Feb 2014

The CCFM Monte Carlo generator CASCADE Version 3.0.01-beta01

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Abstract

CASCADE is a full hadron level Monte Carlo event generator for ep, γp and $p\bar{p}$ and pp processes, which uses the CCFM evolution equation for the initial state cascade in a backward evolution approach supplemented with off - shell matrix elements for the hard scattering. A detailed program description is given, with emphasis on parameters the user wants to change and common block variables which completely specify the generated events.

PROGRAM SUMMARY

Title of Program: CASCADE 3.0.01-beta01

Computer for which the program is designed and others on which it is operable: any with standard Fortran 77 (g77 or gfortran), tested on SGI, HP-UX, SUN, PC, MAC

Programming Language used: FORTRAN 77

High-speed storage required: No

Separate documentation available: No

Keywords: QCD, small x, k_t- factorisation, CCFM, parton showers, leptoproduction, photoproduction, pp- and $p\bar{p}$-scattering, heavy quark production, unintegrated PDFs.

Nature of physical problem: High-energy collisions of particles at moderate values of the fractional momentum x are well described by resummation of leading logarithms of transverse

momenta $(\alpha_s \ln Q^2)^n$, generally referred to as DGLAP physics. At small x leading-logs of longitudinal momenta, $(\alpha_s \ln x)^n$, are expected to become equally if not more important (BFKL). An appropriate description valid for both small and moderate x is given by the CCFM evolution equation, resulting in an unintegrated gluon density $\mathcal{A}(x, k_t, \bar{q})$, which is also a function of the evolution scale $\bar{q}$.

Method of solution: Since measurements involve complex cuts and multi-particle final states, the ideal tool for any theoretical description of the data is a Monte Carlo event generator which embodies small-x resummation, in analogy to event generators which use DGLAP resummation. The CCFM evolution equation forms a bridge between the DGLAP and BFKL resummation and can be applied to generate the initial state branching processes. The CCFM equation can be formulated in a way suitable for carrying out a backward evolution, which is an essential requirement to efficiently generate unweighted Monte Carlo events.

Restrictions on the complexity of the problem: The following hard subprocesses can be simulated:
$\gamma^* g^* \to q\bar{q}(Q\bar{Q})$,
$\gamma g^* \to J/\psi g$,
$g^* g^* \to q\bar{q}(Q\bar{Q})$,
$g^* g^* \to J/\psi g$,
$g^* g^* \to \chi$,
$g^* g \to gg$,
$g^* q \to gq$,
$g^* g^* \to h^0$,
$g^* q \to Z(W)q$,
$g^* g^* \to ZQ\bar{Q}$, $g^* g^* \to Zq\bar{q}$,
$g^* g^* \to Wq_i q_j$,
$g^* g^* \to J/\psi J/\psi$

The present version is applicable for HERA, TEVATRON and LHC processes.

Other Program used: PYTHIA (*version* > 6.4) for hadronisation, BASES/SPRING 5.1 for integration (supplied with the program package).

Download of the program: `http://www.desy.de/~jung/cascade`

Unusual features of the program: None

1 The CCFM evolution equation

The formulation of the CCFM [1–4] parton evolution for the implementation into a full hadron level Monte Carlo program is described in detail in [5, 6]. Here only the main results are summarized and discussed. The pattern of QCD initial state radiation in a small-x

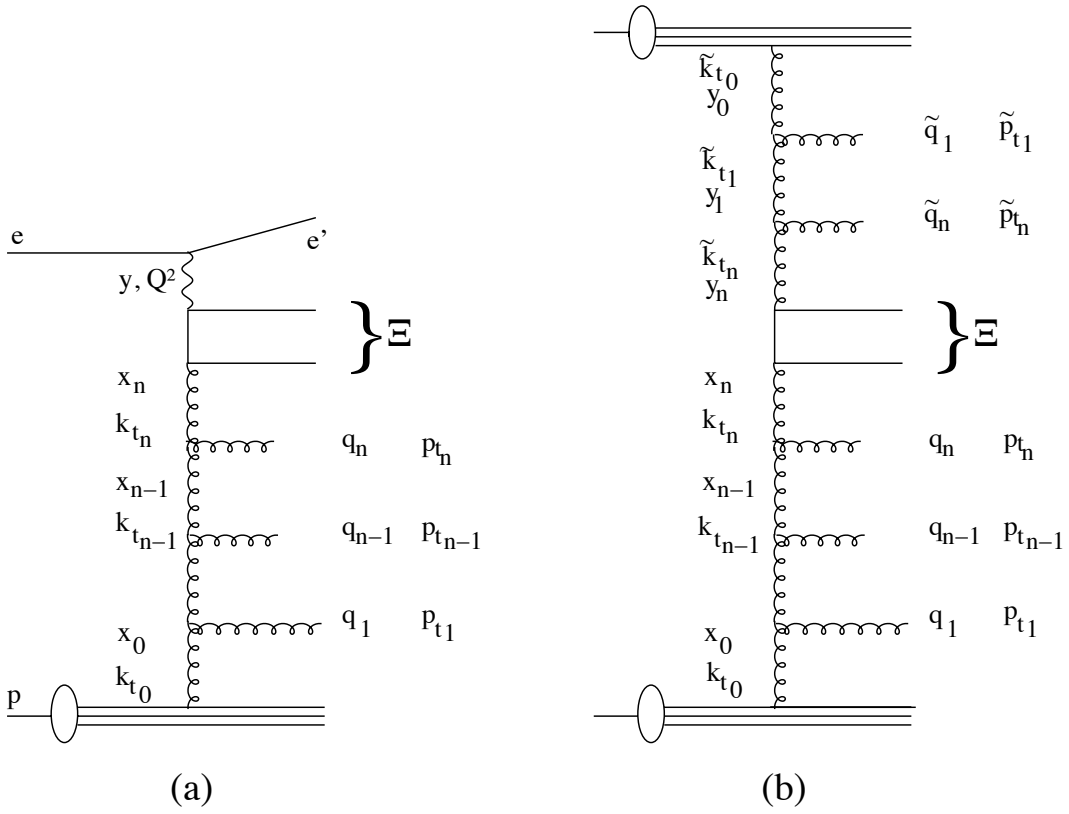

Figure 1: *Kinematic variables for multi-gluon emission in leptoproduction (a) and hadroproduction (b). The t-channel gluon four-vectors are given by k_n and the gluons emitted in the initial state cascade have four-vectors p_n. The maximum angle (a function of the rapidity) for any emission is obtained from the quark box, as indicated with* Ξ.

event in ep and $p\bar{p}$(pp) collisions is illustrated in Fig. 1 together with labels for the kinematics. According to the CCFM evolution equation, the emission of partons during the initial cascade is only allowed in an angular ordered region of phase space. In terms of Sudakov variables Υ and Ξ the quark pair momentum is written as:

$$p_q + p_{\bar{q}} = \Upsilon(p^{(1)} + \Xi p^{(2)}) + Q_t \ , \tag{1}$$

where $p^{(1)}$ and $p^{(2)}$ are the four-vectors of incoming particles (electron-proton, proton-antiproton or proton-proton), respectively and Q_t is the transverse momentum of the quark pair in the

center of mass frame of $p^{(1)}$ and $p^{(2)}$ (cms). The variable Ξ is related to the rapidity Y in the center of mass (CMS) frame via

$$Y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\log\left(\frac{1}{\Xi}\right). \tag{2}$$

Using $E = E_q + E_{\bar{q}}$ and $p_z = p_{q\,z} + p_{\bar{q}\,z}$ gives $E + p_z = \Upsilon\sqrt{s}$, $E - p_z = \Upsilon\Xi\sqrt{s}$ with $E = \sqrt{s}/2$ and $s = (p^{(1)} + p^{(2)})^2$ being the squared center of mass energy. Therefore Ξ can be used to define the maximum allowed angle in the evolution. The momenta p_i of the gluons emitted during the initial state cascade are given by (here treated massless):

$$p_i = \upsilon_i(p^{(1)} + \xi_i p^{(2)}) + p_{ti}\ , \quad \xi_i = \frac{p_{ti}^2}{s\upsilon_i^2}, \tag{3}$$

with $\upsilon_i = (1 - z_i)x_{i-1}$ and $x_i = z_i x_{i-1}$. The variables x_i and υ_i are the momentum fractions of the exchanged and emitted gluons, while z_i is the momentum fraction in the branching $(i-1) \to i$ and p_{ti} is the transverse momentum of the emitted gluon i. Again the rapidities y_i are given by $y_i = -0.5\log\xi_i$ in the CMS frame.

The angular ordered region is then specified by (Fig. 1a and the lower part of the cascade in Fig. 1b, for the upper part the variables have to be changed accordingly):

$$\xi_0 < \xi_1 < \cdots < \xi_n < \Xi, \tag{4}$$

which becomes:

$$z_{i-1}q_{i-1} < q_i, \tag{5}$$

where the rescaled transverse momentum q_i of the emitted gluon is defined by:

$$q_i = x_{i-1}\sqrt{s\xi_i} = \frac{p_{ti}}{1 - z_i}. \tag{6}$$

The scale $\bar{q}$ (related to the maximum angle) can be written as:

$$\bar{q}^2 = \Upsilon^2\Xi s = \hat{s} + Q_t^2, \tag{7}$$

with $\hat{s} = (p_q + p_{\bar{q}})^2$ and the relation of $\bar{q}$ to a particular choice of the factorisation scale μ_f in the collinear approach becomes obvious.

The CCFM evolution equation can be written in a differential form [4], which is best suited for a backward evolution approach adopted in the Monte Carlo generator CASCADE [5,6]:

$$\bar{q}^2\frac{d}{d\bar{q}^2}\frac{x\mathcal{A}(x,k_t,\bar{q})}{\Delta_s(\bar{q},Q_0)} = \int dz\frac{d\phi}{2\pi}\frac{\tilde{P}(z,\bar{q}/z,k_t)}{\Delta_s(\bar{q},Q_0)}\,x'\mathcal{A}(x',k_t',\bar{q}/z), \tag{8}$$

where $\mathcal{A}(x,k_t,\bar{q})$ is the unintegrated gluon density, depending on x, k_t and the evolution variable $\bar{q}$. The splitting variable is $z = x/x'$ and $\vec{k_t}' = (1-z)/z\vec{q} + \vec{k_t}$, where the vector $\vec{q}$ is at an azimuthal angle ϕ. The Sudakov form factor Δ_s is given by:

$$\Delta_s(\bar{q},Q_0) = \exp\left(-\int_{Q_0^2}^{\bar{q}^2}\frac{dq^2}{q^2}\int_0^{1-Q_0/q}dz\frac{\bar{\alpha}_s(q^2(1-z)^2)}{1-z}\right), \tag{9}$$

with $\bar{\alpha}_s = \frac{C_A \alpha_s}{\pi} = \frac{3\alpha_s}{\pi}$. For inclusive quantities at leading-logarithmic order the Sudakov form factor cancels against the $1/(1-z)$ collinear singularity of the splitting function.

The original splitting function $\tilde{P}_g(z_i, q_i, k_{ti})$ for branching i is given by (neglecting finite terms as they are not obtained in CCFM at the leading infrared accuracy (cf p. 72 in [3]):

$$\tilde{P}_g(z_i, q_i, k_{ti}) = \frac{\bar{\alpha}_s(q_i^2(1-z_i)^2)}{1-z_i} + \frac{\bar{\alpha}_s(k_{ti}^2)}{z_i}\Delta_{ns}(z_i, q_i^2, k_{ti}^2), \tag{10}$$

where the non-Sudakov form factor Δ_{ns} is defined as:

$$\log \Delta_{ns} = -\bar{\alpha}_s(k_{ti}^2) \int_0^1 \frac{dz'}{z'} \int \frac{dq^2}{q^2} \Theta(k_{ti} - q)\Theta(q - z'q_{ti}). \tag{11}$$

The implementation of the full splitting function including non singular terms can lead to inconsistencies. Replacing naively only $\frac{1}{1-z} \to \frac{1}{1-z} - 2 + z(1-z)$ in the CCFM splitting function can lead to negative branching probabilities.

In [7] it was suggested to use:

$$\begin{aligned} P(z,q,k) &= \bar{\alpha}_{\rm s}\left(k_t^2\right)\left(\frac{(1-z)}{z} + (1-B)z(1-z)\right)\Delta_{ns}(z,q,k) \\ &\quad + \bar{\alpha}_{\rm s}\left((1-z)^2 q^2\right)\left(\frac{z}{1-z} + Bz(1-z)\right), \end{aligned} \tag{12}$$

where B is a parameter to be chosen arbitrarily between 0 and 1, we take $B = 0.5$. As a consequence of the replacement, the Sudakov form factor will change, but also the non-Sudakov form factor needs to be replaced by:

$$\log \Delta_{ns} = -\bar{\alpha}_s\left(k_t^2\right) \int_0^1 dz' \left(\frac{1-z}{z'} + (1-B)z(1-z)\right) \int \frac{dq'^2}{q'^2} \Theta(k - q')\Theta(q' - z'q). \tag{13}$$

2 Backward evolution: CCFM and CASCADE

The idea of a backward evolution [8,9] is to first generate the hard scattering process with the initial parton momenta distributed according to the parton distribution functions. This involves in general only a fixed number of degrees of freedom, and the hard scattering process can be generated quite efficiently. The initial state cascade is generated by going backwards from the hard scattering process towards the beam particles.

According to the CCFM equation the probability of finding a gluon in the proton depends on three variables, the momentum fraction x, the transverse momentum squared k_t^2 of the exchanged gluons and the scale $\bar{q} = x_n\sqrt{s\Xi}$, which is related to the maximum angle Ξ allowed for any emission. To solve eq.(8) the unintegrated parton distribution $\mathcal{A}(x, k_t, \bar{q})$ has to be determined beforehand.

Given $\mathcal{A}(x, k_t, \bar{q})$, the generation of a full hadronic event is separated into three steps, as implemented in the hadron level Monte Carlo program CASCADE:

- The hard scattering process is generated,

$$\sigma = \int dk_{t1}^2 dk_{t2}^2 dx_1 dx_2 \mathcal{A}(x_1, k_{t1}, \bar{q}) \mathcal{A}(x_2, k_{t2}, \bar{q}) \hat{\sigma}(k_1 + k_2 \to X) \,, \tag{14}$$

  with $k_1(k_2)$ being the momenta of the incoming partons to the subprocess $k_1 + k_2 \to X$ with X being the final state. The definition of $\hat{\sigma}$ follows [10]. The available processes are shown in Tab 2. The momenta of the incoming partons are given in Sudakov representation:

$$k_1 = x_1 p^{(1)} + \bar{x}_2 p^{(2)} + k_t \simeq x_1 \, p^{(1)} + k_{t1}$$
$$k_2 = \bar{x}_1 p^{(1)} + x_2 p^{(2)} + k_t \simeq x_2 \, p^{(2)} + k_{t2}$$

  where the last expression comes from the high energy approximation ($x_{1,\,2} \ll 1$), which then gives $-k^2 \simeq k_t^2$.

- The initial state cascade is generated according to CCFM in a backward evolution approach.

- The hadronisation is performed using the Lund string fragmentation implemented in PYTHIA /JETSET [11].

The parton virtuality enters the hard scattering process and also influences the kinematics of the produced particles (Z_0, W, Higgs and quarks) and therefore the maximum angle allowed for any further emission in the initial state cascade. This virtuality is only known after the whole cascade has been generated, since it depends on the history of the parton evolution (as $\bar{x}$ in eq.(15) may not be neglected for exact kinematics). In the evolution equations itself it does not enter, since there only the longitudinal energy fractions z and the transverse momenta are involved. This problem can only approximately be overcome by using $k^2 = k_t^2/(1-x)$ for the virtuality which is correct in the case of no further parton emission in the initial state.

The Monte Carlo program CASCADE can be used to generate unweighted full hadron level events, including initial state parton evolution according to the CCFM equation and the off-shell matrix elements for the hard scattering process. It is applicable for $p\bar{p}$, pp, photoproduction as well as for deep inelastic scattering. A discussion of the phenomenological applications of CASCADE can be found in [12].

The typical time needed to generate one event is similar to the time needed by standard Monte Carlo event generators like PYTHIA [11].

2.1 The unintegrated parton density

The CCFM unintegrated parton density $x\mathcal{A}(x, k_t, \bar{q})$ can be obtained from a forward evolution procedure as implemented in SMALLX [17,18] by a fit to the measured structure function F_2 as described i.e. in [5, 6]. From the initial parton distribution, which includes a Gaussian

parton	uPDF set	$x\mathcal{A}_0(x,k_t,\bar{q}) = Nx^{-B}(1-x)^C$		$\Lambda^{(4)}_{qcd}$	k_t^{cut}	Q_0	ref
		B	C				
gluon	set JS	0	4	0.25	0.25	1.4	[13]
	set A0	0	4	0.25	1.3	1.3	[13]
	set A0+	-0.01	4	0.25	1.3	1.3	[13]
	set A0-	-0.01	4	0.25	1.3	1.3	[13]
	set A1	-0.1	4	0.25	1.3	1.3	[13]
	set B0	0	4	0.25	0.25	1.3	[13]
	set B0+	0.01	4	0.25	0.25	1.3	[13]
	set B0-	0.01	4	0.25	0.25	1.3	[13]
	set B1	-0.1	4	0.25	0.25	1.3	[13]
	set C	0.25	4	0.13	1.1	1.1	[14]
	set 1	0	4	0.25	1.33	1.33	[15]
	set 2	0	4	0.25	1.18	1.18	[15]
	set 3	0	4	0.25	1.35	1.35	[15]
	JH 2013 set1	-	-	0.2	2.2	2.2	[16]
	JH 2013 set2	-	-	0.2	2.2	2.2	[16]
quark	set A	–	–	0.25	1.3	1.3	
	JH 2013 set1	-	-	0.2	2.2	2.2	[16]
	JH 2013 set2	-	-	0.2	2.2	2.2	[16]

Table 1: *Recommended CCFM unintegrated parton distribution functions included in* CASCADE. *See also sec. 4.5.5.*

intrinsic k_t distribution, a set of values x and k_t is obtained by evolving up to a given scale $\log \bar{q}$ using a forward evolution procedure. Technically the parton density is stored on a grid in $\log x$, $\log k_t$ and $\log \bar{q}$ and a linear interpolation is used to obtain the parton density for values in between the grid points. The data file (i.e. `ccfm-xxxx.dat`) containing the grid points is read in at the beginning of the program.

Several sets (**J2003 set 1 - 3** [15] (`IGLU=1001-1003`), **set A** [13] `IGLU=1010-1013` and **set B** [13] `IGLU=1020-1023`) of unintegrated gluon densities are available with the input parameters fitted to describe the structure function $F_2(x, Q^2)$ in the range $x < 5 \cdot 10^{-3}$ and $Q^2 > 4.5$ GeV^2 as measured at H1 [19,20] and ZEUS [21,22]. Set **JS** [6] (`IGLU=1`) is fitted only to $F_2(x, Q^2)$ of Ref. [19]. The collinear cutoff $k_t^{cut} = Q_0$ which regulates the region of $z \to 1$, is applied both to the real emissions as well as inside the Sudakov form factor. In **JS**, **J2003 set 1 - 3** and **set A** we have $k_t^{cut} = Q_0 = 1.3$ GeV. Similarly, fits can be obtained using different values for the soft cut $k_t^{cut} = 0.25$ GeV, which are available in **set B**. The **set C** (`IGLU=1101`) [14] uses the full splitting function, as described in eq.(12), with a value for $\Lambda^{(4)}_{QCD} = 0.13$ GeV. This set was obtained by fitting simultaneously the inclusive $F_2(x, Q^2)$ and jet measurements in DIS resulting in a changed intrinsic k_t distribution. A CCFM parametrisation of the valence quark distribution is available (using as starting distribution CTEQ 5 [23] and evolved with a splitting function P_{qq} [3] including angular ordering of the emitted gluon). The set **JH 2013 set1(2)** [16] were determined from a precision fit to the combined HERA F_2 data, using the full splitting function, eq.(12), and 2-loop α_s. This set comes together with a CCFM evolution of the valence quark density using same cutoff parameters and α_s. The available CCFM uPDF sets with the parameters of the starting distributions are listed in Tab. 2.1.

With the parameter `IGLU` also other unintegrated gluon densities are accessible: a simple numerical derivative of a standard integrated gluon density $\frac{dxg(x,Q^2)}{dQ^2}$ taken from [24] (`IGLU=2`), the one in the approach of Blümlein [25] and coded by [26, 27] (`IGLU=3`), the unintegrated gluon density of KMS[1] [28] (`IGLU=4`, stored in `kms.dat`), the one of the saturation model by [29] (`IGLU=5`, i.e. parameter set including charm)[2] and the one of KMR[3] [30] (`IGLU=6`, stored in `kmr.dat`).

Initial state parton showers can be only generated for the CCFM unintegrated gluon density (with `IGLU=1` and `IGLU=1001-1023,1101,1201-1213,1301-1313`). For all other sets only the cross section can be calculated without explicit inclusion of initial state parton showers, since the angular variable, essential for angular ordering in the initial state cascade, is not available in the uPDFs. However, the transverse momenta of the incoming partons are properly treated. Only the KMR set (`IGLU=6`) provides a prescription for the emission of at most one additional gluon.

[1] A. Stasto kindly provided the program code.

[2] The values of α_s and quark masses of [29] are not automatically used in the cross section calculation, but need to be set explicitly.

[3] M. Kimber kindly provided the program code .

3 Hard processes in CASCADE

Different sets of hard processes applicable for lepto (photo) - and hadroproduction have been calculated and are implemented in CASCADE. The available processes are listed in Tab. 2.

Lepto(photo)production	process	IPRO	Reference
	$\gamma^* g^* \to q\bar{q}$	10	[10]
	$\gamma^* g^* \to Q\bar{Q}$	11	[10]
	$\gamma^* g^* \to J/\psi g$	2	[31–34]
Hadroproduction			
	$g^* g^* \to q\bar{q}$	10	[10]
	$g^* g^* \to Q\bar{Q}$	11	[10]
	$g^* g^* \to J/\psi g$	2	[34]
	$g^* g^* \to \Upsilon g$	2	[34]
	$g^* g^* \to \chi_c$	3	[34]
	$g^* g^* \to \chi_b$	3	[34]
	$g^* g^* \to J\psi J\psi$	21	[35]
	$g^* g^* \to h^0$	102	[36]
	$g^* g^* \to ZQ\bar{Q}$	504	[37,38]
	$g^* g^* \to Zq\bar{q}$	503	[37,38]
	$g^* g^* \to Wq_iQ_j$	514	[37,38]
	$g^* g^* \to Wq_iq_j$	513	[37,38]
	$qg^* \to Zq$	501	[39]
	$qg^* \to qg$	10	[40]
	$gg^* \to gg$	10	[40]

Table 2: *Processes included in* CASCADE. *Q stands for heavy quarks, q for light quarks.*

3.1 Lepto(photo)production

CASCADE can be used to simulate leptoproduction events over the whole Q^2 range. By fixing the light quark masses to $m_q = 0.25$ GeV and α_s for small μ, the hard scattering matrix element remains finite over the full phase space. The total cross section is simulated by selecting `IPRO=10` and `NFLAV=4(5)`. With `IPRO=10` light quarks (u, d, s) are selected and with `NFLAV>3` the program automatically includes heavy flavour production via the process `IPRO=11` and `IHFLA=4` up to `IHFLA=NFLAV`. The flag `IRE1` indicates, whether beam 1 has a internal structure: `IRE1=1` is used to generate resolved photon events.

Heavy flavour production can be generated separately via `IPRO=11`. The value of `IHFLA` determines the heavy flavour to be generated.

The matrix element for $\gamma g^* \to J/\psi(\Upsilon)g$ calculated in [32–34] is available for quasi-real γ's via the process `IPRO=2`. The flavour of the Onium is selected via `IHFLA`, i.e. `IHFLA=4` for

J/ψ and IHFLA=5 for Υ. The matrixelement including $J/\psi(\Upsilon)$ polarisation and subsequent leptonic decay can be selected with IPSIPOL=1.

CASCADE can be used to simulate real photoproduction events by using KBE1=22. The same options as for leptoproduction are available. Resolved photon events can be generated with IRE1=1.

3.2 Hadroproduction

The hadroproduction processes available are listed in Tab 2. The flavour code for beam 1 (2) can be chosen as KBE1=2212 for proton or KBE1=-2212 for anti - proton, for beam 2 KBE2 is changed accordingly.

CASCADE can be used to simulate heavy quark production in pp or $p\bar{p}$ collisions ($g^*g^* \to Q\bar{Q}$ IPRO=11 for heavy flavour production, and IHFLA=4(5) for charm (bottom) quarks), but also for light quarks with IPRO=10. The matrix element for $g^*g^* \to J/\psi g$ calculated in [32–34] is available via the process IPRO=2. The matrixelement including J/ψ polarisation and subsequent leptonic decay can be selected with IPSIPOL=1. The process $g^*g^* \to \chi$ is available with IPRO=3 including all three χ states with appropriate spin and angular momentum. The flavour of the Onium is selected via IHFLA, i.e. IHFLA=4 for $J/\psi(\chi_c)$ and IHFLA=5 for $\Upsilon(\chi_b)$.

Apart from the ground states, the $2S$ and $3S$ states for the Υ family and the $2S$ state for the J/ψ family can be generated vis i23s=2,3. The wavefunction is calculated from the corresponding leptonic decay width, as done for the $1S$ state. Also the $2P$ states of χ_b with subsequent decay into $\Upsilon(2S)$ are included. The wavefunction for the$1P$ and $2P$ states are taken from [41]. The decay of the $\Upsilon(nS)$ and $J/\psi(2S)$ as well as the χ states is performed within the PYTHIA framework by adding new particles and decay modes via PYUPDA. The flavor codes used are given in tab. 3. Double J/ψ (or Υ) production $g^*g^* \to J/\psi J/\psi$ (in single parton scattering SPS) is selected with IPRO=21.

The process $g^*g^* \to h^0$ with the matrix element calculated in [36] is available via IPRO=102, the Higgs mass can be selected via PMAS(25).

The process $g^*g^* \to Zq\bar{q}$, calculated in [37,38], is available via IPRO=503 for light quarks and IPRO=504 for the heavy quarks. The flavor of the heavy quark is selected via IHFLA=4 (5,6) for charm(bottom, top). The process $g^*g^* \to Wq_iq_j$, calculated in [37,38], is available via IPRO=513 for light quarks and IPRO=514 for heavy quarks, where the flavour of the heaviest quark is defined by IHFLA=3, (4,5). Which of the quarks are produced depends on the charge of the W which is randomly selected.

The processes $g^*g \to gg$ and $g^*q \to gq$ [40] are included via process IPRO=10. The individual processes can be selected for $g^*g^* \to q\bar{q}$ via IRPA=1, $g^*g \to gg$ via IRPB=1 and $g^*q \to gq$ via IRPC=1. Note that here one of the partons is treated on-shell. For the quarks the unintegrated quark distribution (for valence quarks) is used.

The process $qg^* \to Zq$, calculated in [37,39], is available via IPRO=501, using the unintegrated (valence) quark distribution for the on-shell quark.

Vectormeson	Flavorcode
$J/\psi(1S)$	443
$J/\psi(2S)$	100443
$\Upsilon(1S)$	553
$\Upsilon(2S)$	100553
$\Upsilon(3S)$	200553
$\chi_{b0}(1P)$	10551
$\chi_{b1}(1P)$	20553
$\chi_{b2}(1P)$	555
$\chi_{b0}(2P)$	110551
$\chi_{b1}(2P)$	120553
$\chi_{b2}(2P)$	100555

Table 3: *Flavor codes used to define the excited states of vectormesons.*

3.3 α_s and the choice of scales

The strong coupling α_s is calculated via the PYTHIA [11] subroutine `PYALPS`. Maximal and minimal number of flavours used in α_s are set by `MSTU(113)` and `MSTU(114)`, Λ_{QCD} = `PARU(112)` with respect to the number of flavours given in `MSTU(112)` and stored in the PYTHIA common block `COMMON/PYDAT1/`. In the initial state cascade according to CCFM, the transverse momenta of the t-channel gluons are allowed to perform a random walk for small z values and k_t can become very small. In the $1/z$ part of the splitting function we use $\mu = k_t$ as the scale in $\alpha_s(\mu)$ and in the $1/(1-z)$ part $\mu = p_t$ is used. In addition we require $\mu > Q_0$, resulting in $\alpha_s(\mu > Q_0) < 0.6$.

The scale μ, which is used in α_s in the hard scattering matrix element, can be changed with the parameter `IQ2`, the default choice is $\mu^2 = p_t^2$.

The renormalisation scale dependence of the final cross section can be estimated by changing the scale used in α_s in the off-shell matrix element. Since here we are using the LO α_s matrix elements, any scale variation will change the cross section. In order to obtain a reasonable result, the uPDF was fitted to describe F_2 by varying the scale μ_r. The **set A0-,B0-** correspond to a scale $\mu_r = 0.5 p_t$ whereas **set A0+,B0+** correspond to a scale $\mu_r = 2 p_t$.

In order to investigate the uncertainties coming from the specific choice of the evolution scale, another definition is applied, relating the factorisation scale only to the quark (or anti-quark): $\mu_f = \frac{p_t}{1-z}$ with p_t being the transverse momentum of the quark (anti-quark) and $z = \frac{\tilde{k}_t}{y x_g s}$. The **set A1,B1** correspond to a scale $\mu_f = \frac{p_t}{1-z}$. In the PDF **set C** $\Lambda^{(4)}_{QCD}$ was fixed to $\Lambda^{(4)}_{QCD} = 0.13$ GeV.

3.4 Quark masses

The quark mass for light quarks (u, d, s) is fixed to $m_q = 0.25$ GeV. This, together with the treatment of α_s at small scales μ, gives also a reasonable total cross-section for photoproduction at HERA energies. The masses for heavy quarks are given by the JETSET / PYTHIA defaults ($m_c = 1.5$ GeV, $m_b = 4.8$ GeV) and can be changed according to the PYTHIA prescription.

3.5 Initial and final state parton showers

Initial state parton showers are generated in a backward evolution approach described in detail in [5, 6]. The initial state parton shower consists only of gluon branchings and is generated in an angular ordered region in the laboratory frame. The gluons emitted in the initial state can undergo further timelike branchings. The maximum timelike mass m_{max} is calculated using the angular constraint. With this mass, the parton which can further undergo a timelike branching is boosted to its rest frame with m_{max} but keeping the original energy. The timelike branching is performed with the PYTHIA routine `PYSHOW`. After successful timelike branching, the proper mass is associated to the parton and the kinematics are calculated appropriately. Gluon radiation from the valence quarks is also included.

All parameters (like the scale μ in α_s, the collinear cut-off $k_t^{cut} = Q_0$) for the initial state cascade are fixed from the determination of the unintegrated gluon density. The transverse momenta of the partons which enter the hard scattering matrix element are already generated in the beginning and are not changed during the whole initial and final state parton showering.

The final state parton shower uses the parton shower routine `PYSHOW` of PYTHIA with the default scale $\mu^2 = 2 \cdot (m^2_{1\perp} + m^2_{2\perp})$ (`IFIN=1`), with $m_{1(2)\perp}$ being the transverse mass of the hard parton 1(2). Other choices are possible: $\mu^2 = \hat{s}$ (`IFIN=2`) and $\mu^2 = 2 \cdot (m_1^2 + m_2^2)$ (`IFIN=3`). In addition a scale factor can be applied: `SCAF`$\times\mu^2$ (default: `SCAF=1`).

3.6 Remnant treatment

In CASCADE version 1 the proton remnant was built in subroutine `CAREMN`, which is a slightly modified version of the PYTHIA/LEPTO subroutine `PYREMN`. No intrinsic transverse momentum, in addition to the transverse momentum from the initial state cascade, was included.

From version 2.0 on the proton remnant can be generated directly via PYTHIA by selecting `ILHA=10` (which is now the default). The structure of the event record is then identical to the one obtained from a standard PYTHIA run.

3.7 Hadronization

In CASCADE version 1 the hadronization was done exclusively by PYTHIA. From version 2 onwards, events can be written into a file (via switch `ILHA=1`) according the LHA Accord [42], which can be read by any hadronization program (like PYTHIA or HERWIG), gen-

erating the remnants and performing the hadronization. With ILHA=10 the hadronization is performed within PYTHIA. The old CASCADE format is obtained with ILHA=0. Please note, that top decays can only be simulated properly within the PYTHIA fragmentation and are therefore available only with ILHA=10.

4 Description of the program components

In CASCADE all variables are declared as Double Precision. The Lund string model is used for hadronization as implemented in PYTHIA [11]. The final state QCD radiation is performed via PYSHOW from PYTHIA . The treatment of the proton remnant follows very closely the ones in LEPTO [43] for the leptoproduction case and the one in PYTHIA for the proton - proton case. However slight modifications were needed to adapt to the cascade treatment here.

The unintegrated gluon density is stored on data files (ccfm.dat,kms.dat,kmr.dat), and is read in at the beginning of the program.

The program has to be compiled and linked together with PYTHIA 6, to ensure that the double precision code of JETSET is loaded.

4.1 Random number generator

Since the variables are declared as double precision, also a double precision random number generator has to be used to avoid any bias. The function DCASRN gives a single random number, the function DCASRNV returns an array of length LEN of random numbers. The default random number generator is RANLUX (called in DCASRN and DCASRNV) The source code of RANLUX (extracted from CERNLIB) is included in the distribution. The user can change this to any preferred Double Precision random number generator.

4.2 Integration and event generation

The integration of the total cross section and the generation of unweighted events is performed with the help of BASES/SPRING [44], which is included in the distribution package.

4.3 Program history

```
CASCADE
*            Version  2.3.12 (02 2014)
*            inconsistencies in steer.F cascha.F cauniglu.F corrected
*            Version  2.3.11 (02 2014)
*              new CCFM gluon included: JH 2013 set1, JH 2013 set2
*              2.*Ca*alphas/2./pi  added in casbran.F
CASCADE
*            Version  2.3.10  (03 2013)
*              QCDLAM set in cascps
CASCADE
*            Version  2.3.08  (02 2013)
*              meoffsh corrected for proper prefactors for gg_> and qg->qg
CASCADE
*            Version  2.3.07  (02 2013)
*              bug in event (2.3.06 corrected)
*              use proper alphas and QCDlam in casbran.F
CASCADE
```

```
*            Version  2.3.06  (12 2012)
*              CKM matrix for Wq production bug corrected
CASCADE
*            Version  2.3.05  (10 2012)
*              CKM matrix for Wqq production included+adding all pieces separately
CASCADE
*            Version  2.3.04  (10 2012)
*               chib(3P) states included
*               copy from timel.cc (from cernlib) included
*               convhepmc.cc for conversion of hepevt to hempc record included
*               further printout in caend added
*
CASCADE
*            Version  2.3.03  (7 2012)
*               PDG code for onium states updated... before nonstandard codes
*
CASCADE
*            Version  2.3.02  (? 2012)
*               caupevent corrected to treat properly excited Onium states
*
CASCADE
*            Version  2.3.01  (Mar 2012)
*               alphas in casbran.F changed to allow also 2loop alphas (NEEDs
*               further checks)
CASCADE
*            Version  2.3.01  (Mar 2012)
*                treatment of potential double counting in gg->gg->qqbar and
*                gg->qqbar (new veto in caps.F)
*                bug fix in meoffsh: Rleg was not kept fixed for multiple
*                calculation of xsec in event.F
*-------------------------------------------------------------------------------
CASCADE
*            Version  2.2.07  (Aug 2011)
*   seed for random numbers is now set by environment variable CASEED
*   -> minuts.F no longer needed
*   convhepmc included for writing out hepmc format:
*  hepmc output file is specified by environment variable: HEPMCOUT
*
CASCADE
*            Version  2.2.06  (May 2011)
*  meoffsh: IQ2=7 same as IQ2=8: max fact. scale.
*            allow for qg->q: changes in caps.F etc.
CASCADE
*            Version  2.2.05  (May 2011)
*   caps.F changes for scale of final state PS
*   IQ2 = 8: scale for alphas = max(factorization scale) included
*   casbran.F: allow for full shower in KMR, not only first emission
CASCADE
*            Version  2.2.04  (Nov 2010)
*  factor 1/2 for identical particles for gg->gg included in meoffsh
*   optional kt for scale for alphas consistently introduced
*
CASCADE
*            Version  2.2.03  (Nov 2010)
*            vector-meson production Y(2S) and Y(3S) and PSI(2S) included.
*  wave function for chi_c,chi_b production in 1P,2P,3P states included
*            decays are updated via data file to be read in
*            bug corrected when setting stable h0,W,Z
CASCADE
*            Version  2.2.02  (Oct 2010)
*            problem when linking with shared libraries solved by explicitly
*            calling a dummy subroutine with PYDATA as argument in the main
*            program.
CASCADE
*            Version  2.2.01  (Sep 2010)
*  scales for 2->1 processes corrected (before was using only stmax)
*  bug for chi production in caps corrected (7.Sep 2010)
CASCADE
*            Version  2.2.01  (Aug 2010)
*  bug in caps.F corrected, when resonance was set stable resulted
*    e/p violation
*  pdfname now changed to character*512
*                installation procedure with autotools changes:
*       - pythia6 and lhapdf lib paths now as input string to ./configure
*  incorrect path in ktstfu corrected
*-------------------------------------------------------------------------------
CASCADE
*            Version  2.2.00  (Aug 2010)
*            timelike showering in initial state cascade
*            forward DY process added
```

```
*            J/psi and chi_c (b) production added
*            all commons/variables now in double precision (version before cause
*            problems for LHC energies and small x)
*            obsolete routines from bases removed
*     Bug in kinematics for Higgs prod corrected.
*
*-------------------------------------------------------------------------
*            Version  2.1.00  (31. Dec 2009)
*            pt cuts are now done all in meoffsh routines on partons entering ME calc
*            W/Z + QQ production added
*            QCD jet production with qg->qg and gg->gg for onshell quark (onshell g) included
*
*-------------------------------------------------------------------------
CASCADE
*            Version  2.0.02-beta  (Sept 2009)
*  meoffsh includes again correction for k^2 = kt^2 (needed for
*             reasonable description of F2 at small x
*         bug corrected for this correction in px,py (generate phi instead of cos phi)
*            only one library created, including all files (16.Aug 2008)
*            IPRO=15 (qg ->qg ) added using valence quarks (12.Aug 2008)
*            CCFMSTFQ for the unintegrated valence quark distribution added(12.Aug 2008)
*            PTCU is now applied always in the lab frame, no longer in the CM
*             frame, since divergencies could be still there.(12.Aug 2008)
*            autotools now also with shared libraries (20. Mar 2008)
*            updated steering files, also for GENSER.(20. Mar 2008)
*            bug in event corrected: only events with xsec>0 accepted (5.4.08)
*  NOW CERNLIB free version
*   in caps: for ILHA=10 MSTJ(41)=1 enforced to avoid isolated photons
*              from FPS in pythia event record
*  Simple MC integration and generation routine included via IINT=1
*  Valence quark distributions and g^*q -> gq and g^*g -> gg processes
 are included.
*-------------------------------------------------------------------------
CASCADE
*            Version  2.0.01  (24.Dec 2007)
*            improvements done on installation using autotools
*            working now with make and make install
*-------------------------------------------------------------------------
CASCADE
*            Version  2.0.00
*            LHA interface for PYTHIA/HERWIG included
*            ILHA=10 uses PYTHIA for final state PS and remnant treatment
*            updates in caupinit,caupevnt
*            update in p_semih.F: removed line with P(2,4)=abs(p(2,3)
*            update in caps.F restored event record also for LST(21)=55
*                            caused energy-mom mismatch before.
*                            for ILHA>1 also use caremn.F
*                            more precise energy-mom check
*            update in caremn.F for ILHA>1 set pt diquark=0
*                            for ILHA>1 limit chi<0.8
*            meoffsh: scale PT2Q changed to average of 2 outgoing quarks
*                     reduces xsection by ca 20% (compared to vers 1.2)
*-------------------------------------------------------------------------
CASCADE
*            Version  12010
*          - insq set to 0, as for updfs... (in casbran.F)
*          - Qlam0 set to Qg0, as in updf .. (in casbran.F)
*          - changed upper limit of xsi_hard to min(xsi_hard(2),5.d8) in cascps.F
*                showed up in wrong Qmax distribution for PS.
*          - no IPS for QG21 (QG22) < Q0 (in cascps.F)
*          - final state PS was always essentially switched off by IFINAL=0 in
*            caps.F. changed to default IFINAL=1.
*          - ordering in casbran.F was wrong, always only q ordering instead of
*            angular ordering (using now casbran-v24.F).
*-------------------------------------------------------------------------
CASCADE
*            Version  12009
*            meoffsh updated: now 2 scales for pp
*            unnecessary cut in caps removed (xgtest), which caused asymmetry
*              in parton showering
*            bug in cascps.F corrected: xsi_hard was wrong for beam 1
*-------------------------------------------------------------------------
CASCADE with LHA interface
*            Version  12008
*            ILHA = 1 added: event record written to file in LHA format to be
*                            read in by PYTHIA or HERWIG
*            ILHA = 10 added: PYTHIA (using LHA interface) is called directly to
*                            do final state PS and hadronsiation.
*-------------------------------------------------------------------------
CASCADE
```

```
*            Version  12007
*            date: 2004/12/23
*            bug in cascade for new gluon dat files corrected:
*            IPS was switched off
*
*            bug in steer corrected Nmax now at 1000
*
*-------------------------------------------------------------------
CASCADE (with PYTHIA6.226)
*            Version  12003
*            bug in cascps corrected
*            date: 2004/11/09 13:42:21;
*            steering files updated to new frag. parameters
*            date: 2004/09/10 17:20:26;
*            updated to read scale parameters from gluon file
*            date: 2004/11/08 06:47:41;
*            bugs in cascps and casbran for ppbar corrected
*            bug in casbran (neg t in log) corrected (found by  Eduardo Rodrigues )
*
*-------------------------------------------------------------------
CASCADE
*            Version  12000
*            Higgs production included
*            e+e- option and resolved photons included
*-------------------------------------------------------------------
CASCADE
*            Version  10000
*            published version for ep and pp
*-------------------------------------------------------------------
```

4.4 Subroutines and functions

The source code of CASCADE and this manual can be found under:
`http://www.desy.de/~jung/cascade/`

`CAMAIN`	main program.
`CASINI`	to initialises the program.
`CASCADE`	to perform integration of the cross section. This routine has to be called before event generation can start.
`CAEND`	to print the cross section and the number of events.
`CAUNIGLU(KF,X,KT,P,XPQ)`	to extract the unintegrated gluon density $x\mathcal{A}(x, k_t, \bar{q})$ for a proton with `KF=2212`, as a function of $x =$`X`, $k_t^2 =$`KT` and $\bar{q} =$`P`. The gluon density is returned in `XPQ(0)`, where `XPQ` is an array with `XPQ(-6:6)`.
`EVENT`	to perform the event generation.
`ALPHAS(RQ)`	to give $\alpha_s(\mu)$ with $\mu =$`RQ`.
`PARTI`	to give initial particle and parton momenta.
`FXN1`	to call routines for selected processes: `XSEC1`.
`CUTG(IPRO)`	to cut on p_t for $2 \to 2$ process in integration and event generation.
`MEOFFSH`	matrix element for $\gamma^* g^* \to q\bar{q}$ and $g^* g^* \to q\bar{q}$ including quark masses. q can be light or heavy quarks.
`MEHIGGS`	matrix element for $\gamma^* g^* \to h^0$.
`DOT(A,B)`	four-vector dot product of A and B.
`DOT1(I,J)`	four-vector dot product of vectors I and J in `PYJETS` common.
`PHASE`	to generate momenta of final partons in a $2 \to 2$ subprocess according to phase space.
`P_SEMIH`	to generate kinematics and the event record for ep, γp and $p\bar{p}$ processes.

CAREMN(IPU1,IPU2) to generate the beam remnants. Copied from LEPTO 6.1 [43] and updated for the use in CASCADE.

CASPLI(KF,KPA,KFSP,KFCH) to give the spectator KFSP and KFCH partons when a parton KPA is removed from particle KF. Copied from LEPTO 6.1 [43] and updated for the use CASCADE.

CAPS to generate color flow for all processes and prepare for initial and final state parton showers.

CASCPS(IPU1,IPU2) to generate initial state radiation.

COLORFLOW to generate color configuration for $g^*g \to gg$ and $g^*q \to qg$ processes.

GADAP Gaussian integration routine for 1-dim and 2-dim integration. Copied from LEPTO 6.1 [43].

4.5 Parameter switches

BASES/SPRING integration procedure.

NCAL: (D:=20000) Nr of calls per iteration for bases.

ACC1: (D:=1) relative precision (in %) for grid optimisation.

ACC2: (D:=0.5) relative precision (in %) for integration.

Event record output.

ILHA: (D: = 0) output in LHA accord [42] format
= 0: CASCADE type output of event record
= 1: output of event record to be read in by fragmentation programs
= 10: use LHA format to produce remnant and fragmentation in PYTHIA style.

4.5.1 Parameters for kinematics

PBE1: (D:=-30) momentum p [GeV/c] of incoming hadron 1 (/INPU/).

KBE1: Lund flavour code of incoming hadron 1 (KBE1=11 for electrons, KBE1=22 for photons, KBE1=2212 for protons)

IRE1: hadron/lepton 1 has a structure (IRE1=1) or interacts directly with the target (IRE1=0 for a DIS electron)

PBE2: (D:=820 momentum p [GeV/c] of incoming proton (/INPU/).

KBE2: Lund flavour code of incoming hadron 2 (KBE2=11 for electrons, KBE2=22 for photons, KBE2=2212 for protons)

IRE2: hadron/lepton 2 has a structure (IRE2=1) or interacts directly with the target (IRE2=0 for a DIS electron)

NFLAV (D: = 5) number of active flavours, can be set by user (/CALUCO/).

4.5.2 Parameters specific for leptoproduction

QMI:	(D: = 5.0) (/VALUES/) minimum Q^2 to be generated
QMA:	(D: = 10^8) (/VALUES/) maximum Q^2 to be generated.
YMI:	(D: = 0.0) (/VALUES/) minimum y to be generated.
YMA:	(D: = 1.0) (/VALUES/) maximum y to be generated.
THEMA, THEMI	(D: THEMA = 180., THEMI = 0) maximum and minimum scattering angle θ of the electron (/CAELEC/).

4.5.3 Parameters for hard subprocess selection

IPRO:	(D: = 10) (/CAPAR1/) selects hard subprocess to be generated. =2: $\gamma g^* \to J/\psi(\Upsilon)g$, $g^*g^* \to J/\psi(\Upsilon)g$. =3: $g^*g^* \to \chi_{c(b)}$. =10: $\gamma^*g^* \to q\bar{q}$, $g^*g^* \to q\bar{q}$, $g^*g \to gg$ and $g^*q \to gq$ for light quarks. =11: $\gamma^*g^* \to Q\bar{Q}$ or $g*g^* \to Q\bar{Q}$ for heavy quarks. =21: $g^*g^* \to J/\psi J/\psi(\Upsilon\Upsilon)$. =102: $g^*g^* \to h^0$ for Higgs production in hadron-hadron collisions. =501: $qg^* \to Zq$ for Z+jet production in hadron-hadron collisions. =503: $g*g^* \to Zq\bar{q}$ for Z+jet production in hadron-hadron collisions. =504: $g*g^* \to ZQ\bar{Q}$ The flavour index of the heaviest quark is selected via IHFLA =513: $g*g^* \to Wq_iq_j$ for W+jet production in hadron-hadron collisions. =514: $g*g^* \to Wq_iQ_j$ for W+jet production in hadron-hadron collisions.
IRPA:	= 1 $g^*g^* \to q\bar{q}$ switched on for IPRO=10.
IRPB:	= 1 $g^*g \to gg$ switched on for IPRO=10.
IRPC:	= 1 $g^*q \to gq$ switched on for IPRO=10.
IHFLA:	(D:=4) = 4 flavor of heavy quark produced (in IPRO=10, IPRO=504 and IPRO=514).
IPSIPOL:	(D:=0) (/JPSI/) = 1 use matrixelement including J/ψ (Υ) polarisation and subsequent leptonic decay for IPRO=2.
I23s:	(D:=0) (/JPSI/) = 0 use $1S$ and $1P$ sates for vectormeson production via IPRO=2,3 =2 use $2S$ and $2P$ states =3 use $3S$ states
PT2CUT(IPRO):	(D=0.0) minimum $\hat{p}_\perp^2$ for process IPRO (/CAPTCUT/).

4.5.4 Parameters for parton shower and fragmentation

NFRAG:	(D: = 1) switch for fragmentation (/CAINPU/). = 0: off = 1: on
IFPS:	(D: = 3) switch for parton shower (/CAINPU/).

= 0: off
= 1: initial state
= 2: final state
= 3: initial and final state

`ITIMSHR:` (D: =1)
=0: no shower of time like partons
=1: time like partons may shower

`ICCFM:` (D: =1)
=1: CCFM evolution (all loops)
=0: DGLAP type evolution (one loop)

`IFIN` (D:=1) scale switch for final state parton shower
= 1: $\mu^2 = 2(m_{1\,t}^2 + m_{2\,t}^2)$
= 2: $\mu^2 = \hat{s}$
= 3: $\mu^2 = 2(m_1^2 + m_2^2)$

`SCAF` (D:=1.) scale factor for final state parton shower

4.5.5 Parameters for structure functions, α_s and scales

`IRUNAEM:` (D: = 0) (`/CAPAR1/`) select running of $\alpha_{em}(Q^2)$.
=0: no running of $\alpha_{em}(Q^2)$
=1: running of $\alpha_{em}(Q^2)$

`IRUNA:` (D: = 1) switch for running α_s.
=0: fixed $\alpha_s = 0.3$
=1: running $\alpha_s(\mu^2)$

`IQ2:` (D: = 3) select scale μ^2 for $\alpha_s(\mu^2)$.
=1: $\mu^2 = 4 \cdot m_q^2$ (use only for heavy quarks!)
=2: $\mu^2 = \hat{s}$ (use only for heavy quarks!)
=3: $\mu^2 = 4 \cdot m^2 + p_\perp^2$
=4: $\mu^2 = Q^2$
=5: $\mu^2 = Q^2 + p_\perp^2 + 4 \cdot m^2$

`IGLU:` (D: = 1201) select unintegrated gluon density (`/GLUON/`).
Note that initial state parton showers not possible for `IGLU=2, 3, 4, 5`
=1: CCFM old set JS2001 [6]
= 1001: CCFM J2003 set 1 [15]
= 1002: CCFM J2003 set 2 [15]
= 1003: CCFM J2003 set 3 [15]
= 1010: CCFM set A0 [13]
= 1011: CCFM set A0+ [13]
= 1012: CCFM set A0- [13]
= 1013: CCFM set A1 [13]
= 1020: CCFM set B0 [13]
= 1021: CCFM set B0+ [13]

= 1022: CCFM set B0- [13]
= 1023: CCFM set B1 [13]
= 1101: CCFM set C [14]
= 1201 (-1213): CCFM JH 2013 set1 [16] (uncertainty sets 1202-1213)
= 1301 (-1313): CCFM JH 2013 set2 [16] (uncertainty sets 1302-1313)
=2: derivative of GRV [24] $\frac{dxg(x,Q^2)}{dQ^2}$.
=3: approach of Blümlein [25]
=4: KMS [28] (`kms.dat`)
=5: saturation model [29]
=6: KMR [30] (`kmr.dat`)

4.5.6 Accessing information

`AVGI`	integrated cross section (`/CAEFFIC/`).
`SD`	standard deviation of integrated cross section (`/CAEFFIC/`).
`SSS`	squared center of mass energy s (`/CAPARTON/`).
`PBEAM`	energy momentum vector of beam particles (`/CABEAM/`).
`KBEAM`	flavour code of beam particles (`/CABEAM/`).
`Q2`	in leptoproduction: actual Q^2 of γ (`/CAPAR4/`).
`YY`	negative light-cone momentum fraction of parton 1 (γ^*, g^*) (`/CASGKI/`).
`YY_BAR`	positive light-cone momentum fraction parton 1 (γ^*, g^*) (`/CASGKI/`).
`XG`	positive light-cone momentum fraction of parton 2 (g^*) (`/CASGKI/`).
`XG_BAR`	negative light-cone momentum fraction of parton 2 (g^*) (`/CASGKI/`).
`KT2_1,KT2_2`	transverse momenta squared $k^2_{t\,1(2)}$ [GeV^2] of partons $1(2)$ which enter to the matrix element.
`YMAX,YMIN`	actual upper and lower limits for $y =$`YY` (`/CAPAR5/`).
`Q2MAX,Q2MIN`	actual upper and lower limits for Q^2 (corresponding to `KT2_1`) of γ (`/CAPAR5/`).
`XMAX,XMIN`	upper and lower limits for x (`/CAPAR5/`).
`AM(18)`	vector of masses of final state particles of hard interaction (`/CAPAR3/`).
`SHAT`	invariant mass $\hat{s}$ [GeV^2] of hard subprocess (`/CAPAR5/`).
`NIA1,NIA2`	position of partons in hard interaction in `PYJETS` event record (`/CAHARD/`).
`NF1,NF2`	first and last position final partons/particles of hard interaction in `PYJETS` (`/CAHARD/`).
`Q2Q`	hard scattering scale μ^2 used in α_s and structure functions (`/CAPAR4/`).
`ALPHS`	actual α_s (`/CAPAR2/`).
`ALPH`	α_{em} (`/CAPAR2/`).
`NIN`	number of trials for event generation (`/CAEFFIC/`).
`NOUT`	number of successful generated events (`/CAEFFIC/`).

4.6 List of COMMON blocks

```
COMMON/CABEAM/PBEAM(2,5),KBEAM(2,5),KINT(2,5)
COMMON/CAHARD/NIA1,NIA2,NIR2,NF1,NF2
COMMON/CAHFLAV/IHFLA
COMMON/CAINPU/PLEPIN,PPIN,NFRAG,ILEPTO,IFPS,IHF,INTER,ISEMIH
COMMON/CALUCO/KE,KP,KEB,KPH,KGL,KPA,NFLAV
COMMON/CAEFFIC/AVGI,SD,NIN,NOUT
COMMON/CAELEC/THEMA,THEMI
COMMON/CAGLUON/IGLU
COMMON/CAPAR1/IPRO,IRUNA,IQ2,IRUNAEM
COMMON/CAPAR2/ALPHS,PI,ALPH,IWEI
COMMON/CAPAR3/AM(18),PCM(4,18)
COMMON/CAPAR4/Q2,Q2Q
COMMON/CAPAR5/SHAT,YMAX,YMIN,Q2MAX,Q2MIN,XMAX,XMIN
COMMON/CAPAR6/LST(30),IRES(2)
COMMON/CAPARTON/SSS,CM(4),DBCMS(4)
COMMON/CAPTCUT/PT2CUT(1000)
COMMON/CASKIN/YY,YY_BAR,XG,XG_BAR,KT2_1,KT2_2,PT2H,SHH
COMMON/VALUES/QMI,YMI,QMA,YMA
```

5 Example Program

```
      PROGRAM CASMAIN
      Implicit None
      Integer N1,N2
      DOUBLE PRECISION  PLEPIN,PPIN
      INTEGER KE,KP,KEB,KPH,KGL,KPA,NFRAG,ILEPTO,IFPS,IHF
      INTEGER INTER,ISEMIH
      INTEGER NIA1,NIR1,NIA2,NIR2,NF1,NF2,NFT,NFLAV
      COMMON/CALUCO/KE,KP,KEB,KPH,KGL,KPA,NFLAV
      COMMON/CAINPU/PLEPIN,PPIN,NFRAG,ILEPTO,IFPS,IHF,INTER,ISEMIH
      COMMON/CAHARD/NIA1,NIA2,NIR2,NF1,NF2
      INTEGER IHFLA
      COMMON/CAHFLAV/IHFLA

      DOUBLE PRECISION THEMA,THEMI,PT2CUT
      INTEGER IRUNA,IQ2,IRUNAEM
      INTEGER IPRO
      COMMON/CAPAR1/IPRO,IRUNA,IQ2,IRUNAEM
      COMMON/CAELEC/ THEMA,THEMI
      COMMON/CAPTCUT/PT2CUT(20)
      REAL ULALPS,ULALEM
      EXTERNAL ULALPS,ULALEM
      DOUBLE PRECISION QMI,YMI,QMA,YMA
      COMMON/VALUES/QMI,YMI,QMA,YMA

      Integer Iglu
      Common/CAGLUON/Iglu

      Integer ISEED,I


      ISEED = 124567
      n1=0
      n2=0
C initialize random number generator
      CALL RM48IN(ISEED,N1,N2)
```

```
C initialize PYTHIA 6 parameters
      CALL GPYINI
C initialize CASCADE parameters
      CALL CASINI


C Select parton shower (IPS=1 initial, =2 final, 3 initial+final PS )
      IFPS = 3
C scale for alpha_s
C IQ2 =1 mu^2 = 4m_q^2 (m_q = light quark or heavy quark depending on IPRO)
C IQ2 =2 mu^2  = shat
C IQ2 =3 mu^2  = 4m_q^2 + pt^2 (m_q = light quark or heavy quark depending on IPRO)
C IQ2 =4 mu^2  = q^2 (q^2 of virtual photon)
C IQ2 =5 mu^2  = q^2 + pt^2 + 4m_q^2(q^2 of virtual photon)
      IQ2=3
C select process (IPRO=10 for light quarks, IPRO=11 for heavy quarks)
      IPRO= 10
C total number of flavours involved
      NFLAV = 4
C select unintegrated gluon density (D=1)
      Iglu = 1
C minimum Q^2 of electron to be generated
      QMI = 0.5d0
C maximum Q^2 of electron to be generated
      QMA = 10D8
C minimum y of electron to be generated
      YMI=0.0d0
C minimum y of electron to be generated
      YMA=1.0d0
C maximum theta angle of scattered electron
      THEMA = 180.0D0
C minimum  theta angle of scattered electron
      THEMI =   0.0D0
C momentum of beam 1 (electron,proton,antiproton)
      PLEPIN =-27.5
C Lund flavour code for beam 1 (electron=11,photon=22,proton=2212,antiproton=-2212)
      KE=11
C momentum of beam 2 (proton)
      PPIN   = 820.
C perform fragmentation NFRAG=0/1
      NFRAG = 1
c for IPRO = 11  which flavour is produced
      IHFLA = 4
c
c Start integration of x-section
c
      CALL CASCADE
c
c Print out result of integration of x-section
c
      CALL CAEND(1)

c
c Start event loop
c
      Do I=1,100
c generate an event
         CALL EVENT
      Enddo
c
c Print out of generated events summary
c
      CALL CAEND(20)

      STOP
      END
```

6 Program Installation

CASCADE now follows the standard AUTOMAKE convention. To install the program, do the following

```
1) Get the source

tar xvfz cascade-XXXX.tar.gz
```

```
cd cascade-XXXX

2) Generate the Makefiles (do not use shared libraries)
./configure --disable-shared --prefix=install-path --with-pythia6="pythia_path"  --with-lhapdf="lhapdflib_path"

with (as example):
pythia_path=/afs/desy.de/group/alliance/mcg/public/MCGenerators/pythia6/422/i586_rhel40
lhapdflib_path=/afs/desy.de/group/alliance/mcg/public/MCGenerators/lhapdf/5.8.1/i586_rhel40

3) Compile the binary
make

4) Install the executable and PDF files
make install

4) The executable is in bin
set the path for the updf data files, if different from
the default (for example)

export PDFPATH=/Users/jung/jung/cvs/cascade2/cascade-2.2.0/share

run it with:
cascade < steer_pp-bottom
```

7 Acknowledgments

We are very grateful to B. Webber for providing us with the SMALLX code, which was the basis for the CASCADE Monte Carlo generator. We are very grateful also to G. Ingelman and T. Sjöstrand for many discussions and for their courtesy to let us use their code for proton remnant treatment. One of us (H.J.) enjoyed very much the collaboration with G. Salam and his patience and help in all different kinds of discussions concerning CCFM and a backward evolution approach. We have enjoyed and learned a lot from the discussions with B. Andersson, G. Gustafson, L. Jönsson, H. Kharraziha and L. Lönnblad during several years. Some of us (S.B., H.J., A.L and N.Z) are very grateful to DESY Directorate for the support in the framework of Moscow – DESY project on Monte-Carlo implementation for HERA – LHC.

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