

The RAPGAP Monte Carlo for Deep Inelastic Scattering

version 3.2

H. Jung
DESY, Notkestr.85, 22603 Hamburg, FRG

November 6, 2011

Abstract

The physics behind the Monte Carlo event generator RAPGAP are discussed, which includes deep inelastic scattering, non - diffraction, diffraction and π - exchange as well as resolved virtual processes.

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. Subroutines for initial state parton showers, remnant treatment and structure functions developed for LEPTO and PYTHIA have been copied and modified for the use in RAPGAP.

1 Tabular Summary

program name	RAPGAP
version	3.20/beta
date of latest version	Sept 2009
author	Hannes Jung (Hannes.Jung@desy.de)
program size	~ 12000 lines of code
input files needed	none
computer types	any with standard Fortran 77, tested on SGI, HP-UX, SUN, PC
operating systems	Unix, Linux
applicability	Deep Inelastic ep Scattering Deep Inelastic ep Scattering with resolved photons Deep Inelastic Diffractive ep Scattering Deep Inelastic ep Scattering with π exchange Photo-production in ep Scattering Diffractive photo-production in ep Scattering Photo-production in ep Scattering with π exchange hard scattering in pp processes: diffractive and non-diffractive
hard sub-processes included	$eq \rightarrow e'q'$ $eq \rightarrow e'qg$ $eg \rightarrow e'q\bar{q}$ $eg \rightarrow e'c\bar{c}$ $eg \rightarrow e'b\bar{b}$ $\gamma q \rightarrow qg$ $\gamma q \rightarrow q\gamma$ $\gamma g \rightarrow q\bar{q}$ $\gamma g \rightarrow c\bar{c}$ $gg \rightarrow gg$ $qg \rightarrow qg$ $q\bar{q} \rightarrow gg$ $q\bar{q} \rightarrow q\bar{q}$ $qq \rightarrow qq$ $qg \rightarrow q\gamma$ $q\bar{q} \rightarrow \gamma g$
QCD cascade	initial and final state parton shower or ARIADNE
initial QED radiation	via HERACLES
fragmentation model	LUND string
other programs called	HERACLES 4.6.6 SOPHIA PYTHIA 6.4 or higher ARIADNE 4.12 BASES 5.1 LHAPDF lib
availability	http://www.desy.de/~jung/rapgap.html

2 Introduction

In high energy physics Monte Carlo Event Generators are heavily used to compare experimental data with theoretical predictions. For example in QCD the interaction between quarks and gluons can be calculated in leading - or next-to-leading order in the strong coupling constant α_s . In experiments only stable particles are measured, but not partons (quarks or gluons), which cannot be described by perturbation theory, because the coupling constant α_s becomes large at scales of the order of the mass of hadrons. Thus the hadronization has to be described by phenomenological procedures, for example with the hadronization packages JETSET [1] or HERWIG [2].

A typical Monte Carlo Event Generator usually starts by generating the momenta of the partons involved in the interaction according to a theoretical prescription. Such a typical event record could look like the following (from the PYTHIAevent record):

Event listing (summary)									
I	particle/jet	KS	KF	orig	p_x	p_y	p_z	E	m
1	!e-	21	11	0	0.000	0.000	156.843	156.843	0.001
2	!p+	21	2212	0	0.000	0.000	-156.843	156.846	0.938
3	!gamma!	21	22	1	1.819	18.493	4.371	3.243	-18.812
4	e-	1	11	1	-1.819	-18.493	152.472	153.601	0.001
5	!u!	21	2	2	0.000	0.000	-23.242	23.242	0.000
6	u	A 2	2	5	1.820	18.496	-18.874	26.488	0.006
7	ud_0	V 1	2101	2	0.000	-0.003	-133.599	133.600	0.579
		sum:	0.00		0.000	0.000	0.000	313.689	313.689

The process described by this event record is deep inelastic electron proton scattering in the electron proton center of mass frame. The first two lines show the beam particles. A status code KS indicates whether the particle (or parton) is kept only for documentation (KS = 21) or whether it is a final state particle (parton) (KS = 1). The flavor code KF identifies uniquely the particle/parton. The row orig shows the line number of mother particle/parton. The third line in this example gives the exchanged virtual photon and the fourth line the scattered electron. In line 5 the parton of the proton struck by the virtual photon is given. Line 6 describes the scattered quark and in line 7 the remnant of the proton is given.

The partons in line 6 and 7 hadronize into visible particles. Of course the incoming parton (line 5) could be a result of QCD radiation from another parton with larger energy. Also the scattered parton (line 6) could radiate further partons before the actual hadronization takes place. Such an example is shown in the following, where both the initial and scattered partons are the result of further QCD radiation.

Event listing (summary)

I	particle/jet	KS	KF orig	p_x	p_y	p_z	E	m		
1	!e-	21	11	0	0.000	0.000	-156.843	156.843	0.001	
2	!p+	21	2212	0	0.000	0.000	156.843	156.846	0.938	
3	!gamma!	21	22	1	1.819	18.493	-4.371	3.243	-18.812	
4	e-	1	11	1	-1.819	-18.493	-152.472	153.601	0.001	
5	!u!	21	2	2	-0.358	0.403	81.763	81.764	0.000	
6	!u!	21	2	5	-0.069	0.246	28.064	27.754	-4.167	
7	!u!	21	2	4	1.797	19.188	21.113	28.585	0.006	
8	u	A	2	2	0	-1.648	8.569	8.978	12.520	0.006
9	g	I	2	21	0	1.795	7.372	8.854	11.660	0.000
10	g	I	2	21	0	0.220	1.524	2.027	2.545	0.000
11	g	I	2	21	0	1.383	1.273	3.833	4.269	0.000
12	g	I	2	21	0	0.506	0.921	1.696	1.995	0.000
13	g	I	2	21	0	-0.559	-0.917	51.687	51.699	0.000
14	ud_0	V	1	2101	2	0.122	-0.249	75.397	75.400	0.579
		sum:	0.00		0.000	0.000	-0.001	313.689	313.689	

In this example the first 4 lines are the same as above, but line 5 now shows the momentum of the parton originating from the proton before any QCD radiation, and line 6 gives the parton struck by the virtual photon (after initial state QCD radiation). Another difference to the first example is that a small primordial transverse momentum has been added to the parton originating from the proton. In line 7 the scattered parton is shown before any final state QCD radiation, whereas in line 8 the final parton after radiation is given. The partons radiated both from initial state and final state are given in the lines following line 8.

More details on how to generate events according to theoretical distributions, the basic physics processes and the way higher order QCD processes are simulated via parton shower cascades are given in the following sections.

3 Basics for Monte Carlo Generators

In Monte Carlo Event Generators one usually wants to calculate the cross section for various processes with the possibility to impose experimental cuts and to generate events according to theoretical distributions. These two subjects are closely related to each other.

First let us consider the integration of a function $f(x)$ with a Monte Carlo method. Having two independent random numbers, say R_1 and R_2 , generated uniformly in the interval $(0, 1)$, then we can calculate x_R with $x_R = x_{min} + R_1 \cdot (x_{max} - x_{min})$ and f_R with $f_R = R_2 \cdot f_{max}$. The integral $\int_{x_{min}}^{x_{max}} f(x)dx$ can be approximated by the sum of $\sum f_R$ for which $f_R < f(x_R)$. However, if the function $f(x)$ is strongly peaked at some value of x , then this method becomes rather inefficient, because most of the time we will have $f_R > f(x_R)$ and thus the pair of random numbers has to be rejected.

The efficiency will increase, if we can generate x values according to some approximation of $f(x)$ by another function $g(x)$ which is much simpler and analytically integrable. Now we generate x values according to the function $g(x)$. This is done by the following:

$$R_1 \int_{x_{min}}^{x_{max}} g(x)dx = \int_x^{x_{max}} g(x)dx$$

Thus if we can integrate $g(x)$ analytically then the equation can be solved for x and we have then x generated according to $g(x)$. Let us assume $f(x)$ can be approximated by a function $g(x) = 1/x$. Then we have:

$$R_1 \int_{x_{min}}^{x_{max}} g(x)dx = R_1 \log \frac{x_{max}}{x_{min}} = \log \frac{x_R}{x_{min}}$$

Solving this equation we obtain $x_R = x_{min}(\frac{x_{max}}{x_{min}})^{R_1}$. In order to calculate the integral we proceed as follows:

$$\int f(x)dx = \int \frac{f(x)}{g(x)}g(x)dx \simeq \sum_i \frac{f(x_{R_i})}{g(x_{R_i})} \int g(x)dx$$

Because of the choice $f(x) \sim g(x)$, the ratio $\frac{f(x)}{g(x)}$ is more or less constant and independent of x . In the example with $g(x) = 1/x$ the integral is given by:

$$\int f(x)dx \simeq \sum_i x_{R_i} f(x_{R_i}) \log \frac{x_{max}}{x_{min}} \quad (1)$$

which can be easily calculated.

Now to generate x values according to $f(x)$ we use the same trick as above: first generate x according to the simple function $g(x)$ and then reject those values of x for which $\frac{f(x)}{g(x)} > R_2$. With this procedure x values are generated according to the function $f(x)$. Moreover this scheme is easily extended to the case of more than one dimension: for each variable x_1, x_2, \dots, x_n the same procedure is applied.

In RAPGAP the BASES [3] integration package is used. This package performs a Monte Carlo integration and according to a given function $f(y_i)$, it generates the variables y_i after internally optimizing a grid. In RAPGAP the random numbers x_i are generated with BASES but they are transformed to the variables y_i according to the procedure described above. Actually the variables y_i are the kinematic quantities $y, Q^2, x_g, x_P, t, \dots$ given in the next section. In all cases the true distribution is approximated by $g(y_i) = 1/y_i$ and the weighting factor (eq.(1)) is applied. This procedure has the advantage of being very efficient, because BASES is used only to optimize the normally small difference between the approximated and the true function.

4 Cross Section and Partonic Subprocesses

4.1 Standard Deep Inelastic Scattering

The inclusive cross section for $e p$ deep inelastic scattering is given in terms of the structure function $F_2^p(x, Q^2)$ and the longitudinal structure function $F_L^p(x, Q^2) = F_2^p(x, Q^2) - 2xF_1^p(x, Q^2)$:

$$\frac{d\sigma(ep \rightarrow e'X)}{dy dQ^2} = \frac{4\pi\alpha^2}{yQ^4} \left(\left(1 - y + \frac{y^2}{2}\right) F_2^p(x, Q^2) - \frac{y^2}{2} F_L^p(x, Q^2) \right) \quad (2)$$

with x defined as $x = Q^2/(2P \cdot q)$, $y = (P \cdot q)/(P \cdot l)$ and $Q^2 = -q^2 = -(l - l')^2$ where P is the initial proton four vector, $q = l - l'$ is the four vector of the virtual photon with l (l') the four vectors of the initial (scattered) electron.

In the QCD improved quark - parton model for deep inelastic scattering the structure function F_2^p is given in terms of the corresponding parton distribution functions:

$$F_2^p(x, Q^2) = \sum_f e_f^2 (xq_f(x, Q^2) + x\bar{q}_f(x, Q^2)) \quad (3)$$

where the sum runs over all quark flavors and $q_f(x, Q^2)$ ($\bar{q}_f(x, Q^2)$) gives the probability of finding a quark (anti-quark) of flavor f with a momentum fraction x of the initial proton momentum.

Different parameterization of the parton densities in the proton can be selected in RAPGAP (via MSTP(51)) and the LHAPDFLIB [4] can be accessed.

4.2 Deep Inelastic Diffractive Scattering and pion exchange

In diffractive scattering (or pion exchange scattering) the inclusive cross section is given by [5]:

$$\frac{d^4\sigma(ep \rightarrow e'Xp')}{dy dQ^2 dx_{\mathbb{P}} dt} = \frac{4\pi\alpha^2}{yQ^4} \left(\left(1 - y + \frac{y^2}{2}\right) F_2^{D(4)}(x, Q^2; x_{\mathbb{P}}, t) - \frac{y^2}{2} F_L^{D(4)}(x, Q^2; x_{\mathbb{P}}, t) \right) \quad (4)$$

where the diffractive structure functions $F_2^D(x, Q^2; x_{\mathbb{P}}, t)$ and $F_L^D(x, Q^2; x_{\mathbb{P}}, t)$ are introduced, depending now on four variables, x , Q^2 defined as above and $x_{\mathbb{P}} = (q \cdot p_{\mathbb{P}})/(q \cdot P)$ and $t = (P - P')^2$ with P' being the four momentum of the elastically scattered outgoing proton. In the case of pion exchange (instead of pomeron exchange) one simply has to replace $F_{2;L}^D$ by the corresponding $F_{2;L}^\pi$ and $x_{\mathbb{P}}$ by x_π .

The interpretation of the diffractive structure function F_2^D in terms of parton distribution functions, in analogy to the proton structure function, is not that clear and different approaches exist [6]:

- **Resolved pomeron a la Ingelman and Schlein**

In the model of Ingelman and Schlein [7] diffractive scattering is described in terms of pomeron \mathbb{P} exchange, where the pomeron has a partonic structure. The structure function F_2^D is then given as the product of the probability for finding a pomeron $f_{p\mathbb{P}}$ and the structure function $F_2^{\mathbb{P}}$ of the pomeron:

$$F_2^{D(4)}(\beta, Q^2; x_{\mathbb{P}}, t) = f_{p\mathbb{P}}(x_{\mathbb{P}}, t) F_2^{\mathbb{P}}(\beta, Q^2) \quad (5)$$

with $\beta = Q^2/(2q \cdot p_{\mathbb{P}})$. In analogy to the quark - parton - model of the proton β can be interpreted as the momentum fraction of the total pomeron momentum carried by the struck quark and $F_2^{\mathbb{P}}(\beta, Q^2)$ can be seen as the quark probabilities in the pomeron. Different parameterization of the parton densities of the pomeron can be selected (NG with details given in the program description). The probability for finding a pomeron in the proton is available in three different parameterization.

The parameterization of Streng and Berger et al. [8–10] can be obtained with NPOM=0:

$$f_{p\mathbb{P}}(x_{\mathbb{P}}, t) = \frac{\beta_{p\mathbb{P}}^2(0)}{16\pi} x_{\mathbb{P}}^{1-2\alpha_{\mathbb{P}}(t)} e^{-b_0|t|} \quad (6)$$

with $\beta^2(0) = 58.74 \text{ GeV}^2$ and $\alpha_{\mathbb{P}} = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t$ and $\alpha_{\mathbb{P}}(0) = 1 + \epsilon$ describing the pomeron trajectory with $\epsilon = \text{EPSP}$, $\alpha'_{\mathbb{P}} = \text{ALPHP}$ and $b_0 = \text{RN2}$ being free parameters.

The parameterization of Ingelman and Bruni [11–13] is given (NPOM=1):

$$f_{p\mathbb{P}}(x_{\mathbb{P}}, t) = \frac{1}{2} \frac{1}{2.3} \frac{1}{x_{\mathbb{P}}} \left[6.38e^{-8|t|} + 0.424e^{-3|t|} \right] \quad (7)$$

Donnachie and Landshoff [14] give the following (via NPOM=2) :

$$f_{p\mathbb{P}}(x_{\mathbb{P}}, t) = \frac{9\delta^2}{4\pi^2} [F_1(t)]^2 x_{\mathbb{P}}^{1-2\alpha_{\mathbb{P}}(t)} \quad (8)$$

with $\delta^2 = 3.26 \text{ GeV}^2$ and the elastic form factor $F_1(t)$:

$$F(t) = \frac{4m_p^2 - 2.8t}{4m_p^2 - t} \frac{1}{(1 - t/0.7)^2} \quad (9)$$

- **Resolved pomeron with a parameterization to H1 data**

In [15] the H1 collaboration has given a parameterization of the diffractive structure function in terms of pomeron and meson trajectories. This parameterization can be selected by NG=-10, -11, -12 for the NLO parameterizations and by NG=-13, -14, -15 for the LO ones, according to a different ansatz for the parton distribution in the pomeron at the starting scale for the Q^2 evolution: NG=-10 assumes only quarks at the starting scale Q_0 , NG=-11 has quarks and gluons, whereas in NG=-12 a gluon distribution peaked at large values ξ , the parton momentum fraction, is assumed.

With NPOM=-10 the predefined flux for pomeron exchange is selected, NPOM=-11 gives the meson contribution only, and NPOM=-12 gives the mix of pomeron and meson as obtained by the H1 collaboration [15].

In [16] a new set of diffractive pdfs was obtained in NLO in the \overline{MS} scheme. They can be selected via $NG=-30, -31$ for set A and set B (respectively). The flux can be selected for pomeron only $NPOM=-30$, Reggeon (meson) only $NPOM=-31$ and a combination $NPOM=-32$. Please note that the pdfs contain only light partons (i.e. gluon, u-,d-, s-quark densities). For the contribution of heavy quarks (charm and beauty) the BGF process via $IPRO=14$ has to be run separatly and added to the light quark cross section.

- **Two gluon exchange for diffraction**

This approach is mainly intended to describe exclusive high p_t jet production, but in the model of [17] estimates on the total inclusive diffractive cross section are given. The calculation of diffractive di-jet production can be performed using pQCD for large photon virtualities Q^2 and high p_t of the $q(\bar{q})$ jets [17–22].

The process is mediated by two gluon exchange. Different assumptions on the nature of the exchanged gluons can be made: in [18,19] ($NG=42, NPOM=42$) the gluons are non perturbative, in [17] ($NG=40, NPOM=40$) they are a hybrid of non perturbative and perturbative ones and in [21,22] ($NG=41$ and $NPOM=41$ or $IPRO=21$, which is done technically different and is more efficient) they are taken from a NLO parameterization of the proton structure function [23,24]. The cross section is essentially proportional to the proton gluon density squared: $\sigma \sim [x_P G_p(x_P, \mu^2)]^2$ with μ^2 the scale explicitly given in the references.

The perturbative calculation of $q\bar{q}$ ($IPRO=21$) and $q\bar{q}g$ ($IPRO=20$) ([21,25,26]) can be used for light quark and heavy quark production. With $Iqqg$ different levels of approximation in the calculation for $IPRO=20$ can be selected. However it is recommended to use the full calculation with $Iqqg=0$.

The un-integrated gluon density needed for the calculation is selected via $IGLU$. Different sets are available: the CCFM unintegrated gluon **set A** [27] with $IGLU=1$, a simple numerical derivative of a standard integrated gluon density $\frac{dxg(x, Q^2)}{dQ^2}$ taken from [28] ($IGLU=2$), the one in the approach of Blümlein [29] and coded by [30,31] ($IGLU=3$), the unintegrated gluon density of KMS¹ [32] ($IGLU=4$, stored in `kms.dat`), the one of the saturation model by [33] ($IGLU=5$) and the one of KMR² [34] ($IGLU=6$, stored in `kmr.dat`).

Due to the different gluon densities different x_P dependencies of the cross sections are expected and further discussed in [20,25,26], where also numerical estimates are presented.

- **Semi-classical approach of Buchmüller, McDermott and Hebecker**

In [35] Buchmüller et al. define an effective diffractive gluon density:

$$x_P G^D(x_P, \beta) = \frac{C_1}{\beta \cdot C_g - \beta + 1} \cdot \frac{1}{x_P} \quad (10)$$

with C_1 and C_g being free parameters. In addition the dipole form factor for the t dependence is applied. Note that with $C_g = 1$ a constant gluon density is obtained. In that approach there is only a $1/x_P$ dependence in contrast to the other models, where at least a $1/x_P^{1+\epsilon}$ is present.

- **Nikolaev Zakharov model for diffraction**

A parameterization of the diffractive structure function in the model of Nikolaev and Zakharov [36] can be selected ($NG=30, NPOM=30$). In the implementation in RAPGAP only QPM type events can be generated, no higher order QCD processes like QCD-C or BGF are possible for $NG=30, NPOM=30$.

- **Saturation Model (SATRAP)**

The saturation model SATRAP [37] is implemented to describe $q\bar{q}$ and $q\bar{q}g$ final states ($IPRO=30$).

- **User defined model for diffraction**

The user can freely define his preferred model for diffraction by supplying an effective diffractive structure function (SUBROUTINE `USDIFFR`). Here no assumption about factorization is made.

The basic partonic subprocesses available are: $eq \rightarrow e'q'$ (QPM), $eq \rightarrow e'qg$ (QCD-C), $eg \rightarrow e'q\bar{q}$ (BGF), $eg \rightarrow e'c\bar{c}$ (BGF), $eg \rightarrow e'b\bar{b}$ (BGF), which are discussed in more detail in the following sections.

In all cases there is the possibility to add primordial p_T (via switch `IALMKT=1`) according to $\exp(-5.5 \cdot p_T^2)$ to the partons when process $IPRO = 12$ is selected.

¹A. Stasto kindly provided the program code.

²M. Kimber kindly provided the program code .

4.3 Deep Inelastic Scattering including Diffraction and Pion exchange

Inclusive deep inelastic scattering obviously includes diffraction and π exchange etc. The total cross section of DIS, F_2 , can be written as a sum of diffractive and non - diffractive contributions:

$$F_2(x, Q^2) = F_2^{non-diff}(x, Q^2) + F_2^{diff}(x, Q^2) + \dots \quad (11)$$

where the dots indicate that other exchanges like pion exchange etc. can be treated similarly.

The diffractive contribution to F_2 is given by F_2^{diff} :

$$F_2^{diff}(x, Q^2) = \int F_2^{D(4)}(x_{\mathbb{P}}, t; \beta, Q^2) \delta(\beta x_{\mathbb{P}} - x) dx_{\mathbb{P}} d\beta dt \quad (12)$$

With the knowledge of F_2 and F_2^{diff} the non - diffractive part can be calculated which is then used in the Monte Carlo to generate the proper mix of diffractive and non - diffractive processes (IDISDIF=1). Similarly non - diffraction, diffraction and pion - exchange are selected with IDISDIF=2.

4.4 QED radiative corrections

Real photon emission from both the incoming and scattered electron can have large effects on the reconstruction of the DIS kinematic variables x , Q^2 , y . These QED radiative effects are simulated with the HERACLES event generator [38,39]. HERACLES is used to generate the $e - \gamma^* - e$ vertex including photon emission from the incoming and outgoing electron as well as virtual corrections. The interface to HERACLES is switched on with IPR0=1200(1400) to generate QED radiative effects for processes IPR0=12(14). For very low masses W an interface to the SOPHIA [40] generator is used.

Since QED radiative effects tend to lower the actual Q^2 of the photon which is available for any subsequent process, one has to ensure that parton densities behave well at very small Q^2 . In the quark parton model the QPM process has to vanish for $Q^2 \rightarrow 0$. On the other hand parton densities are usually only parameterized down to a fixed value of Q_0^2 . In order to ensure a well defined small Q^2 behavior, an exponential suppression factor is applied: $1 - \exp(-Q2SUPP \cdot Q^2)$ with Q2SUPP=3.37 being the default from HERACLES. Values of Q2SUPP=5 seems appropriate for parton densities evolved down to $Q_0^2 \sim 1 \text{ GeV}^2$ and Q2SUPP=10 for $Q_0^2 \sim 0.5 \text{ GeV}^2$.

4.5 Order α_s matrix elements

4.5.1 Order α_s matrix elements with p_T -cutoff

With the knowledge of F_2 the total cross section can be described in terms of scattering a virtual photon on a quark or anti-quark. However this quark may have been originated from another parton, usually described by the Q^2 dependence of the parton densities resulting in a different hadronic final state. The process where a initial parton carrying a momentum fraction x_i , splits into other partons which then hard scatter with the photon, can be simulated in QCD parton showers (selected via IFPS), for incoming (IFPS = 1), outgoing partons (IFPS=2) and both (via IFPS = 3). These QCD parton showers are based on the leading log DGLAP [41-44] splitting functions in leading order α_s .

A more detailed simulation of leading order α_s processes like $\gamma^* g \rightarrow q\bar{q}$ (BGF, Fig. 1c.) and $\gamma^* q \rightarrow qq$ (QCD - Compton, Fig. 1d.) can be obtained when the exact matrix elements for these processes are included.

These processes can be simulated separately with IPR0 = 13 for BGF (light quarks), IPR0=14 for BGF (heavy quarks) and IPR0 = 15 for QCD-C. The prompt photon process $\gamma q \rightarrow \gamma q$ is simulated via IPR0 = 16.

A full simulation including QPM - as well as 1st order α_s - processes is selected with IPR0=12 (or IPR0 =1200 for HERACLES) together with IFULL=1. The decision whether to generate a QPM or a 1st order α_s event is based on the cross section for a particular process at a given x and Q^2 . Therefore for each event the cross section for BGF light quarks, BGF heavy quarks and QCD - Compton has to be obtained by numerical integration including the proper parton densities. If the scale chosen for α_s and the parton densities (IQ2) is Q^2 or \hat{s} , then the matrix elements are integrated analytically over z leaving only a one dimensional numerical integration. If, however, the scale is p_T^2 (or any function of it) then α_s and the parton densities cannot be factorized, and a time

consuming two dimensional numerical integration has to be performed. As an alternative the QCD probabilities are calculated once and stored in a grid (IGRID=1). This approach is faster but less accurate. This procedure is recommended the scale is chosen to be p_T^2 (IQ2=3) or $Q^2 + p_T^2$ (IQ2=5).

In order to avoid divergences in the matrix elements for massless quarks a cutoff in p_T^2 has to be specified (PT2CUT). The minimum p_T^2 is only restricted by the requirement that the sum of the order α_s processes is smaller or equal F_2 .

However care has to be taken in the case of pomeron exchange, that Q^2 evolved parton densities are used with the proper normalizations for quark and gluon densities, otherwise it can occur that the probability for photon - gluon fusion exceeds the total cross section calculated from F_2^P with the quark densities even for relatively large PT2CUT.

4.5.2 NLO and Order α_s matrix elements

The problem using a p_T^2 cutoff, as described in the previous subsection can be overcome by a proper treatment of the NLO corrections to F_2 . Such a scheme is described in detail in [45, 46]. The LO (α_s^0) and the NLO (α_s) part are treated according the \overline{MS} subtraction scheme, reformulated such that it properly can be used together with initial and final state parton showers, avoiding any double counting [47]. When using this scheme, the NLO parton densities calculated in the \overline{MS} scheme should be selected. The program then transforms the parton densities from the \overline{MS} to the BS scheme.³ However, at present only the BGF part is implemented. This scheme is switches on with IBS=1.

4.6 Treatment of heavy flavor production

Heavy flavors, like charm and bottom, are usually produced via boson - gluon fusion. However in the evolution of the parton densities, and similarly in the evolution of $F_2(x, Q^2)$, heavy quarks are often treated in the same way as light quarks, often not even respecting the production threshold properly. Thus when calculating 1st order α_s matrix elements there is a contribution of QCD-C from charm in the proton, together with BGF and eventually also QPM type events with charm. Whether this is a consistent treatment, depends on the details of the Q^2 evolution of the parton densities.

GRV [23, 24], for example, calculate $F_2^{charm}(x, Q^2)$ only via BGF. Thus in their approach the charm quark density is zero. However, for technical reasons for calculation of the total cross section, in the parameterization of the parton densities, as implemented in LHAPDFLIB [4] a charm quark density is provided, which is calculated from the BGF process. This is correct as long as only the total cross section is considered, which is calculated via

$$\sigma^{\gamma^* p}(x, Q^2) = \frac{4\pi^2\alpha}{Q^2} \cdot F_2(x, Q^2) = \frac{4\pi^2\alpha}{Q^2} \cdot \sum_{i=-6}^6 e_i^2 \cdot xq_i(x, Q^2) \quad (13)$$

For a proper description of the hadronic final state using the GRV parton densities, only light quarks are allowed for QPM and QCD-C processes, and all heavy quarks are only produced via BGF.

Just from the parton density parameterization itself, it is nor possible to decide whether heavy quarks are produced only via BGF or not. Thus the user has to take care of this via NFLQCDC, which is set by default to NFLQCDC=3. If heavy quarks are allowed to be produced also by QCD-C processes, then the user should set NFLQCDC=4, or NFLQCDC=5.

³The implementation of this scheme into RAPGAP was done by S. Schilling.

4.7 QCD processes in hadron-hadron collisions

The hard subprocesses implemented are:

$$gg \rightarrow q\bar{q} \quad \text{IRPA}=1 \quad (14)$$

$$gg \rightarrow gg \quad \text{IRPB}=1 \quad (15)$$

$$qg \rightarrow qg \quad \text{IRPC}=1 \quad (16)$$

$$q\bar{q} \rightarrow gg \quad \text{IRPD}=1 \quad (17)$$

$$q\bar{q} \rightarrow q\bar{q} \quad \text{IRPE}=1 \quad (18)$$

$$qq \rightarrow qq \quad \text{IRPF}=1 \quad (19)$$

$$qg \rightarrow q\gamma \quad \text{IRPH}=1 \quad (20)$$

$$q\bar{q} \rightarrow g\gamma \quad \text{IRPI}=1. \quad (21)$$

The corresponding color configurations are given in ICOLORA.

4.7.1 Hadron-hadron collisions

In hadron hadron collisions non-diffractive ($\text{IDIR}=1$) diffractive processes ($\text{IDIR}=0$) with diffractive parton densities and processes with π -exchange ($\text{IDIR}=0, \text{NG}=20$) are available (for details on switches and PDFs see 4.2).

4.7.2 Resolved Photons in γp and DIS

Resolved photon processes play an important role in high p_T jet - production in photo-production. Any internal structure in the proton as well as in the photon can be resolved as long as the scale of the hard subprocess, which is of the order of p_T^2 , is larger than the inverse radius of the proton $1/R_p^2 \sim \Lambda_{QCD}^2$ and the photon $1/R_\gamma^2 \sim Q^2$.

In DIS resolved photon processes [48] can play a role when the scale μ^2 of the hard subprocess is larger than Q^2 , the inverse size of the photon.

Resolved photon processes in DIS are more complicated than in photo-production because one has to treat properly the kinematics of the scattered electron. This is done with the Equivalent Photon Approximation, giving the flux of virtual transverse polarized photons [49]. The structure of the virtual photon is defined by parameterizations of the parton densities of the virtual photon, now depending on the scale μ^2 and Q^2 : $x_\gamma f_\gamma(x_\gamma, \mu^2, Q^2)$ [50–52]. Resolved photon processes can be selected via $\text{IPRO}=18$ for real and virtual photons (depending on Q_{min}^2).

Since these processes can only occur for $\mu^2 > Q^2$, large differences in the cross section are expected when choosing different scales μ^2 , like $\mu^2 = p_t^2$, or $\mu^2 = \hat{s}$. A part of this dependence is removed when next-to-leading order diagrams are considered. For example the process $qg \rightarrow qg$ also occurs in a NLO calculation for jet production in DIS [53–55]. However in resolved photon processes there is also the evolution of the virtual photon parton densities from Q^2 to the scale μ^2 , which is a re-summation to all orders. Therefore differences between full NLO calculations and resolved photon processes are expected [55].

From version 2.06/29 resolved photon processes are also implemented for diffraction and π exchange.

4.8 Scales, α_s and Parton Distribution Functions

In leading order α_s processes the renormalization scale μ_R ($\alpha_s(\mu_R^2)$) and factorization scale μ_F ($xf(x, \mu_F^2)$) are not well defined, and any choice of $\mu_R^2 = \mu_F^2 = Q^2$, p_t^2 , $4p_t^2$, \hat{s} , $Q^2 + p_t^2$ is reasonable. There are essentially two competitive effects: a larger scale gives smaller $\alpha_s(\mu^2)$ but a larger parton density $xf(x, \mu^2)$ at fixed x . The net effect depends on the details of the interaction and the parton density.

RAPGAP offers different choices for the scales: $\mu^2 = m^2$, \hat{s} , $m^2 + p_t^2$, Q^2 , $Q^2 + p_t^2$, selected with $\text{IQ2} = 1, \dots, 5$ ($\text{IQ2}=1$ only makes sense for heavy quark production). A scale factor SCALF can be chosen to study the effect of different scales: $\text{SCALF}=4$ with $\text{IQ2}=3$ will result in a scale $\mu^2 = 4p_t^2$ for α_s and the parton densities. In case of $\text{IQ2}=5$ a scale factor $\text{SCALF}=4$ will result in $\mu^2 = Q^2 + 4 \cdot p_t^2$.

Considering the $O(\alpha_s)$ matrix element processes one could argue that the scale corresponds to the propagator t (u for the crossed diagram) [56], which is

$$\mu^2 = \max(|t, u|) \quad (22)$$

$$= \max(|-Q^2 - 2q \cdot p_{f1}, -Q^2 - 2q \cdot p_{f2}|) \quad (23)$$

$$= \max(1 - z, z) \cdot (\hat{s} + Q^2) \quad (24)$$

with $z = \frac{p_i \cdot p_{f1}}{p_i \cdot q}$ and p_i (p_f) being the momentum of the initial (final) state parton. Expressing p_T^2 in terms of z it is easily seen that this choice of the scale μ^2 is always larger than $p_T^2 = z(1-z)\hat{s}$.

The strong coupling constant is calculated consistently in the one loop expression (using ULALPS from PYTHIA [57–59]):

$$\alpha_s(\mu^2) = \frac{12\pi}{(33 - 2n_f) \log(\mu^2 / (\Lambda_{QCD}^{n_f})^2)}$$

Often Λ_{QCD} is just taken from the parameterization of the parton densities, but when using non-diffractive processes together with diffraction and pion exchange, it is not clear which Λ_{QCD} to take, the one from the parameterization of the proton, or the pomeron or the pion. The same problem occurs when resolved photon processes are included. By default, the value for Λ_{QCD} is taken from the parton density. Using ILAM it can be specified separately by via the switches of PYTHIA: MSTU(112) giving the No. of flavors with respect to Λ_{QCD} , PARU(112) giving the value of Λ_{QCD} . The default value is $\Lambda_{QCD}^5 = 0.25$ and MSTU(112)=5. The number of actual open flavors n_f depends on μ^2 , and α_s is required to be continuous at the flavor thresholds.

Most recent parton density parameterizations of the proton and the pion can be accessed from the LHAPDFLIB [4] with MSTP(51)=NSET (example: MSTP(51)=10150 gives CTEQ6L NLO structure function of the proton). Technically PYSTFU from PYTHIA [1] has been modified to be used within RAPGAP. If the user has no access to LHAPDFLIB internally coded parameterizations can be used with MSTP(51)<10 with details given in the program description.

The parton densities of the pion are accessed similarly with MSTP(52).

The parton densities of the virtual photon are accessed with MSTP(56). In the program the parameterizations GRS [50] (MSTP(56)=1) and SaS [51] (MSTP(56)=2) are available. For MSTP(56)>10 again LHAPDFLIB is used for real photons and the virtual photon suppression factor of Drees - Godbole [52] is applied.

In the resolved photon case a factor SCALQ2 can be specified, which regulates the phase space region, where resolved photon processes are possible: SCALQ2=1 means $\mu^2 \geq 1 \cdot Q^2$, and SCALQ2=10 means $\mu^2 \geq 10 \cdot Q^2$ where μ^2 is the scale specified by IQ2.

4.9 Exclusive Vector-meson Production

Vector meson production is included naturally in diffractive scattering. This is easiest seen for J/ψ production. Suppose we have a system of a $c\bar{c}$ quark, plus eventually additional gluons in the final state. If the invariant mass $m_x = (q + p_P)^2 < 4 \cdot m_{D^0}^2$ then only J/ψ 's can be produced (η_c production is not possible because of spin constraints). Technically this is done in the fragmentation program PYTHIA [57–59]. However the ratio of spin 0 to spin 1 mesons has to be included by hand by setting PARJ(13)=1 (for the light u, d mesons PARJ(11)=1, and for s mesons PARJ(12)=1) for PYTHIA.

Exclusive vector meson production implies certain restrictions on the kinematic variables x_P and β :

$$x_P = \frac{q \cdot p_P}{q \cdot P} = \frac{Q^2 + m_x^2}{Q^2 + W^2}$$

$$\beta = \frac{Q^2}{2 \cdot q \cdot p_P} = \frac{Q^2}{Q^2 + m_x^2}$$

Thus for $m_x = m_{VM}$ and fixed W the variables x_P and β depend only Q^2 . Thus changing Q^2 means moving in the two dimensional $x_P - \beta$ plane, which has consequences on the Q^2 dependence of the $\gamma^* p \rightarrow VMp$ cross section.

The cross section for vector meson production of course depends crucially on the underlying subprocess. Using the recent parameterization of $F_2^{D(3)}(x_P, \beta, Q^2)$ of the H1 collaboration [15] together with IPRO=12 and

IDIR=0 (which is QPM on a parton in the pomeron) J/ψ production as measured by the experiments H1 and ZEUS [61, 62] can be well described as a function of Q^2 and also W [63]. Surprisingly a $\sim 1/Q^4$ dependence of the photon proton cross section appears, which can be interpreted as a higher twist effect. However in the model described here this Q^2 dependence appears naturally from the β dependence of the structure function $F_2^{D(3)}$, since as shown above, changing Q^2 is equivalent with changing β for a given vector-meson.

5 Remnant Treatment and Fragmentation

The fragmentation in RAPGAP is done with the Lund - string model as implemented in PYTHIA/PYTHIA [1]. For the treatment of the remnant and initial state parton showers, subroutines from the programs LEPTO6.1 [56] (LMEPS, LPRIKT, LREMH) and PYTHIA [1] (PYREMN, PYSPLI, PYSSPA) have been copied and modified to be applicable here. The original structure of these subroutines is kept.

Optionally higher order QCD radiation can be simulated via leading log parton showers (IFPS=1 for initial state parton shower, IFPS=2 for final state PS, IFPS=3 for initial and final state PS) or with the color dipole model (as implemented in ARIADNE [64] with IFPS=10).

5.1 Hadronic final state

In a standard inelastic scattering process a parton carrying color is removed from the target (a proton and/or a photon in case of resolved photon processes) and in general colored remnants are left. These remnants together with the colored partons of the hard interaction must form color singlet states (see Fig. 1). Color strings connect the colored partons with the remnants and these color strings generate particle flows between the remnants and the partons of the hard scattering.

In the lowest order process ($\gamma^*q \rightarrow q'$) the remnant is a $di - quark$ when the scattering occurs on a valence quark of the proton (Fig. 1a.). If, however, the scattering occurs on a sea quark or a anti - quark, the remnant is treated as a valence quark and valence $di - quark$ plus the corresponding anti - quark from the sea. This "new" sea quark treatment was first developed and implemented in LEPTO 6.5 [66] (Fig. 1b.).

In the case of BGF a color octet gluon is removed from the proton leaving a quark and a $di - quark$ behind. The quark from BGF forms a color string with the $di - quark$ and the anti - quark from BGF is connected via another string to the remnant valence quark (Fig. 1c.).

For QCD - Compton ($\gamma^*q_i \rightarrow q_f g_f$) the gluon g_f acts as a kick in the color string drawn from the quark q_f to the remnant $di - quark$ (Fig. 1d.). If the quark q_i actually was a sea quark, then the remnant has an additional anti-quark \bar{q}_i . This anti-quark \bar{q}_i forms a color singlet state with the left over valence quark q_v of the proton (Fig. 1e.). If the scattering occurred on a anti quark, then the strings are just reversed.

In rapidity gap events the proton stays intact or becomes a low mass diffractive state, here simply labeled with p' . Because of the emission of the color neutral particle there is no color connection between the outgoing scattered proton p' and the other particles. When a quark (anti-quark) is removed from the pomeron a anti-quark (quark) of the same flavor but with the corresponding anti-color is left (Fig. 2a). When a gluon is removed from the pomeron \mathbb{P} , a color octet remnant is left, here treated as a single gluon. This pomeron remnant together with the $q\bar{q}$ of the hard interaction forms the color singlet state (Fig. 2b).

Pion exchange is treated similarly to pomeron exchange with the corresponding modifications for the outgoing particle p' which is a p , n or Δ^{++} corresponding to π^0 , π^+ or π^- exchange. The treatment of valence and sea quarks follows the same principles as for inclusive ep scattering described above.

The color strings are much more complicated for resolved photon processes because two remnants, one from the proton and one from the photon, have to be considered. Resolved photon processes are similar to $p\bar{p}$ scattering and the relevant color connections are discussed in detail in [67].

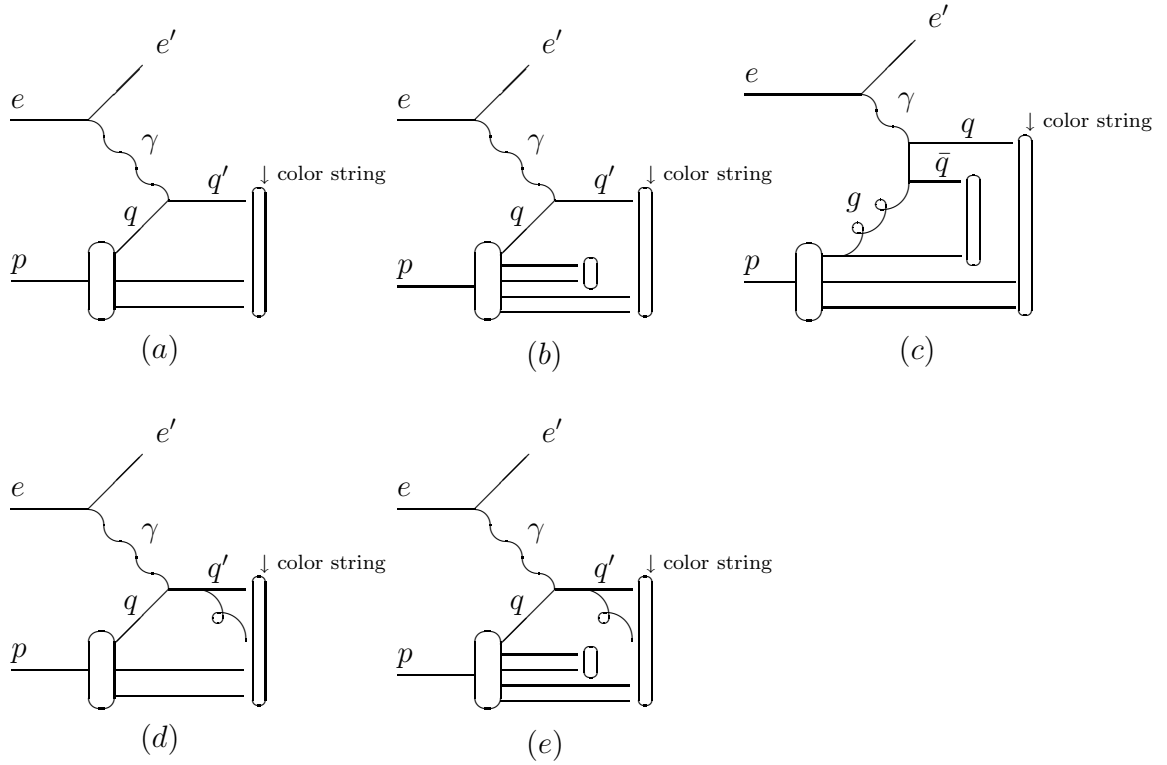


Figure 1: Basic processes for inelastic lepton nucleon scattering. Indicated are the color strings and the proton remnant. *a.* shows the lowest order process for scattering on a valence quark. The remnant of the proton is just a di - quark-quark. *b.* shows the lowest order process for scattering on a sea quark. The remnant of the proton is the corresponding anti-quark , a valence quark and a valence di-quark. *c.* shows the $O(\alpha_{em}\alpha_s)$ for gamma gluon fusion (the crossed diagram is not shown). The proton remnant is the valence quark and valence di-quark. *d.* shows the $O(\alpha_{em}\alpha_s)$ for QCD Compton (the crossed diagram is not shown) on a valence quark. The proton remnant is the same as in *a.* *e.* shows the $O(\alpha_{em}\alpha_s)$ for QCD Compton (the crossed diagram is not shown) on a sea quark. The proton remnant is the same as in *b.*

5.2 Proton dissociation

5.2.1 Proton dissociation ala DIFFVM

Dissociation of the proton according to the model in DIFFVM [68,69] can be included for diffractive events via NFRAG=20. Additional parameters describe the dependence

$$\frac{d\sigma}{dM_Y^2 dt dx_{\mathcal{P}}} \sim \frac{1}{M_Y^{2(1+\epsilon_Y)}} \exp(-B_{diss}|t|)$$

with PEPS= ϵ_Y and PRN2= B_{diss} .

5.2.2 Proton dissociation with a simple model

Dissociation of the proton can be included for diffractive events via NFRAG=10. In this case the proton is split into a quark q_p and di-quark $di - q_p$ system, whereas the pomeron is assumed to couple to a single quark q_p only, and therefore the outgoing quark q'_p carries all of the momentum transfer t giving it a transverse momentum.

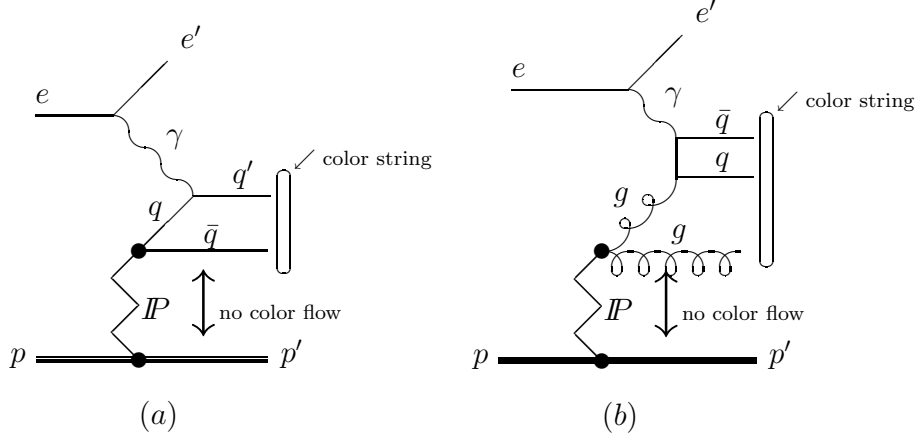


Figure 2: Basic processes for inelastic diffractive lepton nucleon scattering. Indicated are the color strings and the pomeron remnant. *a.* shows the lowest order process for scattering quark. *b.* shows the $O(\alpha_{em}\alpha_s)$ for gamma gluon fusion (the crossed diagram is not shown). The pomeron remnant is a color octet gluon *c.* shows the $O(\alpha_{em}\alpha_s)$ for QCD Compton (the crossed diagram is not shown) on a quark. The pomeron remnant is the same as in *a.*

The quark to which the pomeron couples carries a momentum fraction χ of the protons initial momentum. The momenta of the initial quark q_p and the di-quark $di - q_p$ are given in the following:

$$q_p \simeq \chi p \quad (25)$$

$$di - q_p \simeq (1 - \chi)p \quad (26)$$

$$q'_p = q_p - p_{\mathcal{P}} \simeq \chi p - p_{\mathcal{P}} \quad (27)$$

where $\chi = \frac{q \cdot q_p}{q \cdot p}$ with q (q_p , p) being the photon (quark, proton) momentum. In addition the quark and di-quark get primordial p_{\perp} according to a Gaussian distribution.

The momentum fraction χ can be estimated within the resolved pomeron model:

$$\chi = \frac{x_{\mathcal{P}}}{\beta'} \quad (28)$$

with $\beta' = \frac{q \cdot p_{\mathcal{P}}}{q \cdot q_p}$ being the momentum fraction of the quark q_p of the pomeron momentum, and $x_{\mathcal{P}} = \frac{q \cdot p_{\mathcal{P}}}{q \cdot p}$. The value of $x_{\mathcal{P}}$ is already known from the interaction $\gamma \mathcal{P}$ and β' can be generated according to quark density of the pomeron.

For β' different probability functions are available:

$$P(\beta') = 2(1 - \beta') \quad (\text{IREM}=1), \quad (29)$$

$$P(\beta') = (a + 1)(1 - \beta')^a \quad (\text{IREM}=2), \quad (30)$$

$$P(\beta') = \frac{N}{\beta' \left(1 - \frac{1}{\beta'} - \frac{c}{(1 - \beta')}\right)^2} \quad (\text{IREM}=3) \quad (31)$$

with a chosen such that $\langle \beta' \rangle = 1/(a + 2)$ and c determined by the ratio of masses of the remnant quark and di-quark system. The option IREM=1 corresponds to a hard quark density of the pomeron. Actually all the parameterizations are taken from inclusive DIS scattering as implemented LEPTO 6.1 [56].

The mass distribution M_R of the p - dissociative system follows in general a $1/M_R$ distribution for all the parameterizations of $P(\beta')$ available [63].

Even with proton dissociation switched on, a proton will emerge after fragmentation when the momentum transfer is small and the mass of the $q - di - q$ system remains below the threshold for multi-particle production.

5.3 QCD parton shower evolution

Higher order QCD effects are taken into account using the leading log parton shower approach.

5.3.1 Initial state radiation

Starting from the hard scattering process with x being the fractional momentum of the incoming quark at a suitable scale μ^2 , a backward evolution according to the DGLAP evolution equations [41–44] will lead to larger initial values of x_i and smaller μ^2 . Especially at high center of mass energies initial state QCD radiation will become important and has to be taken into account to model properly the hadronic final state.

The probabilities for a branching of a parton $a \rightarrow bc$ to happen are given by the DGLAP evolution equations:

$$\frac{d f_a(x, t)}{d t} = \frac{\alpha_s(t)}{2\pi} \sum_a \int_x^1 \frac{d x'}{x'} f_a(x', t) P_{a \rightarrow bc} \left(\frac{x}{x'} \right) \quad (32)$$

where $f_a(x', t)$ are the parton density functions, giving the probability of finding a parton a carrying the fraction x' of the momentum fraction x probed at a scale t . $P_{a \rightarrow bc}$ are the DGLAP splitting functions:

$$P_{q \rightarrow qg}(z) = \frac{4}{3} \frac{1+z^2}{1-z} \quad (33)$$

$$P_{g \rightarrow gg}(z) = 6 \frac{(1-z)(1+z)^2}{z(1-z)} \quad (34)$$

$$P_{g \rightarrow q\bar{q}}(z) = \frac{1}{2} (z^2 + (1-z)^2) \quad (35)$$

Soft gluon emission causes problems, since the splitting functions $P_{q \rightarrow qg}, P_{g \rightarrow gg}$ are divergent as $z \rightarrow 1$. Practically in order to avoid divergences, an upper cutoff z_{max} is introduced and the remaining soft gluon emission is treated as an effective shift in z (for details see [70, 71]). The actual value of $z_{max} = \frac{x+\epsilon}{x}$ plays a crucial role in properties of the hadronic final state, such as the transverse energy flow in the proton direction. Using the standard value of PYTHIA for ϵ , which is $\sqrt{s} \cdot \epsilon = 2$ GeV, the transverse energy in the proton direction in DIS away from the current jet falls well below the data [72]. Decreasing ϵ increases the transverse energy flow, and the data are much better described. The value z_{max} chosen in RAPGAP corresponds to the kinematic limit of quark pair creation when the current masses of the quarks are taken into account.

Starting from the hard interaction process at a suitable scale μ^2 ($\mu^2 = \hat{s}, p_{\perp}^2$) the partons are evolved backward. This backward evolution is quite complicated and is used in the Monte Carlo program for efficiency reasons when optimizing the generation of the kinematic variables for the hard scattering process. In a forward evolution scheme the number of degrees of freedom for the generation would vary event by event and no standard optimization procedure would be applicable.

In $p\bar{p}$ collisions the “ \hat{s} approach” is widely used (PYTHIA [70, 71]) whereas a different approach in lepto-production is adapted in LEPTO [56, 73]. The initiators of the parton shower cascade (partons inside the proton for example) are treated collinear with the original particle when effects from primordial k_t are neglected and have negligible mass ($m^2 \leq 1$ GeV). When a branching occurs, $p_3 \rightarrow p_1 + p_2$, the daughter partons p_1 and p_2 will have transverse momenta and virtualities greater than that of the initiator p_3 . Thus after the QCD cascade the partons going into the hard interaction also have transverse momenta compared to the non parton shower case.

In γp and $p\bar{p}$ collisions there is no problem associated with this treatment since the kinematics of the hard interaction usually cannot be determined by measuring the scattered beam-particles either because the beam-particle is totally absorbed (the photon in γp) or because the beam-particle is insufficiently measured by experiment. However in lepto-production the kinematics are usually defined by the scattered lepton (y, Q^2 for example). In that case there will be mismatch between the generated y, Q^2 (before the parton cascade) and after QCD radiation has been added mainly because of the additional transverse momentum. For lepto-production a special approach has been developed “LEPTO approach” [56, 73]) in order to keep the scattered lepton and the (virtual) photon unchanged even with initial state parton shower. This approach is now consistently used in RAPGAP within the subroutine PYSSPA which was taken from PYTHIA and LEPTO [56, 59] with considerable modifications to be used also for low Q^2 processes, photo-production and diffractive scattering.

In DGLAP based parton showers the emitted partons are strongly ordered in p_T , meaning that in a backward evolution the parton with the largest p_T is generated first and closest in rapidity to the hard subprocess partons. The other partons generated must have smaller p_T .

If the hard scattering was just the lowest order process ($\gamma q \rightarrow q$) then the (only available and) largest scale is Q^2 and the p_T of the shower partons can go up to $\sqrt{Q^2}$. The situation is different when $O(\alpha_s)$ matrix element processes are considered. The maximum scale could be Q^2, \hat{s}, p_T^2 . Here we choose the maximum scale to be:

$$\mu^2 = \max(|-Q^2 - 2q \cdot p_{f1}, -Q^2 - 2q \cdot p_{f2}|) \quad (36)$$

This choice [56] is motivated from the propagator of the matrix elements and is of the order of p_T^2 as shown in eq.(24).

When $O(\alpha_s)$ processes are considered in addition to the leading order process ($\gamma q \rightarrow q$) then the maximum scale for parton showers are calculated as follows: parton showers in the leading order process can go up to $\mu^2 = 4 \cdot p_{T\ cut}^2$ instead of Q^2 when no matrix elements are included (with $p_{T\ cut}^2 = \text{PT2CUT}$ being the divergency cut off in the matrix elements). This choice can be understood since parton emissions with $p_T > p_{T\ cut}$ are already included in the matrix element simulation [56]. Parton showers in the matrix element processes can go up to virtualities defined in eq.(24).

It is obvious that the initial state parton shower approach can only be applied correctly when parton densities are available as a function of Q^2 . Moreover this parton densities have to be obtained in a consistent way using the DGLAP evolution equations and consistent definition of α_s .

Now also even for diffractive scattering QCD analysis of $F_2^{D(3)}$ and parameterizations of the diffractive parton densities obtained with DGLAP are available and can be used in initial state parton showers.

Optionally QCD cascades can be simulated according to the color dipole model as implemented in ARIADNE [64]) (via IFPS=10).

5.3.2 Final state parton showers

Final state parton showers are more easily simulated (PYSHOW of PYTHIA) since here a forward evolution scheme is used and no parton densities enter the evolution. The maximum scale is either $\min(4p_{T\ cut}^2, W^2)$ for the leading order processes or \hat{s} for the $O(\alpha_s)$ matrix elements. Details can be found in [59].

6 Description of the program components

6.1 Subroutines and functions

RGMAIN	main program
GRAINI	initializes the program
RAPGAP	performs integration of the cross section. This routine has to be called before event generation can start.
RAEND	prints cross section and the number of events.
EVENT	performs the event generation and the proper mixing of parton shower and matrix elements if selected via IFULL=1. Also the mixing of <i>standard IS</i> , diffractive scattering and pion exchange is done, if selected via IDISDIF=1.
ANALYS	user analysis subroutine.
ALPHAS(RQ)	give $\alpha_s(\mu)$ with $\mu = \text{RQ}$.
PARTI	initial particle and parton momenta are given.
DFUN	interface to FXN1
FXN1	calls routines for selected processes: DIFFR1, DIFFR2, DIFFR3, DIFFR4, DIS1, DIS2, DIS3, DIS4.
CUTG(IPRO)	cuts for process IPRO=13 and IPRO=15 ($\gamma\gamma$ fusion and QCD - Compton) in integration and event generation.
FRAG	generates color string connection for hadronization.

DIFFR1	for diffractive and pion exchange processes $\gamma g_{\mathcal{P}} \rightarrow q\bar{q}$. Calls kinematics and phase space routine PARTDF and matrix element ELEQQL and ELEQQB. Both for light and heavy quarks. Using Equivalent Photon approximation and $\gamma g \rightarrow q\bar{q}$ matrix element.
DIFFR2	for diffractive and pion exchange processes $eg_{\mathcal{P}} \rightarrow e'q\bar{q}$. Calls kinematics and phase space routine PARTDF and matrix element ELEQQF. Both for light and heavy quarks. Using full matrix element for $eg \rightarrow e'q\bar{q}$.
DIFFR3	for diffractive and pion exchange processes $eq(\bar{q}) \rightarrow e'q'(\bar{q}')$. Calls kinematics and phase space routine PARTDF.
DIFFR4	for diffractive and pion exchange processes $eq_{\mathcal{P}} \rightarrow e'qg$. Calls kinematics and phase space routine PARTDF and matrix element ELEQDC. Using full matrix element for $eq \rightarrow e'qg$.
DIS1	for <i>standard</i> inelastic scattering $\gamma g_p \rightarrow q\bar{q}$. Calls kinematics and phase space routine PARTDI and matrix element ELEQQL and ELEQQB. Both for light and heavy quarks. Using Equivalent Photon approximation and $\gamma g \rightarrow q\bar{q}$ matrix element.
DIS2	for <i>standard</i> inelastic scattering $eg_p \rightarrow e'q\bar{q}$. Calls kinematics and phase space routine PARTDI and matrix element ELEQQF. Both for light and heavy quarks. Using full matrix element for $eg \rightarrow e'q\bar{q}$.
DIS3	for <i>standard</i> inelastic scattering $eq(\bar{q}) \rightarrow e'q'(\bar{q}')$ Calls kinematics and phase space routine PARTDI.
DIS4	for <i>standard</i> inelastic scattering $eq_{\mathcal{P}} \rightarrow e'qg$. Calls kinematics and phase space routine PARTDI and matrix element ELEQDC. Using full matrix element for $eq \rightarrow e'qg$.
ELEQQL	matrix element for $\gamma g \rightarrow q\bar{q}$. q stands for light quark.
ELEQQB	matrix element for $\gamma g \rightarrow Q\bar{Q}$ including masses. Q stands for heavy quark.
ELEQQF	matrix element for $eg \rightarrow e'Q\bar{Q}$ including masses. Q stands for light or heavy quark. Masses of light quarks $m_q = 10$ MeV.
ELEQDC	matrix element for $eq \rightarrow e'qg$. Masses of light quarks $m_q = 10$ MeV.
ELERES	matrix elements for resolved photon processes.
ELEQQ	matrix element for exclusive diffractive $q\bar{q}$ production [21, 22].
ELEQQG	matrix elements for diffractive $q\bar{q}g$ production [74].
DOT(A, B)	A.B four vector dot product
DOT1(I, J)	four vector dot product of vectors I and J in LUJETS common.
RANUMS	vector of random numbers used in event generation.
PHASE	phase space and generation for momenta of final partons in hard subprocess. $2 \rightarrow 2$ and $2 \rightarrow 3$ processes.
PARTDF	phase space and event record for diffractive and pion exchange processes.
PARTDI	phase space and event record for <i>standard</i> inelastic scattering processes.
PYSTFU(KF, X, SCALE, XPQ)	parton density in particle KF (KF = 2212 for the proton). XPQ= $xf_i(x, \mu^2)$ with X= x , SCALE= μ^2 . Copied from LEPTO 6.1 [56] and updated to include partons of the pomeron (pion) inside the proton.
RASTFU(KF, X, SCALE, XPQ)	parton density in particle KF (KF = 100 for the pomeron, KF = 211 for the pion). XPQ= $xf_i(x, \mu^2)$ with X= x , SCALE= μ^2 .
RUNIGLU(KF, X, KT, P, XPQ)	to extract the unintegrated gluon density $x\mathcal{A}(x, k_t, \mu)$ for a proton with KF=2212, as a function of $x = X$, $k_t^2 = KT$ and $\mu = P$. The gluon density is returned in XPQ(0), where XPQ is an array with XPQ(-6:6).
RAT2DI(KF, X, XMAX, TMIN, T, WTDIST)	T= t and X= r dependent probability distribution for radiating a parton KF from the proton. (KF = 100 for the pomeron, KF = 211 for the pion).
PYREMN(IPU1, IPU2)	routine for remnant treatment. Copied from LEPTO 6.1 [56] and updated for the use in resolved photon, diffractive and pion exchange processes.
PRODIFF	routine for proton dissociation. The proton is treated as a quark di-quark system.
PYSPLI(KF, KPA, KFSP, KFCH)	give the spectator KFSP and KFCH partons when a parton KPA is removed from particle KF. Copied from LEPTO 6.1 [56] and updated for the use in resolved photon processes, diffraction and pion exchange.
LMEPS	routine for color flow in all processes and preparation for initial and final state parton showers. Copied from LEPTO 6.1 [56] and updated for the use in low Q^2 processes, photo-production, resolved photon processes, diffraction and pion exchange.
PYSSPA(IPU1, IPU2)	routine for initial state radiation. Calls LSCALE. Copied from LEPTO 6.1 [56] and updated for the use in low Q^2 processes, photo-production, resolved photon processes, diffraction and pion exchange.

LSCALE	gives the maximum virtuality to be used for initial state parton shower generation. Copied from LEPTO 6.1 [56] and updated for the use for diffractive and pion exchange processes.
GADAP	Gaussian integration routine for 1-dim and 2-dim integration. Copied from LEPTO 6.1 [56].
RALMKT	generate primordial p_T according to the Aligned Jet Model.
RYSTGA	master routine for parton densities of the virtual photon. Calls GRSPAR and SASGAM.
GRSPAR	parameterization of Gluck, Reya, Stratman [50].
SASGAM	parameterization of Schuler, Sjöstrand [51].
F2DHW	calculation of diffraction for NG=40 [17].
F2BLW	calculation of diffraction for NG=41 [21, 22].
F2MD	calculation of diffraction for NG=42 [18, 19].
F2MCD	calculation of diffraction for NG=45 [35].
USDIFFR(BETA, SCALE, XPQ, X_POM, T2)	user supplied effective diffractive parton density with the fractional momentum BETA= ξ_i of the pomeron momentum carried by the parton i , the scale SCALE= μ of the structure function XPQ(-6:6)= $\xi q(\xi, \mu^2)$, X_POM= x_P and T2= t (all variables in SINGLE PRECISION).

6.2 Parameter switches

IINT:	(D:=0) select integration procedure =0 BASES/SPRING Integration procedure =1 DIVON Integration procedure
NCAL:	(D:=10000) 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

6.2.1 Parameters for kinematics in lepton-hadron collisions

PLEPIN:	momentum p [GeV/ c] of incoming electron (D=-30) (/INPU/)
PIN:	momentum p [GeV/ c] of incoming proton (D=820)(/INPU/)
QMI:	(D: = 5.0) (/DIFFR/)Minimum Q^2 to be generated
QMA:	(D: = 10^8) (/DIFFR/)Maximum Q^2 to be generated
YMI:	(D: = 0.0)(/DIFFR/) Minimum y to be generated
YMA:	(D: = 1.0) (/DIFFR/)Maximum y to be generated
THEMA, THEMI	(D: THEMA = 180., THEMI = 0) maximum and minimum scattering angle θ of the electron (/ELECT/).
NFLAV	(D: = 5) number of active flavors, can be set by user. (/LUCO/)
NFLQCDC	(D: = 3) number of flavors allowed for QCD Compton processes, can be set by user (/LUCO/).

6.2.2 Parameters for kinematics in hadron-hadron collisions

PLEPIN:	momentum p [GeV/ c] of incoming hadron 1 (/INPU/)
PIN:	momentum p [GeV/ c] of incoming hadron 2 (/INPU/)
NFLAV	(D: = 5) number of active flavors, can be set by user. (/LUCO/)
NFLQCDC	(D: = 3) number of flavors allowed for QCD Compton processes, can be set by user (/LUCO/).

6.2.3 Parameters for hard subprocess selection

IPRO:	(D: = 12) (/RAPA/) select hard subprocess to be generated. The selection of pomeron, pion or <i>standard</i> inelastic scattering is done via IDIR, IDISDIF, NG, NPOM described below. =10: $\gamma g \rightarrow q\bar{q}$ using EPA =11: $\gamma g \rightarrow c\bar{c}$ using EPA =12: $eq \rightarrow e'q'$ =13: $eg \rightarrow e'q\bar{q}$ using full Matrix Element =14: $eg \rightarrow e'c\bar{c}$ using full Matrix Element =15: $eq \rightarrow e'qg$ using full Matrix Element =16: $eq \rightarrow e'q\gamma$ using EPA with $\gamma q \rightarrow \gamma q$.
-------	--

	=18: resolved photon processes, selected via using full Matrix Element
	=20: $\gamma^*p \rightarrow q\bar{q}gp$ [74].
	=21: $\gamma^*p \rightarrow q\bar{q}p$ [21, 22]. Exclusive diffractive dijet production, the same process as IPR0=12 together with NG=41 and NPOM=41, but technically calculated differently and more efficient.
	=30: saturation model for $\gamma^*p \rightarrow q\bar{q}p$ $\gamma^*p \rightarrow q\bar{q}gp$ [37].
	=1200: use HERACLES [38, 39] (optional for simulation of QED radiation) for $eq \rightarrow e'q'$
	=1400: use HERACLES [38, 39] (optional for simulation of QED radiation) for heavy quark production via boson gluon fusion: $eg \rightarrow e'Q\bar{Q}$
Q2SUPP	(D=3.37) exponential low Q^2 suppression of the parton densities to be used with HERACLES: $1 - \exp(-Q2SUPP \cdot Q^2)$, can be changed by user (/LOWQ2S/).
IBS	(D: = 0) select type order $alpha_s$ corrections. = 0 using p_t cutoff scheme = 1 using Collins scheme for NLO [45, 46].
IDIR	(D: = 0) select type of events to be generated. (/DISDIF/) = 1 <i>standard</i> inelastic scattering
IDISDIF	= 0 diffractive and pion exchange processes (D: = 0) choose mixing of <i>standard</i> inelastic scattering, diffractive and pion exchange processes according to cross section(/DISDIF/). = 0 generates only the processes selected by IDIR. If IDIR = 0 then pomeron or pion exchange is selected via NG and NPOM. = 1 mixing of <i>standard</i> inelastic and diffractive processes. = 2 mixing of <i>standard</i> inelastic, diffractive and pion exchange processes.
IFULL	(D: = 1) switch to select lowest order process (IFULL = 0) or quark parton model with $O(\alpha_s)$ matrix elements (IFULL = 1) (/OALPINI/).
IQCDGRID	(D: = 1) switch to select generation of $O(\alpha_s)$ processes in a grid (/OALPINI/).
INTER:	(D: =0) interaction type(/INPU/) = 0 neutral current photon interaction =2 charged current interaction
SIN2W	(D:=0.23) for electroweak processes \sin^2_W (/EWEAK).
XMW2	(D:= 80 · 80 GeV ²) for electroweak processes m_W^2 (/EWEAK).
ISEMIH:	not used at present(/INPU/)
PT2CUT(IPRO):	(D=5.0) minimum p_{\perp}^2 for process IPRO (/PTCUT/). Must be used for generation of light quarks in processes IPRO=10, 13, 15, 18.

6.2.4 Parameters for parton shower and fragmentation

NFRAG:	(D: = 1) switch for fragmentation(/INPU/) = 0 off = 1 on = 10 proton dissociation in simple model = 20 proton dissociation ala DIFFVM
IFPS:	(D: = 3) switch parton shower(/INPU/) = 0 off = 1 initial state = 2 final state = 3 initial and final state = 10 gluon radiation according to ARIADNE.
ILHA:	(D: = 0) Les Houches accord interface = 0 off = 1 use Les Houches accord interface to write parton level event on file <code>rapgap.gen</code>
IORD:	(D: = 1) ordering for initial state P.S. =0 no ordning =1 Q^2 values at branches are strictly ordered, increasing towards the hard scattering strict ordered in Q^2 =2 Q^2 and opening angles of emitted (on shell or time like) partons are both strictly ordered, increasing towards the hard interaction as 1 but also strict ordered in angle
IALP:	(D: = 1)

=1 α_s first order with scale Q^2
 =2 α_s first order with scale $k_t^2 = (1 - z) \cdot Q^2$
 ITIM: (D: =1)
 =0 no shower of time like partons
 =1 time like partons may shower
 ISOG: (D: =1) treatment of soft gluons
 =0 soft gluons are entirely neglected
 =1 soft gluons are resummed and included together with the hard radiation as an effective z shift
 KT1: (D:=0.7) width of a gaussian for intrinsic k_t for photon
 KT2: (D:=0.44) width of a gaussian for intrinsic k_t for proton

6.2.5 Parameters for resolved photon processes

process and color configuration for resolved photon processes (/COLCON/)

IRPA =1(0) (D:=1) process $gg \rightarrow q\bar{q}$ switched on(off)
 IRPB =1(0) (D:=1) process $gg \rightarrow gg$ switched on(off)
 IRPC =1(0) (D:=1) process $qg \rightarrow qg$ switched on(off)
 IRPD =1(0) (D:=1) process $q\bar{q} \rightarrow gg$ switched on(off)
 IRPE =1(0) (D:=1) process $q\bar{q} \rightarrow q\bar{q}$ switched on(off)
 IRPF =1(0) (D:=1) process $qq \rightarrow qq$ switched on(off)
 IRPG =1(0) (D:=0) process $qq \rightarrow qq$ (BFKL) switched on(off)
 IRPH =1(0) (D:=1) process $qg \rightarrow q\gamma$ switched on(off)
 IRPI =1(0) (D:=1) process $q\bar{q} \rightarrow g\gamma$ switched on(off)
 SCALQ2 (D:=1.) specifies the cut on $\frac{\mu^2}{Q^2} = \text{SCALQ2}$ for resolved processes in DIS, can be changed by user (/RESGAM).
 OMEG2: (D:=0.01) $\omega = \text{OMEG2}$ suppression factor for virtual resolved photons in the Dress - Godbole model [52].

6.2.6 Parameters for structure functions α_s and scales

IRUNAEM: (D: = 0) 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: = 5) 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: $\mu^2 = Q^2 + p_\perp^2$
 SCALFA (D=1) (/SCALF/) factor which the scale μ^2 used in α_s and structure function evaluation is multiplied with. For example SCALFA=4 and IQ2=3 means: $\mu^2 = 4 \cdot m^2 + 4 \cdot p_\perp^2$, whereas for IQ2=5 the meaning is $\mu^2 = Q^2 + 4 \cdot p_\perp^2$.
 MSTP(51) : MSTP(51), MSTP(51) MSTP(56) is used to select structure function parameterizations (/PYPARS/).
 With MSTP(51) < 10 the parameterization of p structure function from PYSTFU are used:
 = 0: Simple scaling Function
 = 1: EHLQ set 1
 = 2: EHLQ set 2
 = 3: Duke-Owens set 1
 = 4: Duke-Owens set 2
 = 5: Morfin-Tung set 1 (S1)
 = 6: Morfin-Tung set 2 (B1)
 = 7: Morfin-Tung set 3 (B2)
 = 8: Morfin-Tung set 4 (E1)

= 9: Gluck-Reya-Vogt LO set
 = 10: Gluck-Reya-Vogt HO set
 MSTP(51) > 10 parameterization from LHAPDFLIB [4] is used
 example: 10150 for CTEQ6L NLO proton parton density.

MSTP(52) : MSTP(52) < 10 parameterization of π structure function from PYSTFU (Owens set) is used
 MSTP(52) > 10 parameterization from LHAPDFLIB is used
 example: 211 for for GRV LO [23,24] pion parton density.

MSTP(56) : MSTP(56) < 10 inbuild parton densities are used:
 = 1: GRS [50]
 = 2: SaS [51]
 MSTP(56) > 10 parameterization from LHAPDF is used
 example: Nset= 391 for SaS [51] virtual photon parton density together with the Drees-Godbole Q^2 [52] suppression factor.

6.2.7 Parameters for diffraction

NG: (D: = -14) select pomeron structure function $xf(x)$ (/DIFFR/).
 = 0: $xf_0(x) = 6x(1-x)$ for gluons. For quarks $xq(x) = \frac{1}{4}xf_0(x)$
 = n: $xf_n(x) = (n+1)(1-x)^n$ for $1 \leq n \leq 5$ for gluons. For quarks $xq(x) = \frac{1}{4}xf_n(x)$
 = 10: $xf(x) = (0.18 + 5.46x)(1-x)$ only gluons.
 = 11: $xq(x) = \frac{1}{3}C\pi x(1-x)$ Donnachie Landshoff quark density in pomeron.
 = 12: Kniehl, Kohrs, Kramer parton density [75,76] for pomeron including direct coupling.
 = 20: parton density for π^\pm . If MSTP(52) < 10 Owens set from PYSTFU is used. IF MSTP(52) > 10 parton density for pion used from LHAPDFLIB [4]
 = 21: parton density for π^0 . If MSTP(52) < 10 Owens set from PYSTFU is used. IF MSTP(52) > 10 parton density for pion used from LHAPDFLIB
 = 30: Nikolaev, Zakharov model [36].
 = 40: Wüsthoff model [17].
 = 41: Bartels, Lotter, Wüsthoff model [21,22].
 = 42: Diehl model [18,19].
 = 45: Buchmüller, Hebecker, McDermott model [35].
 = -10: H1 fit 1 (quarks only) (NLO) [15]
 = -11: H1 fit 2 (quarks and gluons) (NLO) [15]
 = -12: H1 fit 3 (quarks and gluons peaked at $z \rightarrow 1$) (NLO) [15]
 = -13: H1 fit 1 (quarks only)(LO) [15]
 = -14: H1 fit 2 (quarks and gluons) (LO) [15]
 = -15: H1 fit 3 (quarks and gluons peaked at $z \rightarrow 1$) (LO) [15]
 = -30: H1 set A (NLO) [16]
 = -31: H1 set B (NLO) [16]
 < 0: user supplied structure function via subroutine

USDIFFR. The parton density must be put in the array XPQ(-6:6) with the gluon at position 0, u, d, s, c, b, t quarks at positions 1, 2, 3, 4, 5, 6 and the anti-quarks at -1, -2, -3, -4, -5, -6.

NPOM: (D: = -10) select pomeron distribution $f_{p/\mathbb{P}}$ (/DIFFR/)
 = 0: pomeron distribution $f_{p/\mathbb{P}}^S$
 = 1: pomeron distribution $f_{p/\mathbb{P}}^{IS}$
 = 2: pomeron distribution $f_{p/\mathbb{P}}^{DL}$
 = 20: $\pi^- t$ - distribution [77]
 = 21: $\pi^0 t$ - distribution [77]
 = 22: $\pi^+ t$ - distribution [77]
 = 30: Nikolaev, Zakharov model [36].
 = 40: Wüsthoff model [17].
 = 41: Bartels, Lotter, Wüsthoff model [21,22].
 = 42: Diehl model [18,19].
 = 45: Buchmüller, Hebecker, McDermott model [35].
 = -10: H1 fit pomeron only [15]

= -11: H1 fit meson only [15]
 = -12: H1 fit pomeron and meson [15]
 = -30: H1 fit pomeron only [16]
 = -31: H1 fit meson only [16]
 = -32: H1 fit pomeron and meson [16]
 < 0: user supplied pomeron distribution via subroutine USDIFFR.
 Parameters for the diffractive gluon density in the semi-classical approach of Buchmüller, Hebecker, McDermott [35].

C1: (D: = 1) $C_1 = \mathbf{C1}$ (/BUCHMUE/).
Cg: (D: = 1) $C_g = \mathbf{Cg}$ (/BUCHMUE/).
Iqqg allows different levels of approximation in the matrix element calculation of IPR0=20. Iqqg=0 is the full matrix element, Iqqg=1,2 approximates the matrix element as described in [25]
IGLU: (D: = 1) select unintegrated gluon density/GLUON/.
 =1: CCFM set A0 [27]
 =2: derivative of GRV [28] $\frac{dxg(x,Q^2)}{dQ^2}$.
 =3: approach of Blümlein [29].
 =4: KMS [32] (**kms.dat**).
 =5: saturation model [33].
 =6: KMR [34] (**kmr.dat**).
IREM: (D: = 1) select momentum distribution of proton dissociation (/PREMNANT/).
 = 1: $P(\beta') = 2(1 - \beta')$
 = 2: $P(\beta') = (a + 1)(1 - \beta')^a$
 = 3: $P(\beta') = \frac{N}{\beta' \left(1 - \frac{1}{\beta'} - \frac{c}{(1-\beta')}\right)^2}$
IVM: (D: = 0) select exclusive vector meson production in diffractive scattering (/VMESON).
 = 0: no special selection done.
 > 1 and < 443 :production of light vector mesons
 = 443 :production of J/ψ mesons.
 = 553 :production of Υ mesons.
IALMKT: (D: =0)(/INPU/) include primordial k_t for diffractive processes according to the Aligned Jet Model: $e^{-5.5k_t}$ for IALMKT=1 (/INPU/).
T2MAX: (D: = 5) maximum t [GeV^2/c^2] (/DIFFR/).
XF: (D: = 0.9) minimum XF $x_P = 1 - x_f = 1 - \frac{E'_f}{E_p}$ (/DIFFR/).
 Parameters for proton dissociation:
PEPS: (D:=0.0) ϵ_Y for M_Y^2 spectrum
PRN2: (D:=4.0) B_{diss} for $\exp(-B_{diss}|t|)$
 Parameters for pomeron flux (only for NPOM=0,1,2):
ALPHP: (D: = 0.25) α_P [GeV^{-2}] (/DIFFR/).
RN2: (D: = 4.7) RN2= b_0 as defined above (/DIFFR/).
EPSP: (D: = 0.085) EPSP= ϵ (/DIFFR/).

6.2.8 Accessing information

AVGI integrated cross section (/EFFIC/).
SD standard deviation of integrated cross section (/EFFIC/).

SSS total center of mass energy s (/PARTON/)
PBEAM energy momentum vector of beam particles (/BEAM/)
KBEAM flavor code of beam particles (/BEAM/)
Q2 in lepto-production: actual Q^2 of γ (/PARAE/).
YY energy fraction lost by incident electron (/RAPGKI/)
XEL energy fraction of parton on electron side (/RAPGKI/)
XPR energy fraction of parton on proton side (/RAPGKI/)
YMAX, YMIN actual upper and lower limits for y (/PARAT/).
Q2MAX, Q2MIN actual upper and lower limits for Q^2 of γ (/PARAT/).
XMAX, XMIN upper and lower limits for x (/PARAT/).

PT2H	\hat{p}_\perp^2 [GeV ² /c ²] of parton in hard subprocess <i>cm</i> (/RAPGKI/) system
SHH	invariant mass \hat{s} [GeV ²] of hard subprocess (/RAPGKI/)
T2GKI	for diffractive processes T2GKI = t [GeV ²] (/RAPGKI/)
XFGKI	for diffractive processes XFGKI = x_P (/RAPGKI/)
	$O(\alpha_s)$ matrix element information (/MEINFO/)
AM(18)	vector of masses of final state particles of hard interaction.
SHAT	\hat{s} of hard subprocess (/PARAT/)
ZQGKI	$z = \frac{p_i \cdot p_f}{p_i \cdot q} = \text{ZQGKI}$ (/MEINFO/)
XPGKI	$x_p = \frac{Q^2}{2p_i \cdot q} = \text{XPGKI}$ (/MEINFO/)
PHIGKI	$\phi = \text{PHIGKI}$ azimuthal angle (/MEINFO/)
NIA1, NIA2	position of partons in hard interaction in LUJETS event record (/HARD/)
NF1, NF2	first and last position final partons/particles of hard interaction in LUJETS (/HARD/)
NFT	total number of final particles; for $2 \rightarrow 2$ process NFT = 2
Q2Q	hard scattering scale μ^2 used in α_s and structure functions (/PARAE/).
ALPHS	actual α_s (/PARAM/).
PI	π (/PARAM/).
ALPH	α_{em} (/PARAM/).
NIN	number of trials for event generation (/EFFIC/).
NOUT	number of successful generated events (/EFFIC/).
SCAL1, SCAL2	scale for structure function on beam 1 and 2 respectively (/STRU/).
XDP1, XPD2	value of parton density on beam 1 and 2 respectively (/STRU/).

6.3 List of COMMON blocks

```

COMMON/BEAM/PBEAM(2,5),KBEAM(2,5)
COMMON/BUCHMUE/C1,Cg
COMMON/COLCON/ICOLORA,IRESPRO,IRPA,IRPB,IRPC,IRPD,IRPE,IRPF,IRPG
COMMON/DIFFR/T2MAX,XF,ALPHP,RN2,EPSP,QMI,YMI,QMA,YMA,NG,NPOM
COMMON/DISDIF/IDIR,IDISDIF
COMMON/EFFIC/AVGI,SD,NIN,NOUT
COMMON/ELECT/THEMA,THEMI
COMMON/EWEAK/SIN2W,XMW2
COMMON/F2INT/F2DIS,F2DIF,F2PI COMMON/HARD/NIA1,NIR1,NIA2,NIR2,NF1,NF2,NFT
COMMON/INPU/PLEPIN,PPIN,NFRAG,ILEPTO,IFPS,IHF,IALMKT,INTER,ISEMIH
COMMON/LOWQ2S/Q2SUPP
COMMON/LUCO/KE,KP,KEB,KPH,KGL,KPA,NFLAV,NFLQCDC
COMMON/MEINFO/ZQGKI,XPGKI,PHIGKI
COMMON/OALPINI/IFULL,IQCDGRID
COMMON/PARAE/Q2,Q2Q,PCM(4,18)
COMMON/PARAM/ALPHS,PI,ALPH,IWEI
COMMON/PARAT/AM(18),SHAT,YMAX,YMIN,Q2MAX,Q2MIN,XMAX,XMIN
COMMON/PARTON/SSS,CM(4),DBCMS(4)
COMMON/PREMNANT/IREM
COMMON/PTCUT/PT2CUT(100)
COMMON/PYPARS/MSTP(200),PARP(200)
PARAMETER (NY=40,NQ=20)
COMMON/QCDGRI/QY(NY),QQ(NQ),
& QPMDF(NY,NQ),QQBDF(NY,NQ),QQBHDF(NY,NQ),QCDCDF(NY,NQ),
& QPMPPI(NY,NQ),QQBPPI(NY,NQ),QQBHPI(NY,NQ),QCDCPI(NY,NQ),
& QPM(NY,NQ),QQB(NY,NQ),QQBH(NY,NQ),QCDC(NY,NQ)
PARAMETER (NBQ2=20,NBX=20)
COMMON/RAHER/IHERPYS,XPQDIF(-6:6,NBX,NBQ2),XPQPI(-6:6,NBX,NBQ2)
COMMON/RGRIDF2/XX(NBX),Q2X(NBQ2)
COMMON/F2VAL/F2_DIS(NBX,NBQ2),F2_DIF(NBX,NBQ2),F2_PI(NBX,NBQ2)
COMMON/RAPA/IPRO,IRUNA,IQ2,IRUNAEM,Q2START,W_Q2,OMEG2
COMMON/RAPGKI/YY,XEL,XPR,PT2H,SHH,T2GKI,XFGKI

```

```

COMMON/RESGAM/SCALQ2
COMMON/SCALF/SCALFA
COMMON/STRU/SCAL1,XPD1,SCAL2,XPD2
COMMON/VMESON/IVM

```

7 Example Program

```

PROGRAM RGMMAIN
Implicit None
#include "rgfull.inc"
#include "rgdisdif.inc"
#include "rgluco.inc"
#include "rgludat1.inc"
#include "rgpara.inc"
#include "rgpypars.inc"
#include "rgdiffr.inc"
#include "rgscq2.inc"
#include "rglq2.inc"
#include "rghsunts.inc"
#include "rghsoptn.inc"
#include "rghscuts.inc"
#include "rghsvglp.inc"
Integer Nevent
Common/steer1/Nevent
    Integer N1,N2

real timeleft
    Integer Minuts
    External Minuts
External pydata

    Integer I,ISEED
C---initialise ARIADNE parameters, now done via block data
C---initialise PYTHIA 6 parameters, via pythia block data
C    initialize random number generator
    ISEED = 213123
    ISEED = Iabs(MINUTS())
    N1 = 0
    N2 = 0
    CALL RM48IN(ISEED,N1,N2)
C---initialise RAPGAP parameters
    CALL GRAINI
C-- read in parameters from file
    Call Steer
C-- change standard parameters of RAPGAP
    Call rapcha
C-- change standard parameters of HERACLES
    Call hercha
C-- change standard parameters of \PYTHIA
    Call pytcha
C-- change standard parameters of ARIADNE
    Call aricha

C Initialize ARIADNE
    CALL ARINIT('RAPGAP')

```



```

C-- change standard parameters of ARIADNE
Call aricha
C--- CALCULATE X SECTION
      CALL PTIME(' rapgap ',1,0)
      CALL RAPGAP
C--- print x section
      CALL RAEND(1)
C--- event generation
      DO 10 I=1,Nevent
          CALL PTIME(' event ',1,0)
c      call timel(timeleft)
c      if(timeleft.le.10.) then
c          write(6,*) ' *** time limit reached. time left = ',timeleft
c          goto 123
c      endif
          CALL EVENT
C--- user analysis routine
c      CALL ANALYS
C--- user analysis routine (hztool)
cc     CALL hzraana
      CALL PTIME(' event ',2,0)
C---
      10 CONTINUE
123   Continue
C---PRINT NR OF GENERATED EVENTS
      CALL RAEND(20)
C--- user terminate routine (hztool)
cc CALL hzraend

      CALL PTIME(' rapgap ',2,0)
      CALL PTIME(' ',2,99)
      STOP
      END
#include "../pythia-bkdata/pydata.f"

```

In the distribution example programs are given also for the use with the HZTOOL [78]. package. The source code is in directory `examples` and the executable is stored in the `bin` directory. To access different subroutines form HZTOOL the file `hzxxxx.inc` has to be changed accordingly.

The `bin` directory contains also sample steering files, for different processes.

To run RAPGAP just type:

```

rapgap32 < steer.charm
or using the HZTOOL verison:
rapgaphztool < steer.charm

```

8 Installation Instructions

Please note:

```

RAPGAP 3.2 contains the source code of HERACLES 4.63 (from .. )
RAPGAP 3.2 contains the source code of BASES/SPRING 5.1 (from ..)
RAPGAP 3.2 contains explicitly the block data from pythia.
      to change/update to newer version, please copy the block data
      pydata.f from the latest PYTHIA version into the directory
      rapgap-3.2/src/pythia-bkdata/pydata.f

```

1) Get the source

```
tar xvfz rapgap-3.2.tar.gz
cd rapgap-3.2
```

2) set environment variables for PYTHIA, CERMLIB and HZTOOL
example (Please change to the proper path of the libraries):

in csh:

```
setenv PYTHIA "/Users/jung/jung/cvs/pythia6410"
setenv LHAPDF "/Users/jung/jung/cvs/lhapdf/lhapdf-5.7.0"
```

If you want to use ARIADNE, you need:

```
setenv ARIADNE "/Users/jung/jung/cvs/ariadne412"
```

If the HZTOOL interfae is wanted, you need in addition:

```
setenv CERN_LIBS "/sw/lib -lmathlib -lkernlib -lpacklib"
setenv HZTOOL "/Users/jung/jung/cvs/hztool-4/hztool-4.2"
```

in zsh:

```
export PYTHIA="/Users/jung/jung/cvs/pythia6410"
export LHAPDF="/Users/jung/jung/cvs/lhapdf/lhapdf-5.7.0"
```

If you want to use ARIADNE, you need:

```
export ARIADNE="/Users/jung/jung/cvs/ariadne412"
```

If the HZTOOL interfae is wanted, you need in addition:

```
export CERN_LIBS="/sw/lib -lmathlib -lkernlib -lpacklib"
export HZTOOL="/Users/jung/jung/cvs/hztool-4/hztool-4.2"
```

2) Generate the Makefiles

```
./configure --disable-shared --prefix=install-path
```

if you want to create an executatble using HZTOOL

```
./configure --disable-shared --prefix=install-path hzexe=yes
```

if you want to create an executatble using ARIADNE

```
./configure --disable-shared --prefix=install-path ariadne=yes
```

3) Compile the binary and the documentation

```
make
```

```
    Install the program
```

```
make install
```

4) the executatble is in "your-installation-directory"/bin

run it with:

```
install-path/bin/rapgap < install-path/share/steer_pp-bottom
```

5.) the documentation is in

```
install-path/share/rapgap32.pdf
```

6.)

9 Acknowledgment

I am grateful to T. Sjöstrand and G. Ingelman, the authors of PYTHIA and LEPTO for their permission to copy and use subroutines from their programs. All the credit concerning initial state parton showers and remnant treatment belongs to them.

I want to thank all those who continue-sly used and checked the program. Special thanks go to G. Briskin, A. Mehta and J. Philipps. Without their ideas, suggestions and comments and heavily use of the program, it would not be like it is now.

10 Update History

RAPGAP 3.2

```
*::>      Version 3.2007 (Nov 2011)
*          prompt photon processes included
*
*::>      Version 3.2006 (May 2011)
*          xf description in manual corrected (Radek Zlebcik)
*          eventpp: removed unnecessary boost to-from CM system (Radek Zlebcik)
*::>      Version 3.2003 (Sept 2010)
*          bug in heavy flavor selection in eleres corrected
*          bug in h1qcd/qcd_2006 on limit of iz,iq2 corrected
*          W/Z production included for pp
*          Higgs production included for pp
*
*::>      Version 3.2002
*          bug in diffraction for pp causing energy momentum conservation problem corrected
*          pp works also with new remnant treatment
*          Lambda_QCD now by default taken from PDF. Use ILAMQCD=0 to switch to steering
*
*::>      Version 3.2001
*          release for hepforge with auto Tools installation
*          For ep: HERACLES 4.6.6
*          CERNLIB lite included
*          problem NFL_GAM in eleres > NFLAV...check and give proper return to program
*-----
```

RAPGAP 3.1

```
*::>      Version 3.1035
*          bug in lmeps for resloved diff scattering corrected
*
*::>      Version 3.1034
*          lower cut for pdfs in h1qcd2006 removed, important for charm
*          f2c for diffraction:printout statements restricted
*
*::>      Version 3.1033
*          bug in rgmain: arinit overwrote changed PYTHIA/JESTET parameters
*
```

RAPGAP 3.1

```
*::>      Version 3.1032
*          mstp(56) changed to mstp(55) for consistency with PYTHIA using LHAPDF
*          nhera mode changed to run with standard lhpdf
*          changes made for proton,pion,photon pdfs
*
*::>      Version 3.1031
*          bug corrected in pion_xpq
*          now also pion pdf from LHAPDF or pdflib (h1qcd2006,h1qcdfit)
```

```

*           problem of very small scales and LHAPDF with HERACLES corrected (rystfu)
*
*
*::>       Version 3.1029
*           new 2006 diff pdfs from H1 included
*           eleres now also for IHFLA=5 working
*
*
*::>       Version 3.1027
*           LHApdf interface for both proton and photon pdfs included
*
*
*::>       Version 3.1026
*           bug of formula for ksi in eleqqf corrected: resulted in wrong
*           xsection for CC heavy quark production via IPR0=14
*
*
*::>       Version 3.1025
*           updated for heracles
*
*
*::>       Version 3.1024
*           for charged current, bug in QCDMIX corrected, to have
*           proper flavor for heavy quarks for IFUL=1
*
*
*::>       Version 3.1023
*           for charged current, bug in HERACLES interface corrected, to have
*           proper neutrino in final state
*
*
*::>       Version 3.1022
*           order of changes of PYHTIA and RAPGAPO params in
*           h1 version changed .... to avoid overwritings ... grapga.F
*           bug for pp version corrected
*
*
*::>       Version 3.1021
*           Updated versions for UPINIT and UPEVNT
*
*
*::>       Version 3.1019
*           PYTHIA block data are now called via external statement
*
*
*::>       Version 3.1020
*           steering files updated according to new frag. parameters
*           Bug in steer corrected: Nmax = 1000
*           Also RGUPINIT and RGUPEVNT added for LHA
*
*
*::>       Version 3.1014
*           bug with splitted variables in rapgap.f corrected
*           bug writing bspdf.dat instead of pdf.dat in rapgap.f corrected
*
*
*::>       Version 3.1013
*           pdiss ala diffvm included also for IPR0=30
*
*
*::>       Version 3.1012
*           pion exchange for neutrons added
*           ARIADNE now for all IPR0 available (also for IPR0=15,18)
*
*
*::>       Version 3.1011
*           updated eleres for charm
*           bug for xb < 0 in PYSSPA corrected

```

```

*::>      Version 3.1008
*          Proton Dissociation included, with routines from DIFFVM (B.List)
*          started by P. Thompson and Y. Coppens
*          Updated treatment of p-diss system acc. to Leszek Adamczyk
*          q-gluon-diq
*
RAPGAP 3.0 (with PYTHIA6)
*::>      Collins NLO (order alphas) for F2 implemented (S. Schilling)
*
*::>
RAPGAP 2.8 (with JETSET 7.4)
*
*::>      VERSION  2.08/19   01/08/2002 12.28.22
*          Bug in initialisation of RM48 found by Thomas Kluge. Thanks.
*
*::>      VERSION  2.08/18   16/01/2002 18.27.20
*          bug in rgsatrev corrected: Phip missing
*
*::>      VERSION  2.08/17   24/10/2001 17.50.59
*          upper scale for final state ps for IPRO 18 updated. Was shat
*          before always !!!
*
*::>      VERSION  2.08/16   14/08/2001 08.27.06
*          bug in eleqqg corrected: 2pi in gamma flux, 2 in l integral
*          bug in partdh corrected: partons for qgg were mixed, caused frag
*          crash in case of charm
*          eleqq updated to use also unintegrated gluon
*
*::>      VERSION  2.08/15   25/06/2001 18.18.51
*          ppbar for incl and diffraction included
*
*::>      VERSION  2.08/14   14/05/2001 13.53.48
*          some double defined subroutines removed and ariadne common blocks
*          and PYPARS updated.
*
*::>      VERSION  2.08/11   08/03/2001 11.00.31
*          small bug in PARTDF corrected, for p* momentum with m ne mp
*
*::>      VERSION  2.08/10   07/02/2001 12.02.40
*          DUDBRB changed to LUDBRB in AREXEC. Bug found by Taro Yamashita
*
*::>      VERSION  2.08/09   17/12/2000 17.00.34
*          In partdi,partdf for heracles mode cut on q2min < q2max removed
*          because events were rejected. Also in parti for HERACLES WEIGHT=1
*          added, all by request from A. Kappes and K.Long.
*          New version of h1qcdfit parameterisation: Redone charm such that
*          charm pdf = BGF *gluon
*          New double precision drapr (using RM48 of CERNLIB). Problems
*          found by Taro in y distribution for IPRO=20. Now is ok.
*
*::>      VERSION  2.08/07   31/07/2000 16.58.11
*          eleqqg (2 gluon exchange) updated for heavy quarks (A. Kyrieleis)
*
*          eleres charge for top corrected
*
*::>      VERSION  2.08/05   30/03/2000 17.28.20
*

```

```

*          rapgap and event changed because of a bug for ipro1200 and pi exchange
*          SATRAP now includes also charm
*
*
*::>      VERSION  2.08/03   10/12/99 12.21.44
*          rgmain bug corrected
*
*::>      VERSION  2.08/02   04/11/99 16.39.29
*          SATRAP (IPRO=30) now included (works also with HERACLES interface
*          IPRO=3000).
*          "Bug" in phi angle of scattered proton for diffraction corrected
*
*::>      VERSION  2.08/01   23/06/99 14.31.37
*          new treatment for diffraction and me mixing...
*
*::>      VERSION  2.08/00   15/06/99 17.31.15
*
*          Bug for IPRO=1200,1400 in diffractive mode with IFULL=1 corrected
*          eta distribution of partons from matrix elements were wrong
*
*          Bug in xpom distribution for diffraction with IFULL=1 corrected
*
*          improved calculation of ME contribution in diffraction, taken into account
*          kinematic limits from pt2cut
*
*          Nr of flavours in structure function now also treated correctly for the
*          HERACLES interface
*
*          test release for IPRO=30, diffraction ala saturation model of M. Wuesthoff
*          coded by H. Kowalski
*
*-----
*
*::>      VERSION  2.07/01   23/03/99 09.07.40
*          heavy flavor excitation in res. photon processes added
*          better treatment of ME mixing in diffr. processes
*
*::>      VERSION  2.07/00   22/01/99 09.30.01
*          pi flux of Holtmann now default
*
*::>      VERSION  2.06/51   10/10/98 18.30.56
*          LEPTOU changed to RAPTOU to avoid confusion with DJANGO
*
*::>      VERSION  2.06/50   30/09/98 08.19.42
*          some default settings updated
*
*::>      VERSION  2.06/49   29/09/98 18.46.00
*          bug for heavy quarks in resolved photon processes corrected
*
*::>      VERSION  2.06/47   19/09/98 19.41.19
*          heavy quark ME's for resolved photons implemented
*          bug for GADAP2 integration of ME corrected
*
*::>      VERSION  2.06/44   01/08/98 18.19.48
*          heracles 4.5 and heracles 4.6 included via SEL=HERACLES46
*
*::>      VERSION  2.06/43   24/07/98 15.25.29

```

```

*          bugs in dimensions for x() corrected
*
*::>     VERSION  2.06/42   23/07/98 15.39.31
*          dimension for x() increased to 20 (necessary for qqg)
*
*::>     VERSION  2.06/41   22/07/98 10.23.45
*          QCDGRID speede up by usage of grid for wmax
*
*::>     VERSION  2.06/38   15/07/98 22.50.21
*          heracles fl included
*
*::>     VERSION  2.06/37   30/06/98 22.30.23
*          Bug in intrinsic k_t for resolved photons corrected (PYREMNN)
*
*::>     VERSION  2.06/36   26/06/98 08.36.26
*          resolved photon BFKL qq -> qq added acc. Cox/Forshaw hep-ph9800506
*
*::>     VERSION  2.06/34   17/06/98 23.08.14
*
*          writing grid file for pdf's included --> faster when same param.
*          processes IPR0=21 included qq 2gluon exchange
*          processes IPR0=20 included qqg 2gluon exchange
*
*::>     VERSION  2.06/33   14/05/98 08.47.12
*          bug when running 1200 with IGRID=1 corrected
*
*::>     VERSION  2.06/32   05/05/98 14.50.19
*          clebsch/cordon coeff for pion exchange corrected in RAT2DI
*
*::>     VERSION  2.06/31   26/03/98 10.34.34
*          2nd attempt for qqg a la Bartels/Wuesthoff
*
*::>     VERSION  2.06/30   18/03/98 13.30.56
*          intrinsic pt for photon and proton changeable by user
*          bug corrected for photon pdfs using pdflib
*
*::>     VERSION  2.06/29   16/03/98 10.08.13
*          1st attempt to include res. gamma also for diffraction
*
*::>     VERSION  2.06/28   13/03/98 12.21.39
*          NFQCDC added: select 3 or more flavours for QCDC
*
*::>     VERSION  2.06/27   09/02/98 11.56.04
*          1st attempt for qqg a la Bartels/Wuesthoff
*
*::>     VERSION  2.06/26   24/01/98 17.15.29
*          fixed problem in phi asym. for hard diffraction
*
*::>     VERSION  2.06/25   14/01/98 20.59.01
*          KPF=KPA added for vm prod in partdf
*
*::>     VERSION  2.06/24   14/01/98 19.40.53
*          wuesthoff new parametrisation included (ANL-HEP-PR 97-03)
*          selected via NG=NPOM=40
*
*::>     VERSION  2.06/23   29/12/97 19.36.49
*          podiff improved.....

```

```

*
*::> VERSION 2.06/22 15/12/97 11.52.17
*      weighting for diffr. with ng>0 improved
*
*
*::> VERSION 2.06/21 09/12/97 16.58.25
*      bug in arexec for diffractive events corrected
*
*
*::> VERSION 2.06/20 26/11/97 16.23.35
*      QCDMIX corrected when using grid
*
*
*::> VERSION 2.06/19 24/11/97 15.40.20
*      bug in lmeps for QED radiation fixed
*
*
*::> VERSION 2.06/17 04/11/97 16.26.19
*      Subroutine EVENT changed so that 1200(nrad) and 12 give same results
*      for diffraction
*
*
*::> VERSION 2.06/16 31/10/97 15.11.16
*      lots of changes in PYSSPA for res. photons needed
*      rearranged switches to be more transparent....
*      included option for angular ordering in PYSSPA
*
*
*::> VERSION 2.06/13 20/10/97 12.22.59
*      bug in small mass collapsing for charm in LMEPS corrected
*
*
*::> VERSION 2.06/12 18/10/97 15.15.55
*      2nd attempt to IPS in resolved photon
*
*
*::> VERSION 2.06/11 18/10/97 00.46.47
*      first attempt to IPS in resolved photon
*
*
*::> VERSION 2.06/10 16/10/97 12.08.35
*      NFLAV added to f2md
*
*
*::> VERSION 2.06/09 11/10/97 14.09.07
*      IPR0=15 PHIGKI changed to region 0 - 2pi
*
*
*::> VERSION 2.06/08 10/10/97 17.17.42
*      bug NIA1 used in AREXEC corrected
*
*
*::> VERSION 2.06/07 10/10/97 12.23.08
*      check on IDISDIF in rapgap improved....
*
*
*::> VERSION 2.06/06 10/10/97 10.37.30
*      bug corrected: mixing F2 and F2D for NG<0
*
*
*::> VERSION 2.06/05 25/09/97 16.31.35
*      initial particle code for res. gamma corrected
*
*
*::> VERSION 2.06/04 23/09/97 10.14.00
*      initial parton for resolved gamma in LMEPS corrected
*
*
*::> VERSION 2.06/03 14/09/97 16.57.59
*      mismatch in dimensions in XXI and Q2I in rapgap cured
*
*
*::> VERSION 2.06/01 21/07/97 16.11.46
*      angular cut for HERACLES included in hercl

```



```

*           to be used together with HERCALES version 4401
*
*::>    VERSION  2.06/00   18/07/97 13.35.24
*           RAPGAP for DIS and DIF including resolved photons for DIS
*
*::>    VERSION  2.05/28   16/07/97 10.42.54
*           HERACL, XMAX=1-XF for diffraction introduced to avoid
*           wispy y%q2 distribution....
*
*::>    VERSION  2.05/26   07/07/97 16.11.31
*           bugs in LMEPS for small systems corrected
*
*::>    VERSION  2.05/23   30/06/97 12.08.49
*           sasgam was not correctly included in car file
*
*::>    VERSION  2.05/22   29/06/97 13.02.39
*
*           PYSSPA: explicit lower limit for soft gluon rad. included
*           --> problem with energy momentum cons. solved
*           Q2SUPP: parameter for HERACLES low Q2 suppression included
*           SCALQ2: parameter for scale/Q2 for resolved photons in DIS incl.
*           IHFLA : flavour code for heavy flavor (IPRO=14,1400) included
*           SCALFA: factor for scale Q2Q included, to switch from
*           Q2Q --> SCALFA*Q2Q
*           LMEPS: changes from G. Briskin for low mass diff. included
*           LUKFDI: changes from G.Briskin for low mass states included
*
*
*::>    VERSION  2.05/20   16/06/97 16.13.21
*           NPOM = -3 only pomeron
*           NPOM = -4 only meson
*
*::>    VERSION  2.05/19   09/06/97 09.02.25
*           scale pT**2 instead of 4*pt**2,
*           lambda consistently set also for PS
*           for HERACLES always fixed alpha_em
*
*::>    VERSION  2.05/16   08/06/97 19.34.46
*           alphas for diffr. was 0 in version 2.05 , corrected
*
*::>    VERSION  2.05/15   05/06/97 15.59.54
*           now QCDCOMPTON only for light quarks
*           some pause statements removed....
*
*::>    VERSION  2.05/13   26/05/97 16.47.48
*           ftncheked --> common mismatches removed
*
*::>    VERSION  2.05/12   16/05/97 16.28.40
*           pt2 scale now 4*pt2 instead of pt2
*
*::>    VERSION  2.05/11   15/05/97 13.30.48
*           w02 in partdi corrected
*
*::>    VERSION  2.05/09   12/05/97 09.38.57
*           res gamma in DIS hopefully correctly implemented
*
*::>    VERSION  2.05/07   30/04/97 17.46.55

```

```

*           parameters for alpha_s changed, MSTU(112) and PARU(112)
*           set properly to                N_flavours   lambda(N_flavours)
*
*::>       VERSION  2.05/06   23/04/97 07.13.59
*           add virtual photon structure parametrisations
*
*::>       VERSION  2.05/05   29/03/97 13.47.29
*           matrix elements for resolved checked
*
*::>       VERSION  2.05/04   10/03/97 10.47.35
*           improved color flow for resolved gamma's
*
*::>       VERSION  2.05/02   06/03/97 20.32.47
*           small bugs corrected, BGF part for heracles included via grid
*
*::>       VERSION  2.05/01   06/03/97 11.18.21
*           bugs of color connection corrected
*
*::>       VERSION  2.05/00   05/03/97 08.10.38
*           resolved photon for DIS included via IPRO = 18
*
*::>       VERSION  2.04/05   01/03/97 14.59.20
*           BGF for bb_bar added and matrix element calculation
*           for alpha_s with different scale than Q2 added
*           --> change in pqcdi and pqcd added for scale pt**2
*
*::>       VERSION  2.04/04   24/01/97 10.47.35
*           test version for charged current (INTER=2)
*
*::>       VERSION  2.04/03   20/01/97 08.45.34
*           test version
*
*::>       VERSION  2.04/02   25/12/96 23.10.05
*           bug corrected in partdi partdf for INTER= 2
*
*-----
*
*::>       VERSION  2.04/00   23/12/96 13.56.36
*           charged current interactions (W exchange) included
*-----
*
*::>       VERSION  2.03/13   18/10/96 09.03.33
*           IVM in partdf corrected
*
*::>       VERSION  2.03/12   14/10/96 14.44.28
*           change in PYSSPA to account for new sea treatment a la LEPTO 65
*
*::>       VERSION  2.03/11   11/10/96 12.46.04
*           change in PYSSPA to ensure energy and momentum conservation
*           for real particle
*           change in RAPGAP to ensure original values of IPY(13) and IPY(14)
*
*::>       VERSION  2.03/10   04/10/96 17.25.26
*           Weighing modified to weight as a function of electron
*           method Q2.
*
*::>       VERSION  2.03/08   03/10/96 20.24.10

```

```

*          GRAWQ2 added for weighting in Q2.
*          Directory H1QCD added for H1 QCD/Phenomenological
*          parameterisations.
*
*::>     VERSION  2.03/07   27/09/96 09.42.02
*          PYSSPA changed for xpq=0
**
*::>     VERSION  2.03/05   06/09/96 13.50.46
*          debug statement in event implemented
*
*::>     VERSION  2.03/04   05/09/96 18.58.09
*          Bugs for HERACLES with user defined parton density etc corrected
*          HARD POM NG=40,41,42 should work now
*::>     VERSION  2.03/03   22/08/96 20.17.55
*          cosmetics
*
*::>     VERSION  2.03/02   18/08/96 17.46.10
*          small bugs in hardpom corrected
*
*::>     VERSION  2.03/01   16/08/96 09.40.35
*          Kt for ALM only for IPRO=12 and add error summary added
*
*::>     VERSION  2.03/00   14/08/96 14.36.32
*          kt for ALM added via switch IALMKT=1
*
*::>     VERSION  2.02/04   14/08/96 14.32.24
*          kt for ALM added via switch IALMKT=1 otherwise =0
*
*::>     VERSION  2.02/02   29/07/96 11.17.05
*          NG = 21 NPOM =21 for pi0 exchange added
*          IPRO = 1400 for cc_bar with HERACLES added
*
*::>     VERSION  2.00/30   01/01/96 17.16.30
*          NIK ZAK included
*          PARTDF corrected for correct treatment of beta,x_pom
*          switch for p diss treatment included
*          info for ME added in common/MEINFO/
*
*::>     VERSION  2.00/29   03/12/95 12.02.34
*          Heracles - pion exchange bug corrected in RAPGAP: PIMAX missing
*
*::>     VERSION  2.00/27   22/11/95 16.35.16
*          treatment of vm production in connection with ariadne corrected
*
*::>     VERSION  2.00/26   21/11/95 12.30.17
*          HERACLES opt in PARTDF updated for initial state PS
*
*::>     VERSION  2.00/24   19/11/95 21.43.54
*          IFULL=1,IQ2=4 and IPRO=12 now default.
*          ARIADNE opt with same ev.record as MEPS option.
*
*::>     VERSION  2.00/22   09/11/95 13.39.40
*          in lmeps corrected to run with final state PS
*          mother of rad gamma included
*          GTR bank filled for beam part. and rad gamma acc. H1 convention
*
*::>     VERSION  2.00/19   07/11/95 14.28.29

```

```

*          bug for ariadne corrected.....
*          bug for x section if IFUL=1 corrected
*          new version for p-diss
*
*::>      VERSION  2.00/18   11/10/95 09.54.37
*          multiple definition of common PYINT1; corrected
*
*::>      VERSION  2.00/17   10/10/95 14.23.58
*          bugs fixed for HERACLES diffraction and ME option
*
*::>      VERSION  2.00/15   06/10/95 15.48.06
*          bugs fixed for HERACLES diffraction and ME option
*
*::>      VERSION  2.00/14   04/10/95 09.57.56
*          typing error for QCDC corrected (thanks to Nils and Gunilla)
*
*::>      VERSION  2.00/12   20/09/95 08.45.47
*          phi asymmetry corrected, wrong frame
*
*::>      VERSION  2.00/10   10/09/95 14.22.11
*          selection for light and heavy vectormesons included: IVM =0/1/443
*
*::>      VERSION  2.00/09   09/09/95 16.56.13
*          prodiff changed: intrinsic pt added, pz_pom subtr.
*
*::>      VERSION  2.00/08   31/08/95 11.23.17
*          bug for phi asymmetries in eleqqf and eleqcdc corrected
*          bug corrected in partdf causing energy momentum nonconserv.
*
*::>      VERSION  2.00/07   28/07/95 15.36.31
*          endless loop fixed in PYREMNM
*
*::>      VERSION  2.00/06   26/07/95 15.18.07
*          small bug for heracles with THEMIN corrected
*
*::>      VERSION  2.00/05   23/07/95 15.20.52
*          no cut necessary: AM(1) was not defined in PARTDI and PARTDF
*
*::>      VERSION  2.00/04   20/07/95 10.10.11
*          tried with a cut in eleqcdc introduced to avoid divergency zq-->1
*
*::>      VERSION  2.00/03   04/07/95 16.01.00
*          full formula for QCD compton added including phi asymmetries
*
*::>      VERSION  2.00/02   16/06/95 08.51.03
*          some printout reduced in partdf and pyremnm
*
*::>      VERSION  2.00/01   11/05/95 11.20.53
*          HERACLES interfaced for DIS and DIF
*
*::>      VERSION  2.00/00   19/04/95 20.21.57
*          new release
*
*::>      VERSION  1.04/03   23/03/95 14.44.49
*          Heracles interface added
*

```

```

*::>      VERSION  1.04/00   19/01/95 19.53.53
*
*      initial and final state parton shower included
*      a la LEPTO.
*      mixing of lowest order and hgher order QCD possible
*      also DIS and DIFF possible via IDIR=1 ==> DIS
*
*              IDIR=0 ==> DIF
*
*
*::>      VERSION  1.04/03   23/03/95 14.44.49
*      Heracles interface added
*
*::>      VERSION  1.04/00   19/01/95 19.53.53
*
*      initial and final state parton shower included
*      a la LEPTO.
*      mixing of lowest order and hgher order QCD possible
*      also DIS and DIFF possible via IDIR=1 ==> DIS
*
*              IDIR=0 ==> DIF
*
*
*::>      VERSION  1.03/04   31/10/94 10.16.50
*      include process IPRO=100
*      gamma + pomeron --> rho + pomeron
*
*      YMAX and Q2MAX cuts implemented
*
*::>      VERSION  1.03/02   21/04/94 11.36.23
*      now also cut on Minimum scattering angle of electron
*      THEMI included
*
*
*::>      VERSION  1.03/01   03/04/94 16.46.19
*      CMZ version of RAPGAP
*
*

```

Index

ALPH, 28
ALPHP, 27
ALPHS, 28
AM, 28
AVGI, 27

C1, 26
Cg, 26

EPSP, 27

IALMKT, 27
IALP, 24
IBS, 23
IDIR, 23
IDISDIF, 23
IFPS, 23
IFULL, 23
IGLU, 27
INTER, 23
IORD, 24
IPRO, 22
IQ2, 25
IQCDGRID, 23
Iqqg, 26
IREM, 27
IRPA, 24
IRPB, 24
IRPC, 24
IRPD, 24
IRPE, 24
IRPF, 24
IRPG, 24
IRUNA, 24
IRUNAEM, 24
ISEMIH, 23
ISOG, 24
ITIM, 24
IVM, 27

KBEAM, 27
KT1, 24
KT2, 24

MSTP(51), 25
MSTP(52), 25
MSTP(56), 25

NF1,NF2, 28
NFLAV, 22
NFLQCDC, 22
NFRAG, 23
NFT, 28
NG, 25
NIA1,NIA2, 28

NIN, 28
NOUT, 28
NPOM, 26

OMEG2, 24

PBEAM, 27
PEPS, 27
PHIGKI, 28
PI, 28
PIN, 22
PLEPIN, 22
PRN2, 27
PT2CUT, 23
PT2H, 27

Q2, 27
Q2MAX,Q2MIN, 27
Q2Q, 28
Q2SUPP, 23
QMA, 22
QMI, 22

RN2, 27

SCAL1,SCAL2, 28
SCALFA, 25
SCALQ2, 24
SD, 27
SHAT, 28
SHH, 28
SIN2W, 23
SSS, 27

T2GKI, 28
T2MAX, 27
THEMA,THEMI, 22

XDP1,XPD2, 28
XEL, 27
XF, 27
XFGKI, 28
XMAX,XMIN, 27
XMW2, 23
XPGKI, 28
XPR, 27

YMA, 22
YMAX,YMIN, 27
YMI, 22
YY, 27

ZQGKI, 28

References

- [1] T. Sjostrand, S. Mrenna, and P. Skands, JHEP **05**, 026 (2006). hep-ph/0603175.
- [2] G. Marchesini, B. Webber, G. Abbiendi, I. Knowles, M. Seymour, and L. Stanco, Comp. Phys. Comm. **76**, 465 (1992). Hep-ph/9912396.
- [3] S. Kawabata, Comp. Phys. Comm. **88**, 309 (1995).
- [4] M. R. Whalley, D. Bourilkov, and R. C. Group (2005). hep-ph/0508110.
- [5] G. Ingelman and K. Prytz, Z. Phys. **C58**, 285 (1993).
- [6] H. Abramowicz, J. Bartels, L. Frankfurt, and H. Jung, *Diffraction Hard Scattering. Summary report of the working group*, in *Proc. of the Workshop on Future Physics at HERA*, eds. A. De Roeck, G. Ingelman, and R. Klanner, p. 635. DESY, Hamburg, 1996.
- [7] G. Ingelman and P. Schlein, Phys. Lett. **B 152**, 256 (1985).
- [8] K. Streng, *Hard qcd scatterings in diffractive reactions at hera*, in *Proc. of the Workshop Physics at HERA*, ed. R. Peccei. Hamburg, 1987.
- [9] K. Streng, *Hard qcd scatterings in diffractive reactions at hera*, 1988. CERN-TH 4949 (1988).
- [10] E. Berger, J. Collins, D. Soper, and G. Sterman, Nucl. Phys. **B 286**, 704 (1987).
- [11] P. Bruni and G. Ingelman, Phys. Lett. **B 311**, 317 (1993).
- [12] P. Bruni and G. Ingelman, *Diffraction hard scattering at e p and p anti-p colliders*, in *Proc. of the EPS International High Energy Physics Conference*, eds. J. Carr and M. Perrottet. Editions Frontieres, Marseille, France, 22-28 Jul, 1993. DESY 93-187.
- [13] P. Bruni, G. Ingelman, and A. Solano, *Diffractively produced hadronic final states and the pomeron structure*, in *Proc. of the Workshop on Physics at HERA, Vol. 1*, eds. W. Buchmüller and G. Ingelman, Vol. 311, p. 363. DESY, Hamburg, 1991.
- [14] A. Donnachie and P. Landshoff, Nucl. Phys. **B 244**, 322 (1984).
- [15] H1 Collaboration; C. Adloff et al., Z. Phys. **C 76**, 613 (1997).
- [16] H. Collaboration, *Measurement and qcd analysis of the diffractive deep-inelastic scattering cross section at hera*, 2006. Hep-ex/0606004.
- [17] M. Wusthoff, *Photon diffractive dissociation in deep inelastic scattering*, 1995. PhD thesis, DESY-95-166.
- [18] M. Diehl, *Diffraction in electron - proton collisions*, 1996. PhD thesis.
- [19] M. Diehl, Z. Phys. **C 76**, 499 (1997). Hep-ph/9610430.
- [20] J. Bartels, C. Ewerz, H. Lotter, M. Wusthoff, and M. Diehl, *Quark - Antiquark Jets in DIS Diffractive Dissociation*, in *Proc. of the Workshop on Future Physics at HERA*, eds. A. De Roeck, G. Ingelman, and R. Klanner. DESY, Hamburg, 1996. Hep-ph/9609239.
- [21] J. Bartels, H. Lotter, and M. Wüsthoff, Phys. Lett. **B 379**, 239 (1996). ERRATUM-ibid. **B 382** (1996) 449, hep-ph/9602363.
- [22] J. Bartels, C. Ewerz, H. Lotter, and M. Wusthoff, Phys. Lett. **B 386**, 389 (1996). Hep-ph/9605356.
- [23] M. Glück, E. Reya, and A. Vogt, Z. Phys. **C 53**, 127 (1992).
- [24] M. Glück, E. Reya, and A. Vogt, Phys. Lett. **B 306**, 391 (1993).
- [25] J. Bartels, H. Jung, and M. Wusthoff, Eur. Phys. J. **C 11**, 111 (1999). Hep-ph/9903265.
- [26] J. Bartels, H. Jung, and A. Kyrieleis, Eur. Phys. J. **C 24**, 555 (2002). Hep-ph/0204269.

- [27] H. Jung, *Un-integrated parton density functions in ccfm*, April 2004. DIS 2004, Strbské Pleso, Slovakia, hep-ph/0411287.
- [28] M. Glück, E. Reya, and A. Vogt, Z. Phys. **C 67**, 433 (1995).
- [29] J. Blümlein, *On the k_t dependent gluon density of the proton*, in *Proc. of the Workshop on Deep Inelastic Scattering and QCD*, eds. J. Laporte and Y. Sirois. 1995. DESY 95-121 and hep-ph/9506403.
- [30] S. Baranov and N. Zotov, Phys. Lett. **B 458**, 389 (1999).
- [31] S. Baranov and N. Zotov, Phys. Lett. **B 491**, 111 (2000).
- [32] J. Kwiecinski, A. Martin, and A. Stasto, Phys. Rev. **D 56**, 3991 (1997).
- [33] K. Golec-Biernat and M. Wusthoff, Phys. Rev. **D 60**, 114023 (1999). Hep-ph/9903358.
- [34] M. A. Kimber, A. D. Martin, and M. G. Ryskin, Phys. Rev. **D63**, 114027 (2001). hep-ph/0101348.
- [35] W. Buchmuller, M. McDermott, and A. Hebecker, Nucl. Phys. **B 487**, 283 (1997). Hep-ph/9607290.
- [36] N. Nikolaev and B. Zakharov, Z. Phys. **C 53**, 331 (1992).
- [37] H. Kowalski and M. Wusthoff, *Satrap model for diffractive dis processes*. Prepared for 8th International Workshop on Deep Inelastic Scattering and QCD (DIS 2000), Liverpool, England, 25-30 Apr 2000.
- [38] A. Kwiatkowski, H. Spiesberger, and H.-J. Möhring, *Heracles 4.1 - an event generator for ep interactions at her a including radiative processes*, in *Proc. of the Workshop on Physics at HERA, Vol. 3*, eds. W. Buchmüller and G. Ingelman, p. 1294. 1991.
- [39] H. Spiesberger, *HERACLES and DJANGO - Event generation of ep interactions at HERA including radiative processes. version 4.6.6*, Aug 2005. <http://wwwthep.physik.uni-mainz.de/~hspiesb/djangoh/djangoh.html>.
- [40] A. Mucke, R. Engel, J. P. Rachen, R. J. Protheroe, and T. Stanev, Comput. Phys. Commun. **124**, 290 (2000). astro-ph/9903478.
- [41] V. Gribov and L. Lipatov, Sov. J. Nucl. Phys. **15**, 438 and 675 (1972).
- [42] L. Lipatov, Sov. J. Nucl. Phys. **20**, 94 (1975).
- [43] G. Altarelli and G. Parisi, Nucl. Phys. **B 126**, 298 (1977).
- [44] Y. Dokshitzer, Sov. Phys. JETP **46**, 641 (1977).
- [45] J. C. Collins and X.-M. Zu, JHEP **06**, 018 (2002). Hep-ph/0204127.
- [46] J. C. Collins and X. Zu (2004). Hep-ph/0411332.
- [47] S. Schilling, *Implementation of bgf-processes in monte carlo generators for electron proton scattering*. DESY-THESIS-2000-040.
- [48] J. Chyla and J. Cvach, *Virtual photon structure from jet production at HERA*, in *Proc. of the Workshop on Future Physics at HERA*, eds. A. De Roeck, G. Ingelman, and R. Klanner. Hamburg, 1996.
- [49] H. Jung, *The RAPGAP Monte Carlo for Deep Inelastic Scattering, version 3.2*. DESY Hamburg, 2007. <http://www.desy.de/~jung/rapgap/>.
- [50] M. Glück, E. Reya, and M. Stratman, Phys. Rev. **D 54**, 5515 (1996).
- [51] G. Schuler and T. Sjöstrand, Phys. Lett. **B 376**, 193 (1996).
- [52] M. Drees and R. Godbole, Phys. Rev. **D 50**, 3124 (1994).
- [53] E. Mirkes and D. Zeppenfeld, Phys. Lett. **B 380**, 105 (1996).

- [54] S. Catani and M. Seymour, *NLO QCD calculations in DIS at HERA based on the dipole formalism*, in *Proc. of the Workshop on Future Physics at HERA*, eds. A. De Roeck, G. Ingelman, and R. Klanner. Hamburg, 1996.
- [55] M. Klasen, G. Kramer, and B. Potter, *Eur. Phys. J. C* **1**, 261 (1998). Hep-ph/9703302.
- [56] G. Ingelman, *Lepto 6.1 the lund monte carlo for deep inelastic lepton-nucleon scattering*, in *Proc. of the Workshop Physics at HERA (1991) Vol. 3, 1366*, eds. W. Buchmüller and G. Ingelman. DESY, Hamburg, 1991.
- [57] T. Sjöstrand, *Comp. Phys. Comm.* **39**, 347 (1986).
- [58] T. Sjöstrand and M. Bengtsson, *Comp. Phys. Comm.* **43**, 367 (1987).
- [59] T. Sjöstrand, *Comp. Phys. Comm.* **82**, 74 (1994).
- [60] G. Briskin. PhD Thesis , changing LUKFDI for vm production.
- [61] H1 Collaboration; S. Aid *et al.*, *Nucl. Phys. B* **468**, 3 (1996).
- [62] ZEUS Collaboration; J. Breitweg *et al.*, *Z. Phys. C* **75**, 215 (1997). Hep-ex/9704013.
- [63] H. Jung, *Modelling diffractive processes*, in *Proc. of the Workshop on Diffractive Interactions*, ed. A. Levy. Eilat, Israel, Feb. 18 - 23, 1995.
- [64] L. Lönnblad, *Comp. Phys. Comm.* **71**, 15 (1992).
- [65] E. Boos *et al.* (2001). Hep-ph/0109068.
- [66] G. Ingelman, A. Edin, and J. Rathsman, *Comp. Phys. Comm.* **101**, 108 (1997). hep-ph/9605286.
- [67] M. H. Bengtsson, *Comp. Phys. Comm.* **31**, 323 (1984).
- [68] B. List, *Diffraktive J/ψ Produktion in Elektron - Proton Stößen am Speicherring HERA* (unpublished). Diploma thesis, Techn. Univ. Berlin, H1 note: H1-10/93-319, 1993.
- [69] B. List and A. Mastroberardino, *Diffvm: A monte carlo generator for diffractive processes in e p scattering*, in *Proceedings of the Workshop on Monte Carlo generators for HERA physics*, eds. A. Doyle, G. Grindhammer, G. Ingelman, and H. Jung, p. 396. DESY, Hamburg, 1999.
- [70] T. Sjöstrand, *Phys. Lett. B* **157**, 321 (1985).
- [71] M. Bengtsson, T. Sjöstrand, and M. van Zijl, *Z. Phys. C* **32**, 67 (1986).
- [72] H1 Collaboration; I. Abt *et al.*, *Z. Phys. C* **63**, 377 (1994). DESY 94-033.
- [73] M. Bengtsson and T. Sjöstrand, *Z. Phys. C* **37**, 465 (1988).
- [74] J. Bartels, *qqg jets in diffraction*, in *Proc. of the LISHEP workshop on diffractive physics*, ed. A. Santoro. Rio de Janeiro, Brazil, Feb 16 - 20, 1998.
- [75] H. Kohrs, *Direct and resolved pomeron*, in *Proc. of the Workshop on Deep Inelastic Scattering and QCD*, eds. J. Laporte and Y. Sirois. 1995.
- [76] B. Kniehl, H. Kohrs, and G. Kramer, *Z. Phys. C* **65**, 657 (1995).
- [77] H. Holtmann, G. Levman, N. Nikolaev, A. Szczurek, and J. Speth, *Phys. Lett. B* **338**, 363 (1994).
- [78] B. M. Waugh *et al.* (2006). hep-ph/0605034.