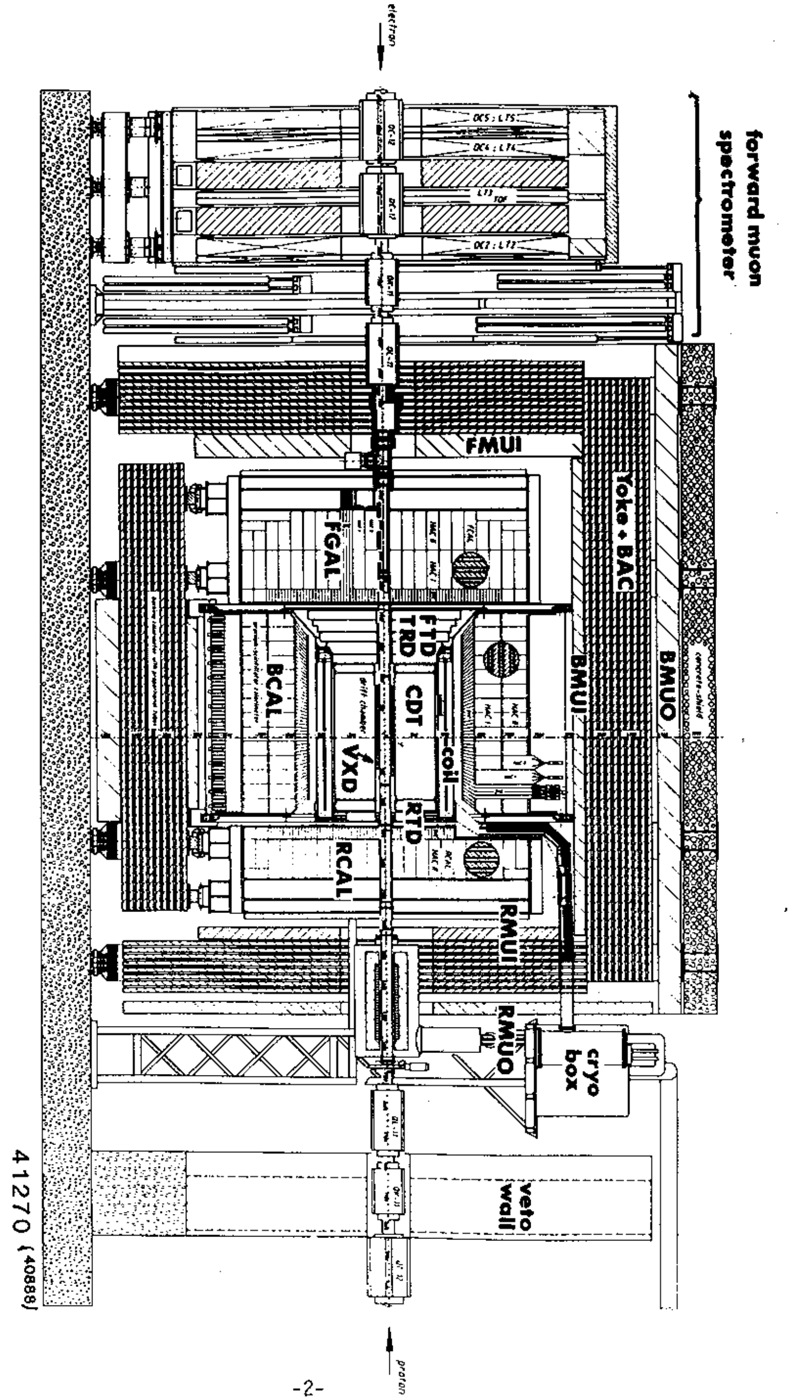

Fig. 1.1 View of the ZEUS detector

2. Heavy Quark Production in *ep* Collisions

In high energy $e-p$ collisions, the main source of heavy flavour production is the boson-gluon fusion (BGF) mechanism. The leading order Feynman diagrams are shown in Fig. 2.1 and correspond to the charged current (CC) and neutral current (NC) processes

$$CC : W^+ + g \to Q + \bar{Q}' \tag{2.1}$$

$$NC : \gamma/Z^0 + g \to Q + \bar{Q} \tag{2.2}$$

The cross sections for these processes can be calculated convoluting the gluon density in the proton with the QCD parton level cross-sections obtained from the diagrams shown in Fig. 2.1.

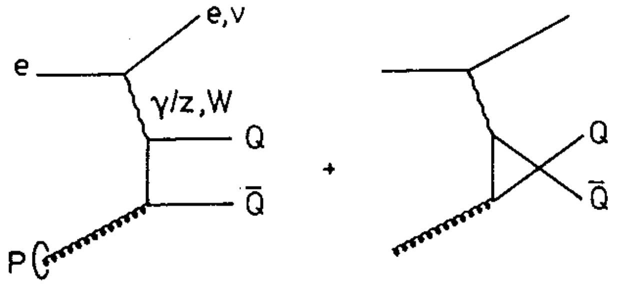

Fig. 2.1 Lowest order QCD diagrams for boson-gluon fusion into a heavy quark-antiquark pair

These calculations to $O(\alpha_S\alpha^2)$ [4–8] are subject to uncertainties due to the choice of

- the gluon density parametrisation
- the scales needed to define the running electromagnetic and strong coupling constants
- the values of the heavy quark masses

We will show results obtained [6] with the parametrisation of Eichten et al. [9]. Uncertainties due to alternative parametrisations of the gluon structure function are very large, $O(100\%)$, for charm production, large, $O(25\%)$, for bottom and small for top production. Uncertainties due to the choice of scales are comparatively smaller, $O(10\%)$, while those coming from the choice of heavy quark masses are also important for charm and bottom cross-sections.

For the values of the parameters in the Standard Model which are quoted in Table 2.1, the cross sections for charm, bottom and top production are given in Tables 2.2, 2.3 and

Table 2.1: Assumed values of the standard model parameters used in the estimates of cross-sections

Quantities	*Values*
CKM matrix elements	$V_{ud}^2 = 0.95$ $V_{us}^2 = 0.05$ $V_{ub}^2 = 10^{-4}$ $V_{cd}^2 = 0.05$ $V_{cs}^2 = 0.948$ $V_{cb}^2 = 0.002$ $V_{td}^2 < 4.10^{-4}$ $V_{ts}^2 = 0.002$ $V_{tb}^2 = 0.998$
Quark masses	$m_s = 0.5\ GeV$ $m_c = 1.5\ GeV$ $m_b = 5.0\ GeV$
Weak boson masses and angle	$m_W = m_z cos\theta_W = \frac{38.68GeV}{sin\theta_W}$ $sin^2\theta_W = 0.226$
Mass scales	$M_s^2 = M_g^2 = \hat{s}$
QCD scale	$\Lambda_{QCD} = 0.2\,\mathrm{GeV}$
No. of flavours in $\alpha_S(Q^2)$	$n_f = 3$

Table 2.2: Charm cross sections at HERA

$\sigma(ep \to cX)$ [pb] at HERA ($m_c = 1.5\,\mathrm{GeV}$)								
	CC			NC $c\bar{c}$				inclusive
e^-p	$\bar{c}d$	$\bar{c}s$	$\bar{c}b$	NC	γ	Z	γ-Z	$c+\bar{c}$
BGF	0.46	8.2	0.012	5.1×10^5	5.1×10^5	0.60	4.7	1.0×10^6
e^-p	$\bar{d}\to\bar{c}$	$\bar{s}\to\bar{c}$						
QPM	0.26	3.3						3.6
e^+p	$d\to c$	$s\to c$						
QPM	0.75	3.3						4.1

Table 2.3: Bottom cross sections at HERA

	$\sigma(ep \to bX)$ [pb] at HERA ($m_b = 5\,\mathrm{GeV}$)							
	CC			NC $b\bar{b}$				inclusive
e^-p	$\bar{u}b$	$\bar{c}b$	$\bar{t}b$	total	γ	Z	γ-Z	$b+\bar{b}$
BGF	$\leq 0.96 \times 10^{-3}$	0.012	0.13	4.2×10^3	4.2×10^3	0.35	0.59	8.4×10^3
e^-p	$u \to b$							
QPM	$\leq 0.56 \times 10^{-2}$							$\leq 0.56 \times 10^{-2}$
e^+p	$\bar{u} \to \bar{b}$							
QPM	$\leq 0.12 \times 10^{-2}$							$\leq 0.12 \times 10^{-2}$

Table 2.4: Top cross sections at HERA for $m_t = 60\,\mathrm{GeV}$

	$\sigma(ep \to tX)$ [pb] at HERA ($m_t = 60\,\mathrm{GeV}$)							
	CC			NC $t\bar{t}$				inclusive
e^-p	$\bar{t}d$	$\bar{t}s$	$\bar{t}b$	total	γ	Z	γ-Z	$t+\bar{t}$
BGF	$\leq 0.14 \times 10^{-3}$	$\leq 0.62 \times 10^{-3}$	0.13	0.09	0.09	0.4×10^{-3}	0.6×10^{-4}	0.31
e^-p	$\bar{d} \to \bar{t}$	$\bar{s} \to \bar{t}$						
QPM	2×10^{-3}	8×10^{-3}						1×10^{-2}
e^+p	$d \to t$	$s \to t$						
QPM	4×10^{-3} QPM	8×10^{-3}						1.2×10^{-2}

2.4, respectively. For completeness, the contributions coming from the Quark Parton Model, which are small compared to the ones stemming from the BGF mechanism, are also given.

The following comments are in order:

- NC cross-sections for charm and bottom quarks dominate over the CC processes.
- Top quark production through CC reactions cannot be neglected, actually this is the dominant contribution for m_t above 55 *GeV*, see Fig. 2.2.

If one takes into account that at LEP-I/SLC one expects [10]

$$\sigma(e^+e^- \to Z_0 \to cX) = 6.5\ nb \tag{2.3}$$

$$\sigma(e^+e^- \to Z_0 \to bX) = 9.0\ nb \tag{2.4}$$

one can conclude that the bottom pair cross-section at HERA is comparable to that at LEP-I/SLC, while the charm cross-section is two orders of magnitude larger at HERA. After five years of running at the expected yearly luminosity of $200pb^{-1}$, we expect to have accumulated $O(10^9)$ charmed hadron events and $O(10^7)$ bottom hadron events.

Summarizing this section, HERA has the potential to be a powerful charm and bottom factory, and will have a chance to see top hadron events if the top mass lies below 80 GeV.

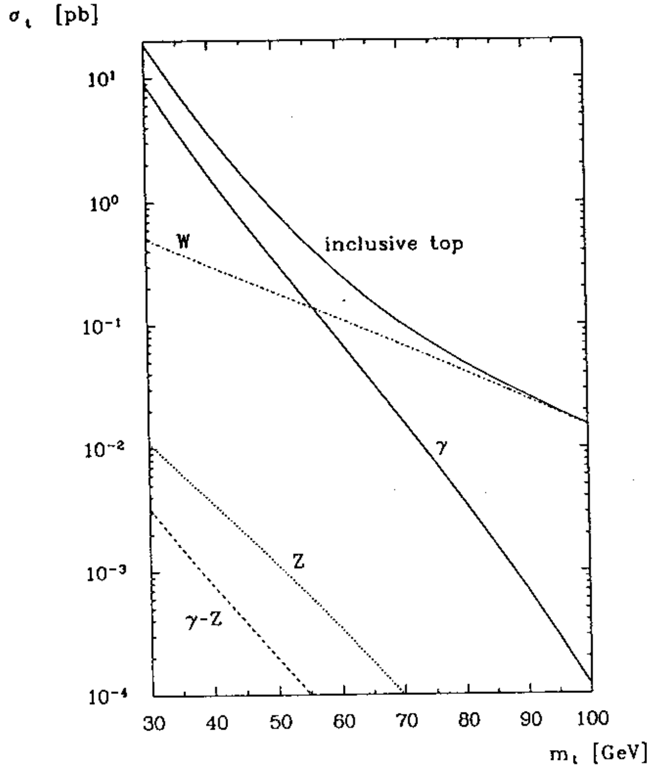

Fig. 2.2 Inclusive cross-section for quark top production via boson gluon fusion as a function of the top quark mass. Curves are for charged current interactions (W) and in the neutral current case separately for pur γ, pure Z and their interference $\gamma - Z$. From [6].

3. General characteristics of heavy flavour production at HERA

In the preceeding section we have seen that the cross sections for heavy quark production at HERA are quite large. The next question we have to address is obviously, how large are the detection efficiencies. Let us first discuss the cross-sections for heavy quark production in the x, Q^2 plane, with x and Q^2 defined as usual in deep inelastic scattering, i.e. Q^2 as the squared momentum transfer at the lepton vertex and x as the fractional momentum carried by the gluon in the proton. For the sake of illustration we show in Tables 3.1 and 3.2 the normalized distributions $\frac{1}{\sigma}\frac{d^2\sigma}{dxdQ^2}$ for $t\bar{b}$ and $b\bar{b}$ production respectively, for an assumed value of the top quark mass of 60 GeV.

Notice that NC processes are dominated by very low x, very low Q^2 values. On the other hand, CC processes have a much broader distribution both in x and Q^2. These are consequences of the fact that NC processes are γ exhange dominated, while CC processes are due to the exchange of heavy W bosons. Thus, the experimental signature for BGF events through NC processes, the dominant source of "light" heavy quark production, is simple to remember:

- the scattered electron goes undetected down the beam pipe, as a consequence of the low-Q^2 dominance discussed above;
- the proton fragments carry also very little transverse momentum and essentially go undetected in the direction opposite to the scattered electron;
- a $Q - \bar{Q}$ pair is produced back-to-back in the transverse or $r - \phi$ plane, as illustrated in fig. 3.1.

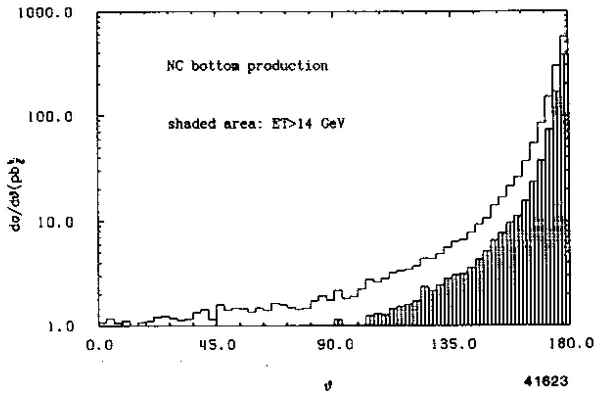

Fig. 3.1 Angular distribution between the b and $\bar{b}$ in the transverse or $r - \phi$ plane in the reaction $ep \to b\bar{b}X$. The shaded area indicates the results when a cut $\sum E_T \geq 20\ GeV$ is applied.

Table 3.1: Percentages of $t\bar{b}$ pairs from boson gluon fusion relative to total $t\bar{b}$ cross section

	$Q^2 \leq 10$	$10 \leq Q^2 \leq 10^2$	$10^2 \leq Q^2 \leq 10^3$	$10^3 \leq Q^2 \leq 10^4$	$10^4 \leq Q^2 \leq 4.10^4$
$x \leq 10^{-3}$	0.40	1.41	–	–	–
$10^{-3} \leq x \leq 10^{-2}$	0.01	2.59	13.93	–	–
$10^{-2} \leq x \leq 5.10^{-2}$	0.0	0.05	15.58	32.08	–
$5.10^{-2} \leq x \leq 10^{-1}$	0.0	0.0	0.51	21.38	–
$10^{-1} \leq x \leq 2.10^{-1}$	0.0	0.0	0.04	8.30	1.20
$2.10^{-1} \leq x \leq 5.10^{-1}$	0.0	0.0	0.0	0.75	0.99
$5.10^{-1} \leq x \leq 1$	0.0	0.0	0.0	0.0	0.0

Table 3.2: Percentages of $b\bar{b}$ pairs from boson gluon fusion relative to total $b\bar{b}$ cross section

	$Q^2 \leq 1$	$1 \leq Q^2 \leq 10$	$10 \leq Q^2 \leq 10^2$	$10^2 \leq Q^2 \leq 10^3$	$10^3 \leq Q^2 \leq 10^4$
$x \leq 10^{-3}$	81.154	8.978	3.065	–	–
$10^{-3} \leq x \leq 10^{-2}$	0.019	0.999	3.399	1.037	–
$10^{-2} \leq x \leq 5.10^{-2}$	0.0	0.014	0.517	0.638	0.031
$5.10^{-2} \leq x \leq 10^{-1}$	0.0	0.0	0.018	0.086	0.014
$10^{-1} \leq x \leq 2.10^{-1}$	0.0	0.0	0.003	0.023	0.006
$2.10^{-1} \leq x \leq 5.10^{-1}$	0.0	0.0	0.001	0.0	0.001
$5.10^{-1} \leq x \leq 1$	0.0	0.0	0.0	0.0	0.0

Up to now, we have restricted our discussion of heavy quark production at the parton level. It is clear that for a realistic estimate of the efficiency to tag charm, bottom or top hadrons, the hadronization of quarks and gluons as well as the weak decays of heavy quarks have to be taken into account. To incorporate these features we have used the Monte Carlo simulation model AROMA [11], which is based on the following ingredients:

- the complete $O(\alpha^2\alpha_S)$ matrix elements for the BGF processes discussed earlier,
- hadronization of the quarks and gluons using the LUND string model [12],
- weak decays of the charm, bottom and top quarks according to the standard V-A matrix elements.

Furthermore, AROMA has built in the possibility of gluon emission from the $Q-\bar{Q}'$ system in a parton shower approach[13]. Gluon emission has clearly to be considered in order to realistically estimate charm and bottom backgrounds for top search. However, it is not yet clear that the parton cascade formalism for time-like processes, which is presently built in AROMA, is adequate for space-like processes considered at HERA.

Since we have seen that $Q-\bar{Q}$ pairs are preferentially produced back-to-back in the transverse plane, and since the transverse momentum of the parton produced in the hard scattering subprocess is essentially given by its mass, we find it convenient to look at the distribution of the total transverse energy $\sum E_T$ deposited by charm, bottom and top events in a quasi-ideal calorimeter, in the sense that only a beam pipe cut of 100 $mrad$ has been considered, but no energy resolution smearing. The total transverse energy has the additional advantage that experimentally it is very easy to implement it in the trigger logic for hadronic events. The distributions obtained are shown in Fig. 3.2. Notice that they peak at values which are roughly the sum of the quark masses, and fall off steeply for higher values.

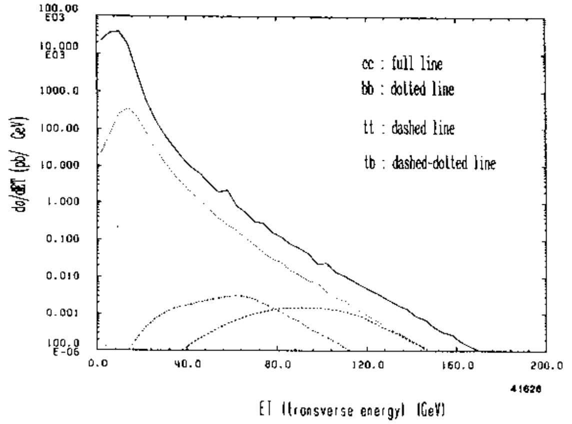

Fig. 3.2 Distribution of the total transverse energy $\sum E_T$ of all stable particles outside a beam pipe cut of 100 $mrad$, with curves corresponding to $t\bar{t}$, $t\bar{b}$ and the various backgrounds

One is therefore tempted to conclude that as far as quark pair production (in the transverse

plane) is concerned, HERA is a $\gamma\ g$ collider and similar to an e^+e^- storage ring with variable centre of mass energy, the luminosity peaking at centre of masses suitable for production of $Q-\bar{Q}$ pairs at rest.

In order to reconstruct the quark direction of flight, one could therefore apply the jet algorithms with which we are familiar in e^+e^- physics [14]. One such possibility is to divide the final state hadrons into two jets, in such a way as to maximize the sum of the longitudinal momenta along these two directions in space. This is the so called twoplicity method, a suitable generalization of thrust to not exactly back-to-back configurations. That one can reliably reconstruct the quark direction of flight is illustrated in fig. 3.3a, where we plot the angle between the generated quark direction and the reconstructed one, for the case of NC bottom pair production. The dotted (solid) line indicates the possibility that the $Q-\bar{Q}$ system does (not) radiate gluons according to the parton shower discussed in the preceeding section. The average angle between the generated and the reconstructed quark direction turns out to be 27° (resp. 26°).

Furthermore one can make use of the standard procedures in e^+e^- jet physics, to select jet-like configurations. It is clear that by increasing the E_T-threshold for triggering, we would select final states with a more pronounced jet structure, and this will ease the problem of reconstructing the original quark direction. As illustrated in fig. 3.3b, the average angle between the generated b direction of flight and the reconstructed axis goes down to 11° (resp. 8°) after imposing a cut on $\sum E_T \geq 20\ GeV$.

We would like to finish this Section, by presenting, see Table 3.3, some average properties characterising the heavy quark induced hadronic final states. Along with the cross sections for the various channels, mean values for $\sum E_T$, charged multiplicity and circularity are given.

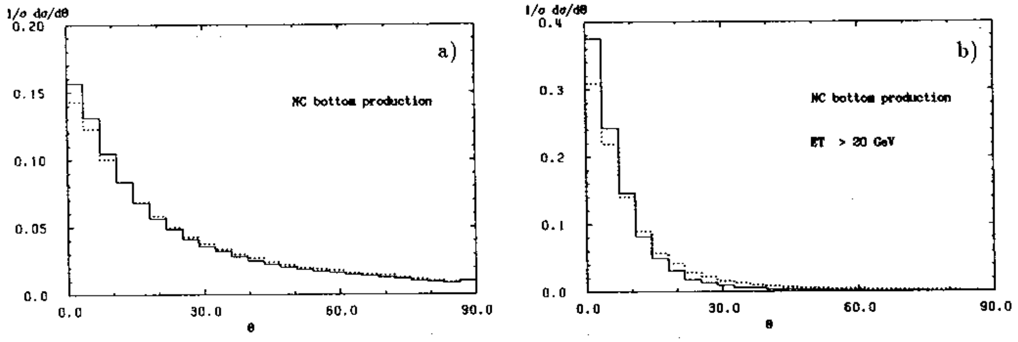

Fig. 3.3 Distribution of the angle between the Monte Carlo generated and reconstructed quark direction of flight, for the process $ep \to eb\bar{b}X$. The dotted line indicates that gluon radiation has been taken according to a parton shower formalism. The full line stands for no gluon radiation out of the $b\bar{b}$ pair. Two cases have been considered a) no cut on $\sum E_T$ and b) a cut on $\sum E_T \geq 20\ GeV$.

Table 3.3: Characteristics of heavy quark production at HERA

general cut: beam hole angle $\theta = 0.1$ rad				
for DIS events: $Q \geq 2\,\mathrm{GeV}$, $x \geq 0.001$, $W^2 \geq 5\,\mathrm{GeV}^2$ for light quark events: $p_\perp^q \geq 1\,\mathrm{GeV}$				
process	σ[pb]	$\langle \sum E_\perp \rangle$[GeV]	$\langle C \rangle$	$\langle n_{ch} \rangle$
NC				
$b\bar{b}$	4.2×10^3	14.	0.44	16
$c\bar{c}$	5.1×10^5	7.2	0.51	12
DIS	1.3×10^5	8.6	0.12	5
qG	7.3×10^5	3.4	0.42	5
$q\bar{q}$	7.8×10^5	6.2	0.50	10
CC				
$\bar{c}s$	8.3	25.	0.18	13
light quarks	71.	42.	0.14	15
$\bar{t}b \quad m_t =$				
40 GeV	0.36	48.	0.30	21
60 GeV	0.13	58.	0.28	21
80 GeV	0.05	70.	0.26	22
$t\bar{t} \quad m_t =$				
40 GeV	1.9	66.	0.36	26
60 GeV	0.09	93.	0.37	28
80 GeV	4.3×10^{-3}	117.	0.38	29

4. Comments on top quark searches at HERA

If one tries to further exploit the analogy discussed in the previous section between $Q - \bar{Q}$ production in e^+e^- annihilation and in $e - p$ collisions at HERA, one would think that imposing stringent cuts on $\sum E_T$ would result in a suppression of the charm and bottom background in a top search. As one can see from fig. 3.1 this will not suffice to isolate a clean top sample. However the jet configuration of the surviving charm and bottom pair final states will be very different from those exhibited by top pair events. The difference will be similar to that between quark pair production in e^+e^- annihilation at centre of mass energies near and much above threshold. Thus, one could think that by judiciously choosing cuts on both $\sum E_T$ and a jet measure like sphericity, circularity or twoplicity, one could select samples with enriched top hadron contents. This illustrated in Fig. 4.1 where we show the circularity distribution for $c\bar{c}$, $b\bar{b}$ and $t\bar{t}$ after imposing a cut on $\sum E_T \geq 100$ *GeV* and demanding at least one lepton in the corresponding final states. Two cases have been considered, namely (a) with and (b) without gluon radiation. The former has been taken into account in the parton shower formalism discussed in previous sections [13]. Notice that the signal over background ratio is significantly larger in case (b) as expected. Just as in top searches at e^+e^- machines one would expect a shoulder in the tail of the sphericity distribution. This illustrated in Fig. 4.2 where the mass of the top quark has been assumed to be 60 *GeV*.

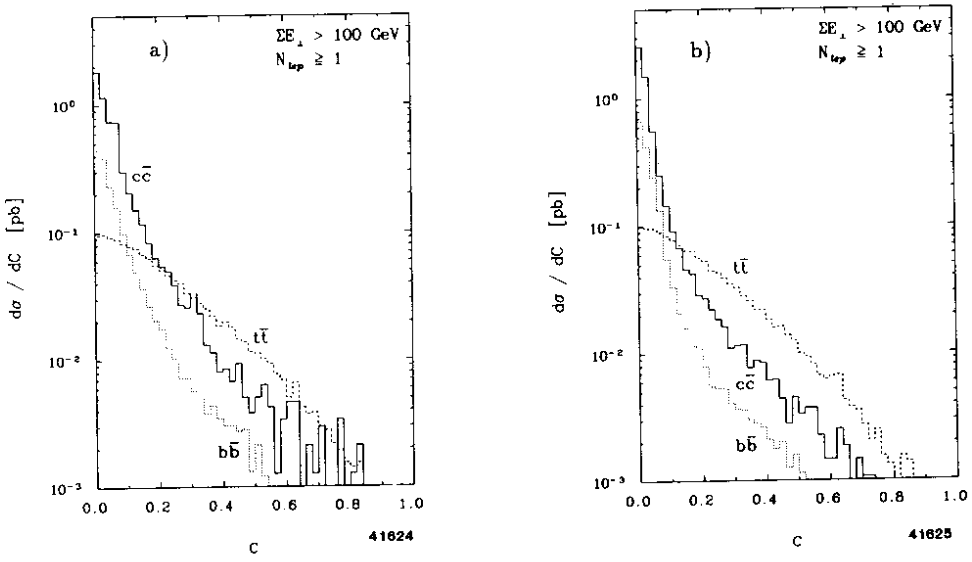

Fig. 4.1 Circularity distribution for $ep \to eQ\bar{Q}X$, with $Q = c, b, t$, a) gluon radiation in a parton shower is considered and b) no gluon radiation at all.

An alternative possibility to search for top hadron events will be to

- divide the event into two jets with the twoplicity method,
- plot the light versus the heavy jet mass.

The corresponding distributions for $c\bar{c}$, $b\bar{b}$ and $t\bar{t}$ production with and without parton cascading are shown in Fig. 4.3. The top quark mass has been assumed to be 60 GeV. Again, a clear separation is possible if gluon radiation were overestimated in the parton shower algorithm presently built in AROMA.

We would like to finish this section with two comments:

- A thorough discussion of top quark search strategies both in NC and CC processes can be found in [15]
- It is imperative to include in current Monte Carlo fragmentation models for heavy quark production at HERA a parton shower formalism appropriate for space like processes as well as the exact $O(\alpha_s{}^2\alpha^2)$ corrections in order to assess the importance of gluon radiation in the heavy quark pair final states at HERA.

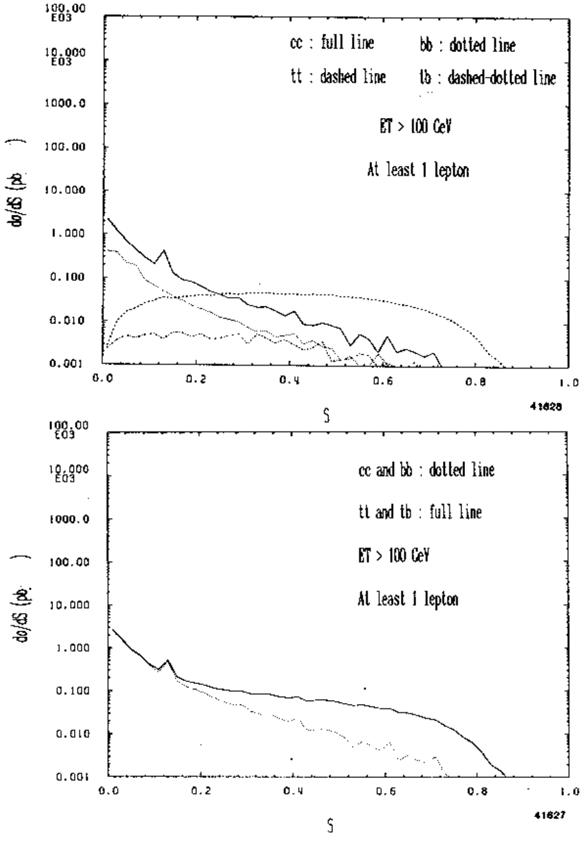

Fig. 4.2 Similar to Fig. 4.1 but for sphericity distributions

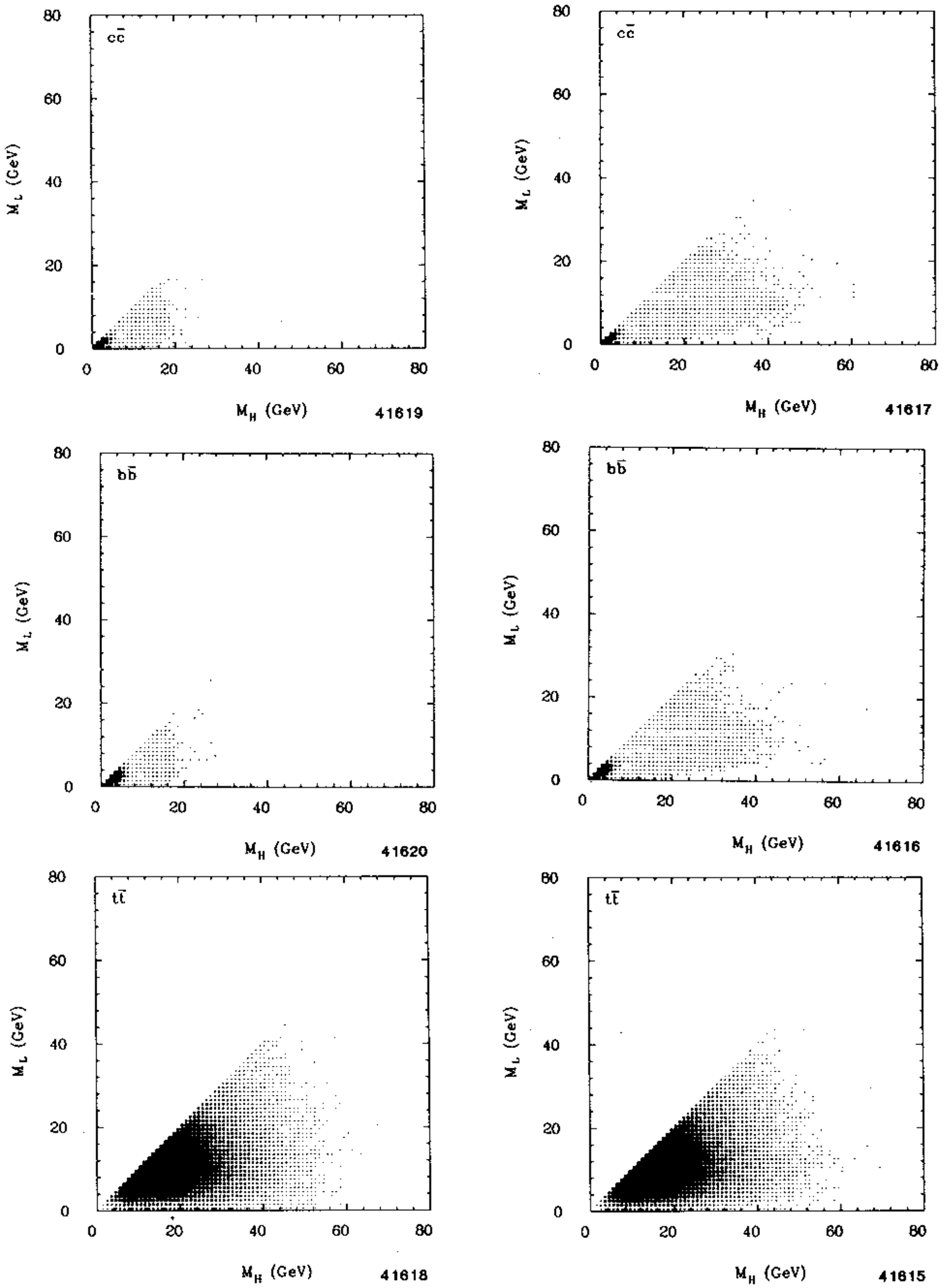

Fig. 4.3 Light vs heavy jet mass in the process $ep \rightarrow Q\bar{Q}X$ with $Q = c, b, t$. Left column: no gluon radiation considered, right column: gluon radiation in a parton cascade considered

5. Charm and Bottom Physics at HERA

We would like to start this section by discussing the energy-angle profiles for charm and bottom jets. As already shown in Sections 2 and 3, charm and bottom production at HERA is dominated by the NC process $\gamma g \to Q\bar{Q}$ with $Q = c, b$ at very low momentum transfers. The scattered electron in $ep \to eQ\bar{Q}X$ is in most of the cases lost in the beam pipe and the Q and $\bar{Q}$ are produced almost back-to-back in the $r - \phi$ plane. The scatter plots $\frac{d^2\sigma}{dE_Q d\theta_Q}$ (θ_Q measured w.r.t. the incoming electron direction) for the heavy mesons produced in the processes $ep \to ecX \to eDX$ and $ep \to ebX \to eBX$ are shown in Fig. 5.1.

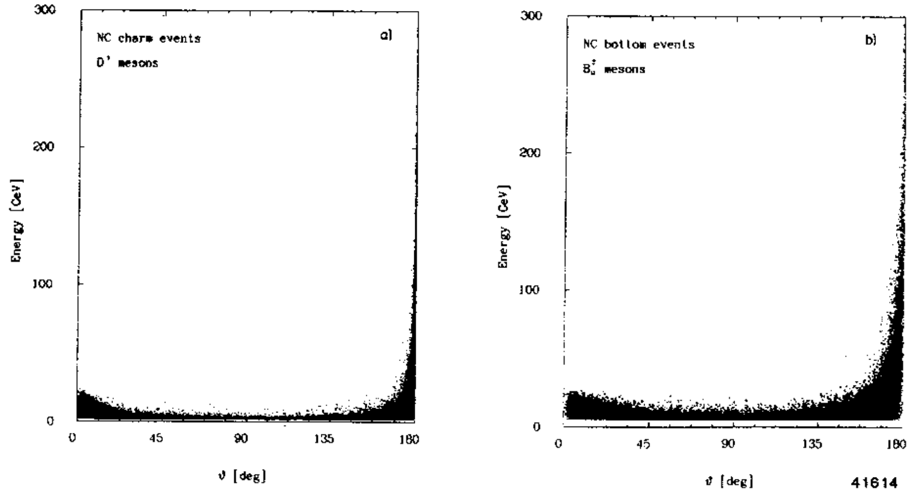

Fig. 5.1 Scatter plot showing the correlation between the energy and polar angle of the heavy mesons produced in the NC process $ep \to eQ\bar{Q}X$, a) $Q = c$, b) $Q = b$. From [16].

This is one of the most interesting results obtained in our study group since it shows that the Lorentz boost is not large enough so as to overcome the effects of the u-channel exchange depicted in Fig. 2.1.

Thus, although the most energetic heavy hadrons fly along the incoming proton beam direction, the fraction emerging along the incident electron is not negligible, see Fig. 5.2. They are even more energetic than those centrally produced and they offer an additional advantage namely their decay products are not contaminated by the proton remnants.

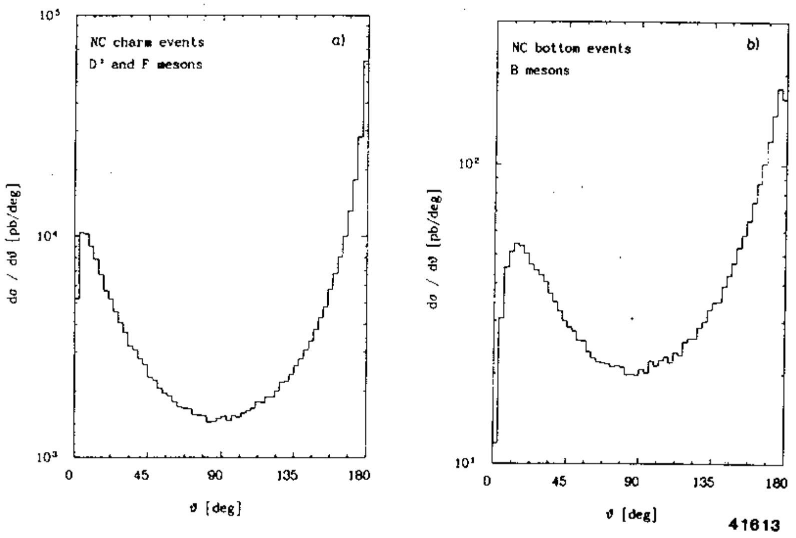

Fig. 5.2 Polar angle distribution of the heavy mesons produced in the NC process $ep \to eQ\bar{Q}X$ at HERA $\sqrt{s} = 310\ GeV$, a) $Q = c$, b) $Q = b$. From [16]

It is interesting to see how a beam pipe cut of approximately 100 *mrad* affects the energy spectrum of charmed and beauty hadrons, as well as their decay leptons and kaons. This is illustrated in Fig. 5.3. The following comments are in order

- heavy hadrons and their decay leptons and kaons have very similar energy distributions
- the effect of the beam pipe is very drastic, despite of which charmed and beauty hadrons with Lorentz factors up to $\gamma_D = 40$, $\gamma_B = 15$, respectively, will be measurable at HERA
- the mean decay lepton and kaon energies are in the 2 GeV region

The separation of charm and bottom events has been a long standing issue in e^+e^- annihilation and $p\bar{p}$ collisions. This separation is neccesary for a number of experimental measurements, like those of

- lifetimes,
- branching ratios.

While the reconstruction of charmed mesons, D^* in particular, is a matter of routine, the efficiency of reconstructing beauty hadrons is of $O(10^{-3})$, mainly due to the large multiplicities involved. Our poor knowledge of exclusive and inclusive B decays makes the separation

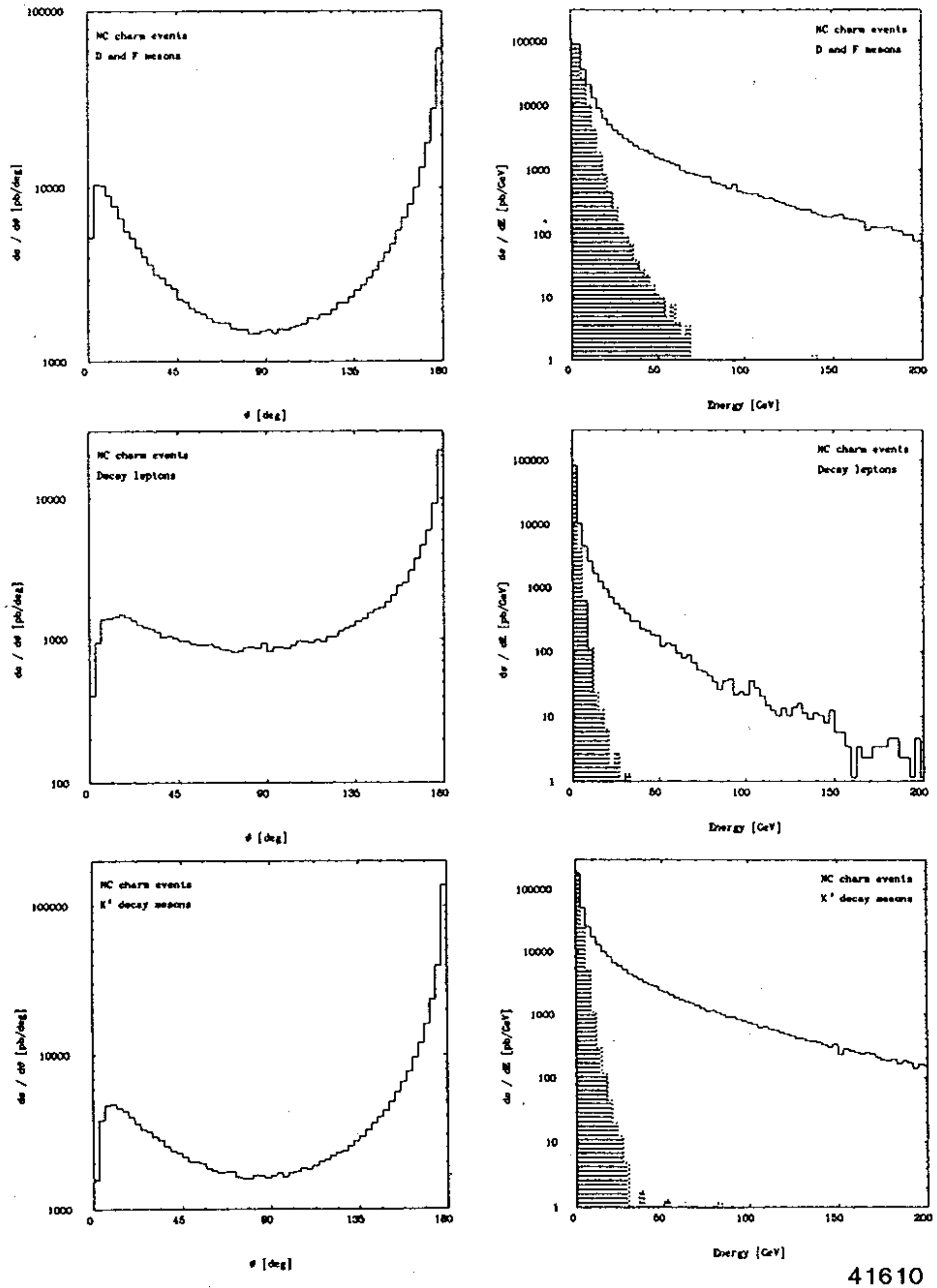

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Fig. 5.3 a) Energy and polar angle distribution for heavy mesons as well as their decay leptons and kaons produced in the NC process $ep \rightarrow ec\bar{c}X$ at HERA, $\sqrt{s} = 310\ GeV$. From [16].

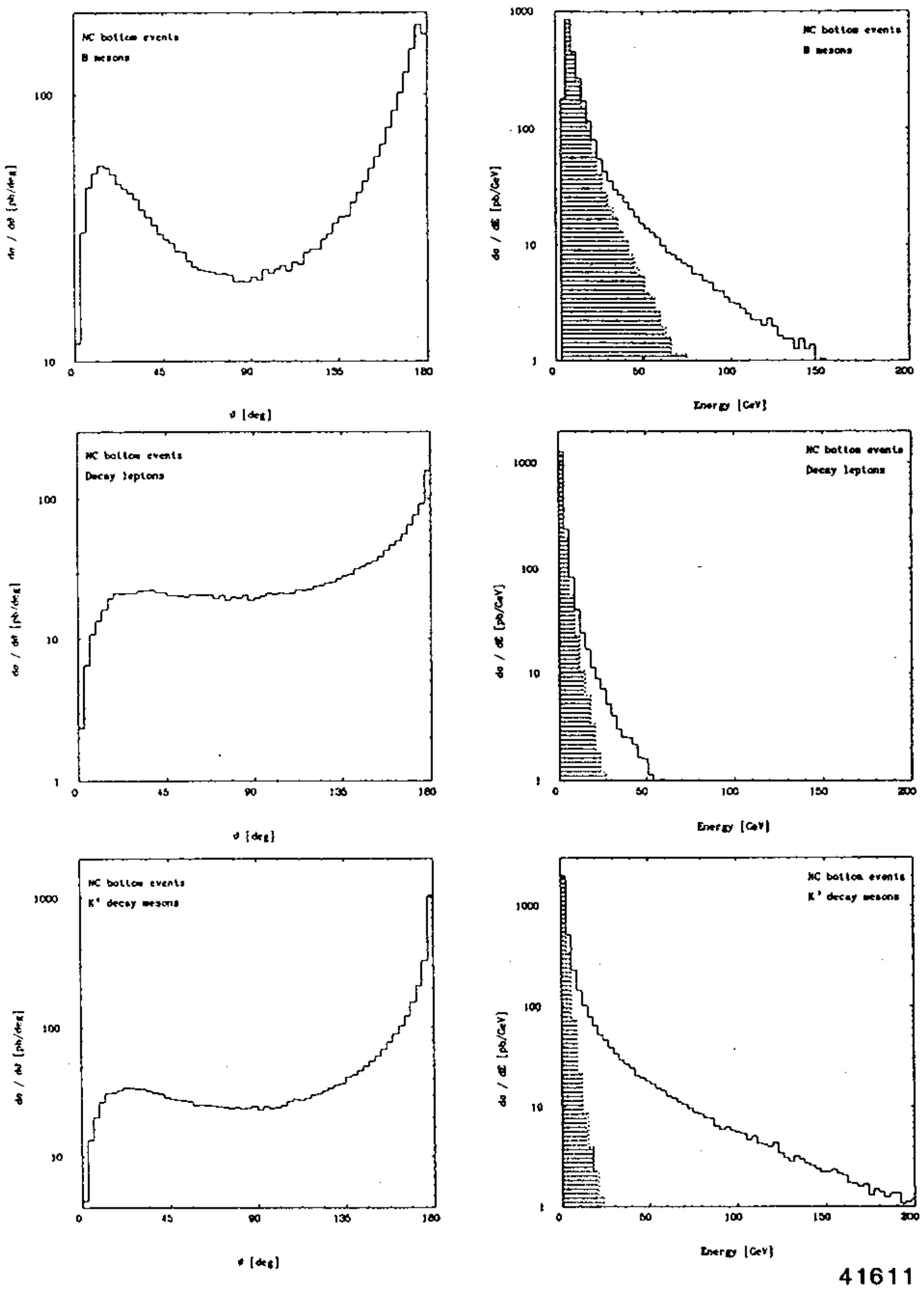

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Fig. 5.3 Energy and polar angle distribution for heavy mesons as well as their decay leptons and kaons produced in the NC process $ep \rightarrow eb\bar{b}X$ at HERA, $\sqrt{s} = 310\ GeV$. From [16]. From [16] between charmed and bottom hadrons difficult. Two tags could be used at HERA to select bottom events inclusively:

- large p_T leptons from the semileptonic decay $b \to cl\nu_l$;
- J/Ψ from the decay $B \to J/\Psi X$ which experimentally has a branching fraction of 1.5%.

The main background source for large p_T leptons comes from the much larger charm cross-section and the subsequent semileptonic decay $c \to sl\nu_l$. If gluon radiation were absent in the $Q\bar{Q}$ system, a well suited method to reconstruct the quark direction of flight, like twoplicity discussed in Section 3, will permit us to properly measure the p_T of the lepton w.r.t the jet axis and exploit the very different end points in the spectra for both decays. This is illustrated in Fig. 5.4. Here again we have considered two cases with and without gluon radiation. If the $Q\bar{Q}$ is subject to a parton showering, the separation is rendered more difficult, see Fig. 5.4b.

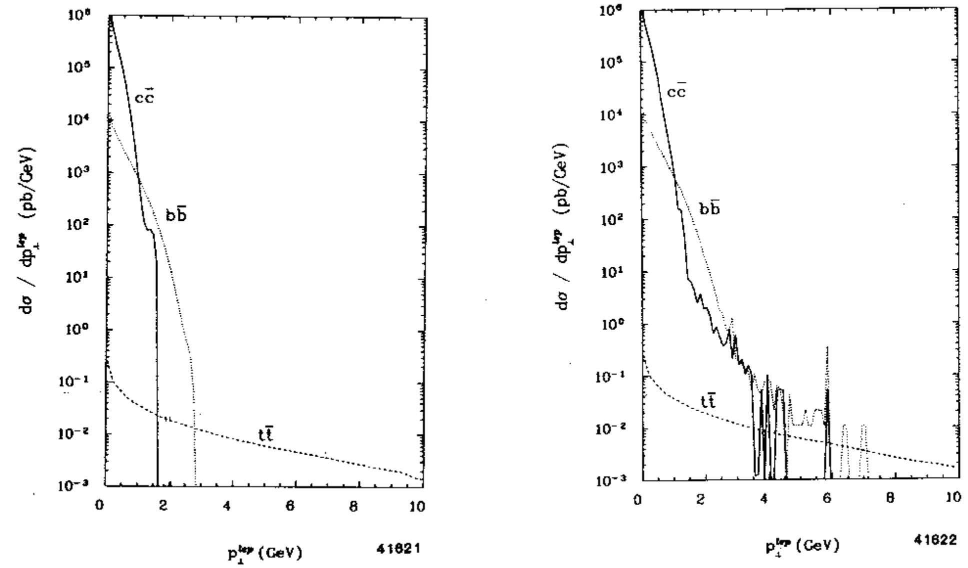

Fig. 5.4 Lepton p_T distribution in the process $ep \to lX$ from semileptonic decays of heavy quarks produced in $ep \to Q\bar{Q}X$. The p_T is measured w.r.t. the quark direction as reconstructed using the twoplicity method. a) no gluon radiation, b) right gluon radiation according to a parton shower

One has then to think of more sophisticated methods like the one discussed in [1] based on imposing a cut on the hadronic energy accompanying the trigger lepton. We estimate $O(10^4)$ bottom events which could be tagged this way per $100pb^{-1}$ integrated luminosity, see Fig. 5.5. This will yield a sizeable sample of bottom events which could be used to undertake more detailed studies like $B-\bar{B}$ oscillations.

6. Summary and Conclusions

We have discussed some aspects of heavy quark pair production at HERA. The cross-sections and relevant distributions were all based on perturbative QCD, including the BGF mechanism. Two extreme cases were considered i.e. with and without gluon radiation in the quark pair final state, the gluon radiation according to a parton shower formalism . Hadronisation and weak decays were taken into account in the LUND string picture. Beam pipe acceptance cuts were imposed but no other detector effects were taken into account.

After five years of running we expect $O(10^9)$, $O(10^7)$ and $O(10^2)$ charm, bottom and top quark jets (for $m_T = 60GeV$) be produced at HERA. A substantial fraction of these events will be measurable but an effort has to be done to

- keep the $\sum E_T$ trigger threshold to a minimum,
- make VXD detectors as long as possible so that they also cover a large fraction of the backward hemisphere,
- keep calorimeters as hermetic as possible and instrumented in 4π with powerful electron-hadron separators.

ZEUS has taken the neccesary steps to implement the points discussed above. Fig. 1.1 shows how the VXD has been enlarged, see dashed area, in the backward direction as a consequence of the results presented so far. This study also prompted the group to equip the rear calorimeter RCAL with silicon diodes for electron identification.

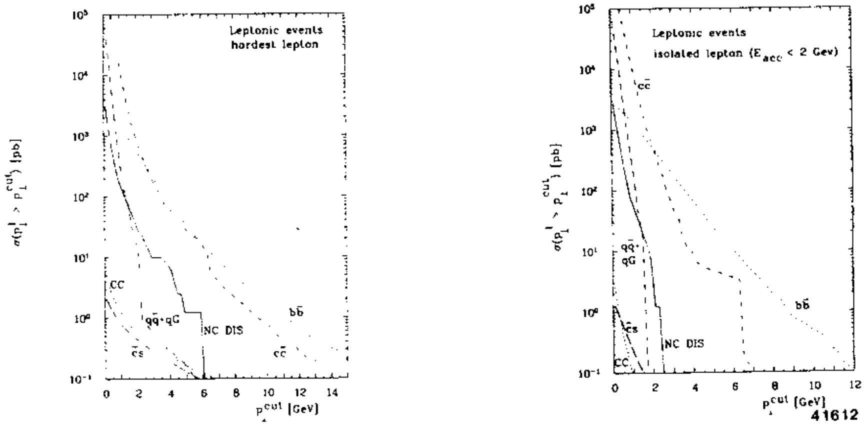

Fig. 5.5 a) integrated cross section for the process $ep \to (e,\nu_e)lX$ as a function of a cut on the p_T of the hardest lepton measured w.r.t. beam axis. Beam pipe cut is 100 $mrad$. b) same but for an isolated lepton defined as $E_{acc} \leq 2\ GeV$.

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