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Heavy flavour production at HERA

Simulation with a new Monte Carlo event generator

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Abstract. The production of heavy flavours at HERA has been investigated with a new Monte Carlo generator, which describes the heavy quark production in $e-p$ scattering via boson–gluon fusion. The program has been developed in the framework of the HERWIG Monte Carlo and, different from the existing generator AROMA from the Lund package, takes account of the initial state radiation associated with higher order QCD corrections. The $b\bar{b}$ production at HERA energies has been studied in the two different approaches. As expected, large differences for the particle and energy flows have been found.

1 Introduction

In $e-p$ collisions at HERA ($\sqrt{s}=314\,\text{GeV}$) the main source of heavy flavours will be the mechanism of boson–gluon fusion [1] (BGF). This process is given by the two diagrams of Fig. 1 in lowest order of perturbation theory. Explicit calculation of the matrix element in the order $\alpha^2\alpha_s$ has been already carried out [2], considering the masses of the heavy quarks and the full electroweak structure of the interaction.

To study the characteristics of complete events, i.e. at the hadron level, a Monte Carlo simulation program has been produced with the AROMA generator [3], which is based on the mentioned matrix element. In this program gluon radiation from the produced heavy quarks is approximately accounted for by a parton shower algorithm. The experimentally detectable stable particles are finally obtained by Lund string fragmentation of the partonic system, weak decays of the heavy-flavoured hadrons and strong or electromagnetic decays for the ordinary ones. Parton showers, string fragmentation and decays are carried out by the program JETSET [4].

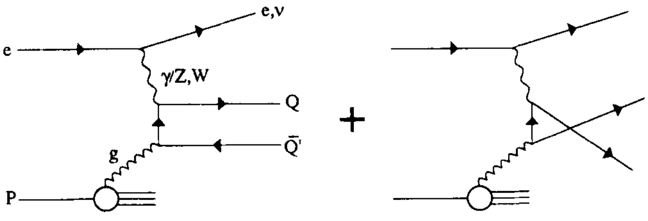

Fig. 1. Lowest order QCD diagrams for Boson–Gluon Fusion into a heavy quark–antiquark pair

However we believe that the AROMA model does not provide a completely satisfactory simulation of the heavy quark production at HERA. Even if the gluon density is correctly given by a parametrization evolved with Altarelli–Parisi equations, no radiation is supposed to be emitted by the proton during this evolution. Then AROMA lacks the so-called initial state radiation, which can modify the distributions of the emitted partons and of course of the observed hadrons too.

Nowadays however the Monte Carlo simulation of the QCD leading singularities has sufficiently advanced to provide a better understanding of the reactions with hadrons in the initial state.

We have developed a new Monte Carlo event generator for the heavy quark production via boson–gluon fusion in $e-p$ collisions. The program, named HARHEA [5], starts from the same matrix element (in order $\alpha^2\alpha_s$) implemented in AROMA. In HARHEA however coherent parton showers are generated for both the final partons, i.e. the produced heavy quark and antiquark, and for the initial gluon. The latter is submitted to a backward evolution. The initial value for the evolution variable of each shower is correctly evaluated to consider the interference of the soft gluonic radiation.

All the event simulation starting from the parton showers development is carried out by the program HERWIG [6]. There, the weak decays of heavy quarks are dealt with as hard subprocesses with the possibility of gluon radiation (and consequently new parton showers) for the decayed quark. The hadronization is performed by the Webber cluster model [7].

The structure of the paper is as follows. Section 2 reports on the details that led us to the new model. In Sects. 3 and 4 results of the comparison between the predictions of HARHEA and AROMA are presented. Beauty production at HERA through neutral current processes has been analyzed at the parton as well as at the stable particle level. Finally the conclusions are drawn in Sect. 5.

2 Rationale for a new Monte Carlo

The AROMA model does not include any emission of radiation from the initial proton. Only the system of produced heavy quark and antiquark can give rise to gluon radiation. This takes place through the same parton shower algorithm which is adopted by the Lund Monte Carlo for e^+e^- annihilation into hadrons. The gluon which enters the fusion process is simply extracted from the proton at an energy scale of the order of the invariant mass of the heavy quark system $\sqrt{\hat{s}}$. The extraction is performed following the gluon density $G(x, \hat{s})$ as obtained from the evolution via the Altarelli–Parisi equations. Then the initial state is described by the gluon (with zero mass) moving along the proton beam direction and by proton remnant which constitutes the spectator system. No resolvable radiation is supposed to come out of the proton. This picture shows clearly an asymmetry in the treatment of the incoming and the outgoing partons of the fusion reaction.

In principle both the outgoing heavy quarks and the initial gluon can be off mass shell due to the contribution of higher order QCD radiative corrections. In particular the gluon can have negative virtuality up to the order of $\hat{s}$. With regard to the gluon radiation of the heavy quarks, their masses reduce in a substantial way the phase space for gluon emission [8] and consequently the corresponding contribution is not really important at HERA energies. Thus, for the simulation of the leading QCD contributions by coherent parton shower algorithms, the initial state radiation plays a much more important role than the radiation from the heavy quark pair in the process under study.

There is another argument for improving the AROMA model. It comes again from QCD predictions and concerns the initial conditions for the development of parton showers from the heavy quarks. In AROMA these conditions are determined in the same way as for the $q-\bar{q}$ jets from an e^+e^- annihilation. However, different from the case of e^+e^-, the $Q\bar{Q}$ pair is not a colour singlet since colour flows from the initial gluon. The colour structure of the fusion diagram is given simply by Fig. 2a, which represents the process in the $Q\bar{Q}$ rest frame. This structure is correct in the planar approximation, i.e. to leading order in the inverse of the number of colours N_c, while contributions from nonplanar colour structures are also strongly suppressed dynamically [6]. As it is known the application of a parton shower algorithm, describing coherence of the soft gluon emissions through angular ordering, needs to fix the initial value of the evolution variable, typically a maximum angle. Such an angle is set in HERWIG to be that between the parton to evolve and its colour-connected partner. Referring to Fig. 2a the partner for both the quark and the antiquark is the initial gluon. Then for example the quark jet will evolve within the cone given by the angle θ between the quark and the gluon. Turning back to AROMA, this restriction is not present since the $Q\bar{Q}$ pair is supposed to be produced as in an e^+e^- annihilation, where the corresponding angle θ' of Fig. 2b is equal to 180°.

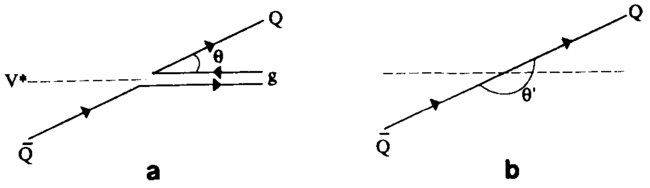

Fig. 2 a, b. Colour structure for the production of an heavy quark–antiquark pair: **a** via Boson–Gluon Fusion; **b** via e^+e^- annihilation

The initial conditions for jet evolution take into account the interference of the soft gluon emissions from different jets, in our case the interference between initial and final states, which is disregarded by AROMA.

In HERWIG the amount of partons radiated in the evolution of the initial state is proportional to the energy scale of the reaction, i.e. for BGF the invariant mass of the heavy quark pair. More precisely the backward evolution starts from an energy scale which depends also on the colour structure of the hard subprocess and goes down to a cut-off scale of few GeV. When the cut-off is reached, the parton shower stops and the remaining spacelike parton is linked to the proton with the spectator system, such that flavour, colour and fourmomentum are conserved.

Among the processes involving heavy flavours, the top quark production is the one most affected by the initial state radiation, due to the high mass of top. However we did not analyze top events, because of their small cross section at HERA. Beauty and charm quarks will be instead largely produced in neutral current reactions as $b\bar{b}$ and $c\bar{c}$ pairs respectively. The largest disagreements between AROMA and HARHEA, at HERA energies, are thus expected for beauty production.

The energy scale for charm events is so low that no substantial backward evolution takes place. Thus the differences which can arise between the programs for charm production are mainly due to minor aspects of the Monte Carlo implementations. Looking for example at the combination of the initial state cascade with the spectators [6], the present version of HERWIG produces an overestimate of the total transverse energy. Furthermore, other differences are present due to the details of the parton shower algorithms, the hadronization models and the input parameters. A reliable solution is possible only by tuning the parameters using the experimental data. At present we have not further investigated this point.

In any case clear results have been obtained, showing that the beauty production at HERA is strongly influenced by initial state radiation; these results are rather stable by varying the HERWIG parameters in reasonable ranges. In particular, variations of the default values in HERWIG of Λ_{QCD} and Q_0, the infrared cut-off on the timelike radiation, have shown deviations of the results less than 10%. On the contrary the Q_s parameter plays a more important role, leading to strong deviations, in particular when it is decreased. However, since Q_s controls the stop of the backward evolution and the energy scale where structure functions of the proton are finally computed, it can not be too small because structure functions are not very well known at lower energies. Again, it should be stressed that it is a matter of a unique tuning that will be necessary for the behaviour of HERWIG with respect to DIS processes.

In the next sections we will describe beauty production only.

3 Parton level results for b production

Let us consider beauty production at HERA ($\sqrt{s}=$ 31·4 GeV) through the neutral current reaction of BGF: $e^- g \to e^- b\bar{b}$.

At the lowest order the differential cross section with respect to the usual DIS variables, the squared momentum transfer Q^2 and the Bjorken-x, is peaked in the region of very small Q^2 and very small x.

Due to the small Q^2 the exchanged boson is dominantly an almost real photon, so the process is often referred to as photoproduction. From an experimental point of view this implies that the scattered electron is generally lost in the beam pipe.

The dominance of the small-x region implies that most of the proton energy does not take part in the hard subprocess but remains attached to the proton remnant. The hadrons from its fragmentation have low transverse momenta and they mostly go into the beam pipe too. In this situation the produced heavy quarks are almost back-to-back in the plane transverse to the beams, and all the energy detected in the calorimeter belongs to the $b\bar{b}$ system.

Let us now consider the corrections to the BGF process due to the higher orders of perturbative QCD. The parton shower approach is a convenient way to approximately evaluate such corrections to all orders by means of Monte Carlo simulation.

The AROMA program, as already said, includes the gluon emission from the heavy quarks through a shower algorithm. However this effect, as we show below, is quite unimportant leaving the final states roughly unchanged, and by consequence AROMA does not modify significantly the lowest order results. The inclusion of initial state radiation through the backward evolution of the incoming gluon, as it is carried out by the program HARHEA, shows instead many important differences from the lowest order results.

We consider first the parton level, i.e. all the outgoing partons (including the scattered electron and the spectator system coming from the proton). The main result is that, as a consequence of the initial radiation, the gluon entering the fusion process can acquire a non negligible transverse momentum p_t. This p_t recoils against the partons emitted in the initial state cascade, which properly constitute the initial radiation. Furthermore this p_t must be conserved in the final state and it is then transferred to the heavy flavour jets and possibly to the scattered electron (see Fig. 3a, b). The gluon makes an angle with respect to the proton beam axis and the whole hard subprocess is "rotated" by this additional p_t, which in average is found to be about 4 GeV/c for $b\bar{b}$ production at HERA. Then, an overall increase in the total transverse energy of all the outgoing partons, written as $\sum_i E_{T_i}$, is expected.

In Fig. 4 the results on $\sum_i E_{T_i}$ of the two programs are compared. The obtained mean values are reported in Table 1 together with the corresponding values before the parton shower development. It is noticeable that the application of the parton shower in AROMA (only on the $b\bar{b}$ system) modifies very little the averaged $\sum_i E_{T_i}$, while in HARHEA a large increase is obtained. In Fig. 5 the transverse energy flow is plotted versus the polar angle θ, conventionally chosen with respect to the electron beam axis. Considering the energies of the colliding beams of HERA (electrons: 30 GeV; protons: 820 GeV) we shall however call "forward" and "rear" respectively the angular regions near $\theta = 180°$ and $\theta = 0°$.

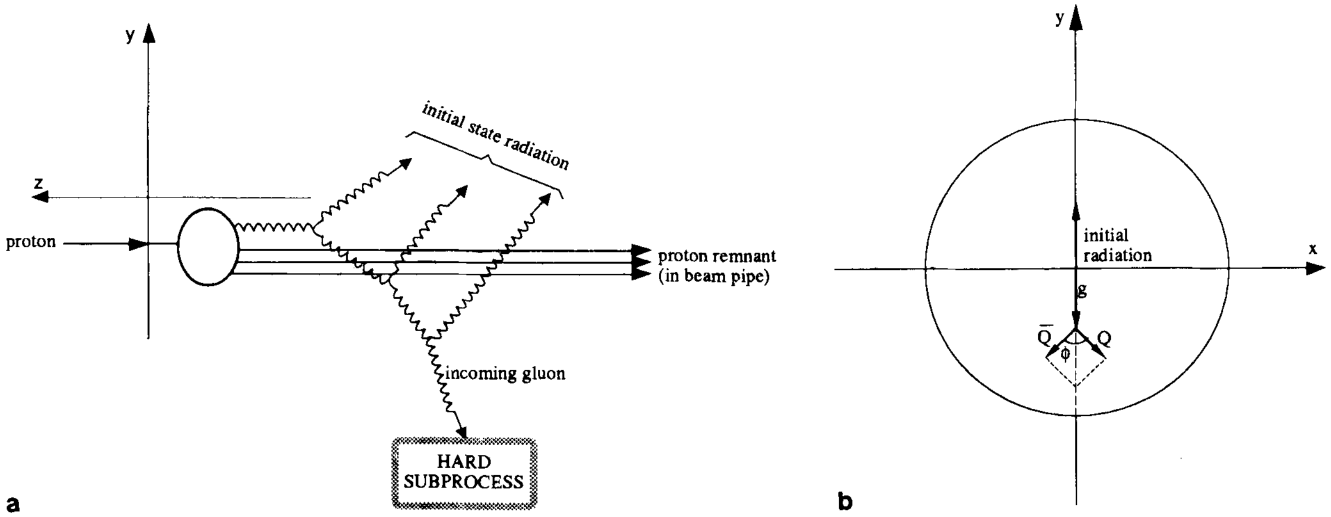

Fig. 3a, b. Parton shower from the initial state of the BGF reaction: **a** scheme in a longitudinal plane containing the beams; **b** momentum conservation in the transverse plane, assuming the scattered lepton with $p_t = 0$

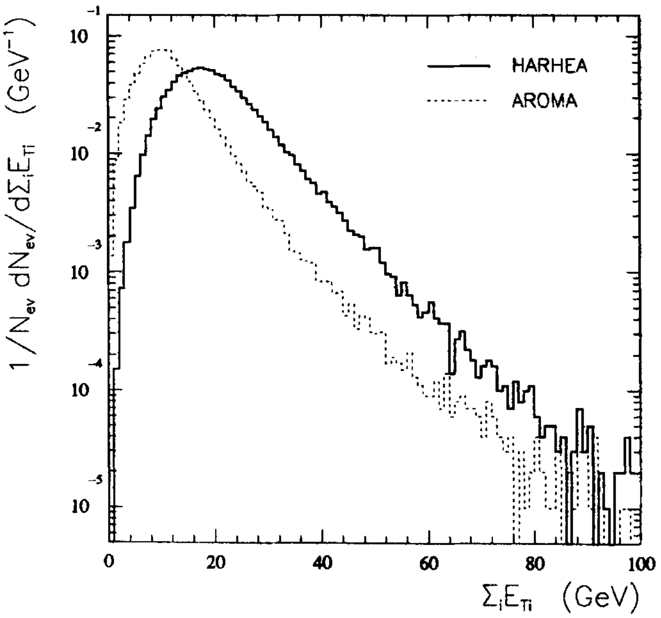

Fig. 4. Distribution of the total transverse energy at the parton level (full line HARHEA, dotted line AROMA)

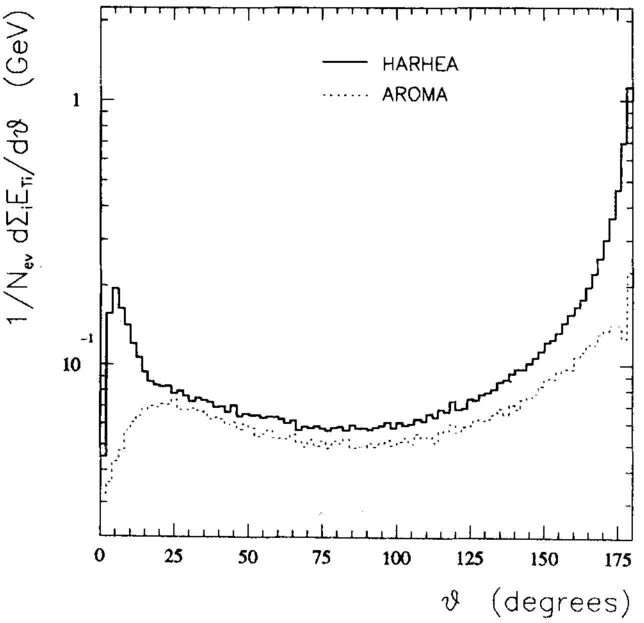

Fig. 5. Flow of the transverse energy in the polar angle θ with respect to the electron beam direction, at the parton level (full line HARHEA, dotted line AROMA)

As one can see the additional energy in HARHEA is mainly concentrated in the forward region, but an increase in the central and rear regions is also present. There are two contributions both related to the initial state radiation. One is the energy of the initial radiation from the gluon; it affects mainly the angular region near the proton beam direction and properly makes visible an amount of energy that otherwise remained undetected in the beam pipe. The second contribution is due to the transfer of the gluon p_t to the final system (heavy quarks plus scattered electron) and it is responsible for the increase of energy in the central and rear regions with respect to the proton axis.

Table 1. Mean values of relevant quantities obtained with the two programs at the parton level: total transverse energy of all the outgoing partons; including the scattered electron $\left(\sum_i E_{T_i}\right)$; azimuthal angle between the heavy quark jets (ϕ); virtual mass of the heavy quark jets (m^*_{hf}). (P.S. stands for parton showers)

		HARHEA	AROMA
$\left\langle \sum_i E_{T_i} \right\rangle$ (GeV)	before P.S.	12.0	12.0
	after P.S.	20.7	12.4
$\langle \phi \rangle$ (degrees)	before P.S.	172.0	168.0
	after P.S.	144.0	167.0
$\langle m^*_{hf} \rangle$ (GeV/c^2)		5.5	5.7

Another important effect of the gluon p_t is evident in the transverse plane, where the two jets of the heavy quarks can be far from the back-to-back configuration (see also Fig. 3b). This can be seen from the distributions of the azimuthal angle ϕ between the jets (Fig. 6) or the corresponding mean values before and after the parton showers (Table 1).

Even if the invariant mass of the $b\bar{b}$ system is not fixed, previous studies [9] assumed that the event analysis in the transverse plane should not be very different from that of two jets events in e^+e^- annihilations. This similarity simplifies the reconstruction and allows the use of well-established algorithms. However with the new insight provided by HARHEA this approach should probably be revised.

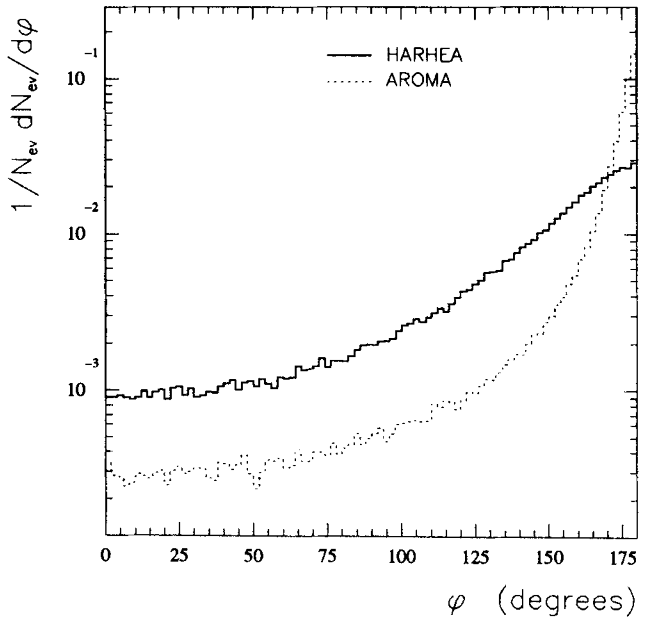

Fig. 6. Distribution of the azimuthal angle between the axis of the produced heavy quark jets, at the parton level (full line HARHEA, dotted line AROMA)

Table 1 also reports the mean values of the virtual mass of the heavy flavour jets, $\langle m^*_{hf} \rangle$, after the parton shower evolution. The mean value for AROMA events is 0.2 GeV greater than for HARHEA events. This agrees with what has been said in Sect. 2. The jets of the heavy quarks are thus more active in AROMA, resulting in more gluon emission than what is presumably the case.

4 Hadron level results for *b* production

We consider here some distributions of "stable" particles, i.e. the particles obtained after hadronization and decays, including $e^\pm, \gamma, \mu^\pm, \pi^\pm, K^\pm, K^0_L, p(\bar{p}), n(\bar{n})$. Neutrinos are discarded since they are not detected in a measurement. At this level the hadronization models employed by the two programs play an important role (AROMA uses the Lund string model, while HARHEA the Webber cluster model). However the differences that arose in the previous section continue to be present.

Figure 7 shows the distributions of the charged multiplicity, with a cut in acceptance of 100 mrad around the beam axis. $\langle n_{\mathrm{ch}} \rangle$ is 14 for AROMA events and 20 for HARHEA ones. The same charged particles which pass the cut have a spectrum in transverse momentum (p_t) slightly softer for HARHEA than for AROMA.

Next we deal with an ideal calorimetric measurement, summing the energies of all the stable particles within the ZEUS [10] calorimeter acceptance: $3.5° < \theta < 177.8°$ with respect to the electron beam direction. Considering the total visible energy, $\sum_i E_i$, and the total transverse energy, $\sum_i E_{T_i}$, and using as angular variable the pseudorapidity[1]

$$\eta = \frac{1}{2} \ln \frac{p + p_z}{p - p_z} = \frac{1}{2} \ln \frac{1 + \cos\theta}{1 - \cos\theta},$$

the distributions of Figs. 8 to 11 are obtained. Figures 8 and 9 refer to $\sum_i E_i$, which in average is quite higher for HARHEA events (the mean value is about 100 GeV compared to 60 GeV for the AROMA events). Figures 10 and 11 refer to $\sum_i E_{T_i}$, which also shows an averaged large increase (from 15 GeV to 22 GeV, a 40% increase). The additional energy is distributed mainly in the forward region ($\eta \leqq -1$) but also the central ($-1 \leqq \eta \leqq 1$) and

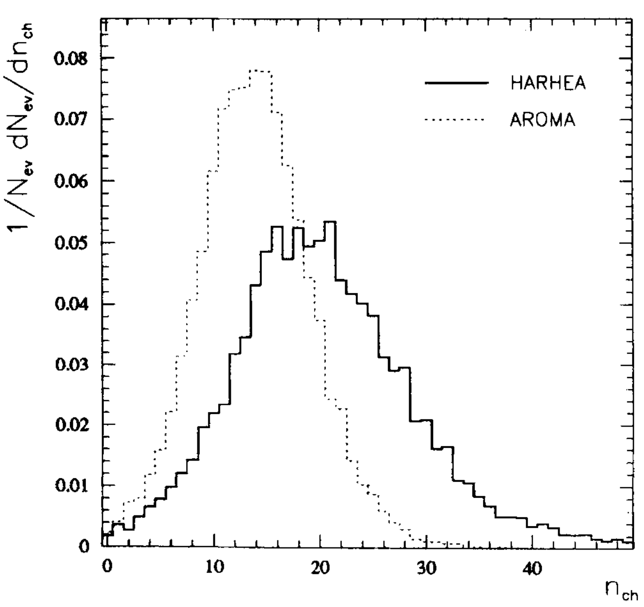

Fig. 7. Distribution of the charged multiplicity, with an acceptance cut of 100 mrad around the beam axis (full line HARHEA, dotted line AROMA)

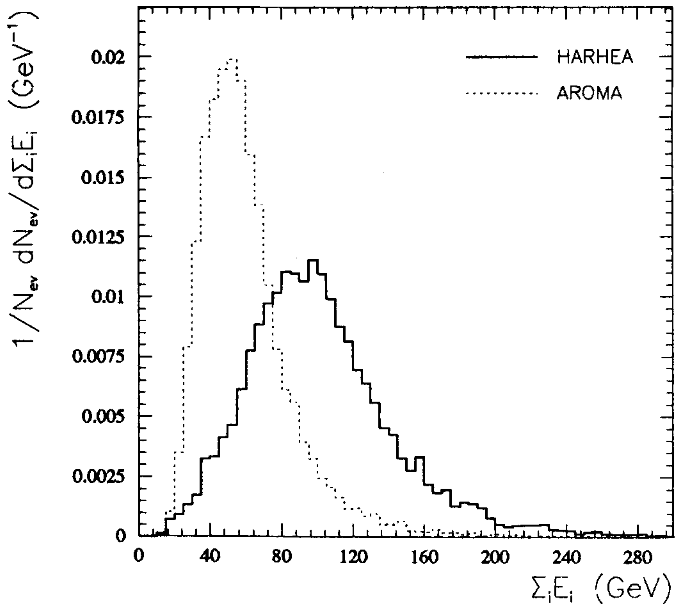

Fig. 8. Distribution of the total visible energy, obtained by an acceptance cut corresponding to the angular covering of the ZEUS calorimeter, $3.5° < \theta < 177.8°$ with respect to the electron beam direction (full line HARHEA, dotted line AROMA)

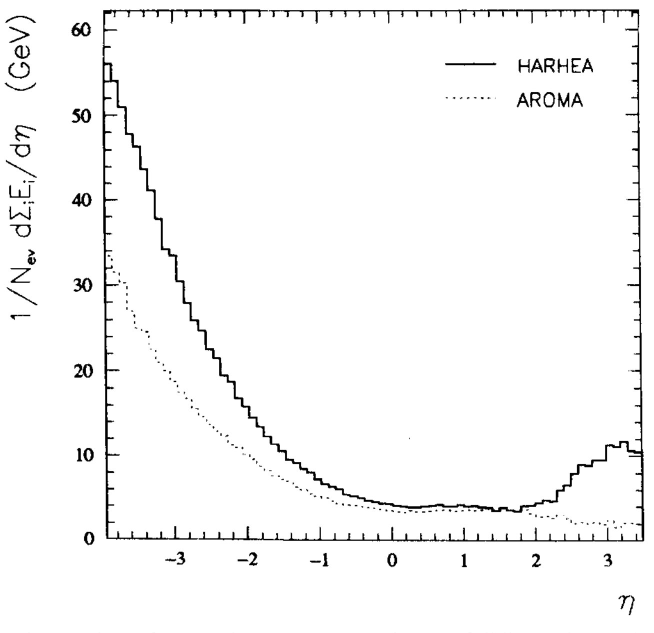

Fig. 9. Flow of energy in the pseudorapidity η (full line HARHEA, dotted line AROMA)

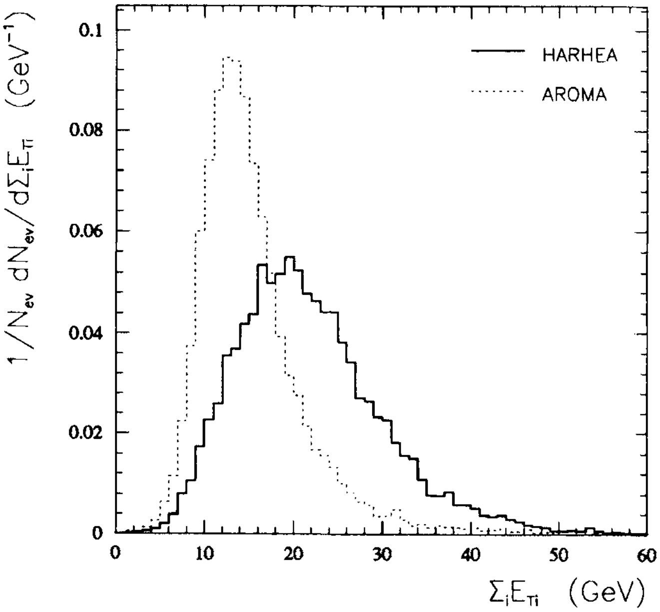

Fig. 10. Distribution of the total transverse energy after the same cut of Fig. 8 (full line HARHEA, dotted line AROMA)

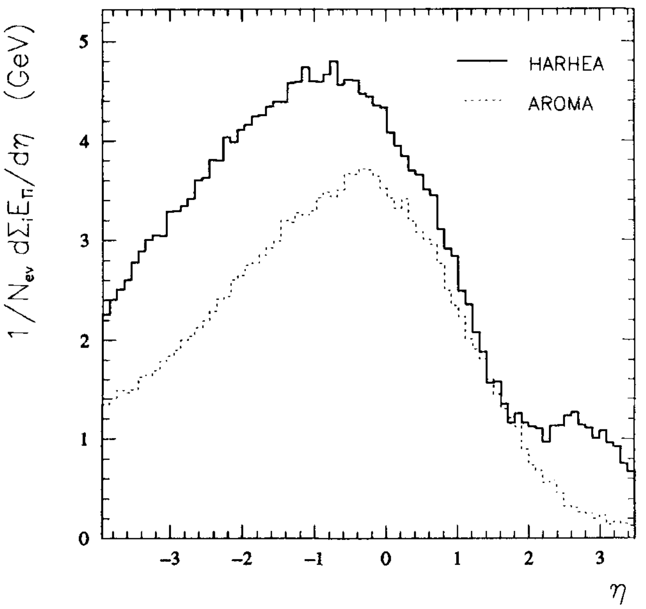

Fig. 11. Flow of the transverse energy in the pseudorapidity η (full line HARHEA, dotted line AROMA)

rear ($\eta \geq 1$) regions receive contributions. These large observable energies could be useful for trigger purpose. Finally the distributions of the number of jets, N_{jet}, are shown in Fig. 12. To define a jet we have used a cluster algorithm based on the LUCLUS routine, from the Lund package, assuming a joining parameter $d_j = 7\,\text{GeV/c}^2$ from previous studies [11].

The mean values of $n_{\text{ch}}, p_t, \sum_i E_i, \sum_i E_{T_i}$ and N_{jet}, with the above specified cuts, are summarized in Table 2.

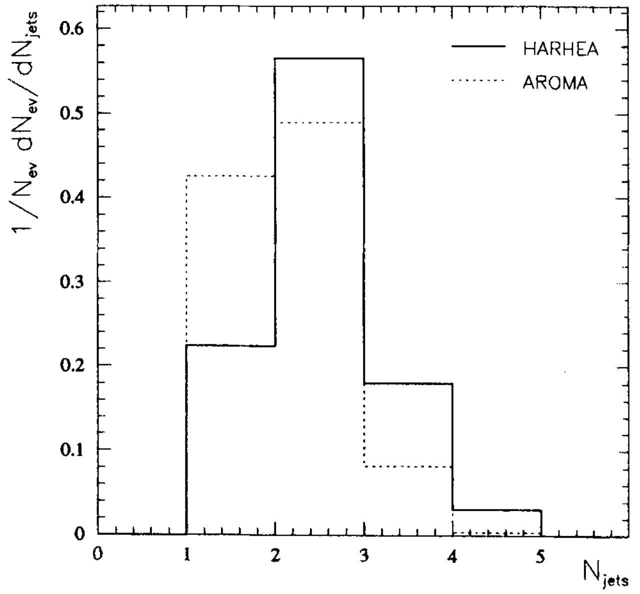

Fig. 12. Distribution of the number of jets, reconstructed by a cluster algorithm (full line HARHEA, dotted line AROMA)

Table 2. Mean values of relevant quantities obtained with the two programs at the hadron level: charged multiplicity (n_{ch}) and transverse momentum of the charged particles (p_t), with a cut in acceptance of 100 mrad around the beam axis; total visible energy $\left(\sum_i E_i\right)$, total transverse energy $\left(\sum_i E_{T_i}\right)$ and number of jets (N_{jet}), obtained summing the energies of all the stable particles within the ZEUS calorimeter acceptance

	HARHEA	AROMA
$\langle n_{\text{ch}} \rangle$	20.4	13.9
$\langle p_t \rangle$ (GeV/c)	0.59	0.64
$\left\langle \sum_i E_i \right\rangle$ (GeV)	102.0	60.0
$\left\langle \sum_i E_{T_i} \right\rangle$ (GeV)	22.0	15.4
$\langle N_{\text{jet}} \rangle$	2.02	1.66

5 Conclusions

A new Monte Carlo event generator has been built for the heavy flavour production via boson–gluon fusion in electron–proton scattering. It treats correctly the colour structure of the hard subprocess and carries out parton cascades from both the produced heavy quarks and the initial gluon (the latter through backward evolution). All the event simulation starting from the parton showers is performed with the HERWIG Monte Carlo.

The importance of the initial state radiation is clearly shown for $b\bar{b}$ production at HERA energies. The fusing gluon can achieve a considerable p_t after the application of the parton cascade algorithm.

Comparison with the previous generator AROMA (from the Lund package), which disregards the initial state radiation, demonstrates large differences. Particularly, the mean charged multiplicity is expected to grow by 50% and the total transverse energy by 40%. These differences slightly depend on the models and the input parameters; their precise amount has to be fixed by further study and comparisons with the experimental data. Nevertheless the obtained results will be important for an event trigger at HERA.

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