The RAPGAP Monte Carlo for Deep Inelastic Scattering
version 3.2

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Abstract

The physics behind the Monte Carlo event generator RAPGAP are discussed, which includes deep inelastic scattering, non-diffraction, diffraction and \( \pi \) - 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.
# Tabular Summary

<table>
<thead>
<tr>
<th>program name</th>
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</tr>
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<tr>
<td>version</td>
<td>3.20/beta</td>
</tr>
<tr>
<td>date of latest version</td>
<td>Sept 2009</td>
</tr>
<tr>
<td>author</td>
<td>Hannes Jung (<a href="mailto:Hannes.Jung@desy.de">Hannes.Jung@desy.de</a>)</td>
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<td>program size</td>
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</tr>
<tr>
<td>input files needed</td>
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<tr>
<td>computer types</td>
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</tr>
<tr>
<td>operating systems</td>
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</table>
| applicability | Deep Inelastic $ep$ Scattering
Deep Inelastic $ep$ Scattering with resolved photons
Deep Inelastic Diffractive $ep$ Scattering
Deep Inelastic $ep$ Scattering with $\pi$ exchange
Photo-production in $ep$ Scattering
Diffractive photo-production in $ep$ Scattering
Photo-production in $ep$ Scattering with $\pi$ exchange
hard scattering in $pp$ processes: diffractive and non-diffractive

<table>
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<th>hard sub-processes included</th>
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</tr>
<tr>
<td>$eq \rightarrow e'qq$</td>
</tr>
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<td>$eg \rightarrow e'q\bar{q}$</td>
</tr>
<tr>
<td>$eg \rightarrow e'c\bar{c}$</td>
</tr>
<tr>
<td>$eg \rightarrow e'bb$</td>
</tr>
<tr>
<td>$\gamma q \rightarrow qg$</td>
</tr>
<tr>
<td>$\gamma q \rightarrow q\gamma$</td>
</tr>
<tr>
<td>$\gamma g \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$\gamma g \rightarrow c\bar{c}$</td>
</tr>
<tr>
<td>$gg \rightarrow gg$</td>
</tr>
<tr>
<td>$qq \rightarrow gg$</td>
</tr>
<tr>
<td>$qq \rightarrow gg$</td>
</tr>
<tr>
<td>$qq \rightarrow q\gamma$</td>
</tr>
<tr>
<td>$qq \rightarrow \gamma g$</td>
</tr>
<tr>
<td>QCD cascade</td>
</tr>
<tr>
<td>initial QED radiation</td>
</tr>
<tr>
<td>fragmentation model</td>
</tr>
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| 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 $\alpha_s$. In experiments only stable particles are measured, but not partons (quarks or gluons), which cannot be described by perturbation theory, because the coupling constant $\alpha_s$ 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 PYTHIA event record):

<table>
<thead>
<tr>
<th>I</th>
<th>particle/jet</th>
<th>KS</th>
<th>KF orig</th>
<th>p_x</th>
<th>p_y</th>
<th>p_z</th>
<th>E</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>!e-!</td>
<td>21</td>
<td>11</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>156.843</td>
<td>156.843</td>
</tr>
<tr>
<td>2</td>
<td>!p+!</td>
<td>21</td>
<td>2212</td>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td>-156.843</td>
<td>156.846</td>
</tr>
<tr>
<td>3</td>
<td>!gamma!</td>
<td>21</td>
<td>22</td>
<td>1</td>
<td>1.819</td>
<td>18.493</td>
<td>4.371</td>
<td>3.243</td>
</tr>
<tr>
<td>4</td>
<td>e-</td>
<td>1</td>
<td>11</td>
<td>1</td>
<td>-1.819</td>
<td>-18.493</td>
<td>152.472</td>
<td>153.601</td>
</tr>
<tr>
<td>5</td>
<td>!u!</td>
<td>21</td>
<td>2</td>
<td>2</td>
<td>0.000</td>
<td>0.000</td>
<td>-23.242</td>
<td>23.242</td>
</tr>
<tr>
<td>6</td>
<td>u</td>
<td>A</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>1.820</td>
<td>18.496</td>
<td>-18.874</td>
</tr>
<tr>
<td>7</td>
<td>ud_0</td>
<td>V</td>
<td>1</td>
<td>2101</td>
<td>2</td>
<td>0.000</td>
<td>-0.003</td>
<td>-133.599</td>
</tr>
</tbody>
</table>

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 the 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)

<table>
<thead>
<tr>
<th>I</th>
<th>particle/jet KS</th>
<th>KF orig</th>
<th>p_x</th>
<th>p_y</th>
<th>p_z</th>
<th>E</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>!e-!</td>
<td>21</td>
<td>0.000</td>
<td>0.000</td>
<td>-156.843</td>
<td>156.843</td>
<td>0.001</td>
</tr>
<tr>
<td>2</td>
<td>!p+!</td>
<td>21</td>
<td>2212</td>
<td>0.000</td>
<td>0.000</td>
<td>156.843</td>
<td>156.846</td>
</tr>
<tr>
<td>3</td>
<td>!gamma!</td>
<td>21</td>
<td>22</td>
<td>1</td>
<td>1.819</td>
<td>18.493</td>
<td>-4.371</td>
</tr>
<tr>
<td>4</td>
<td>e-</td>
<td>1</td>
<td>11</td>
<td>1</td>
<td>-1.819</td>
<td>-18.493</td>
<td>152.472</td>
</tr>
<tr>
<td>5</td>
<td>!u!</td>
<td>21</td>
<td>2</td>
<td>2</td>
<td>-0.358</td>
<td>0.403</td>
<td>81.763</td>
</tr>
<tr>
<td>6</td>
<td>!u!</td>
<td>21</td>
<td>2</td>
<td>5</td>
<td>-0.069</td>
<td>0.246</td>
<td>28.064</td>
</tr>
<tr>
<td>7</td>
<td>!u!</td>
<td>21</td>
<td>2</td>
<td>4</td>
<td>1.797</td>
<td>19.188</td>
<td>21.113</td>
</tr>
<tr>
<td>8</td>
<td>u</td>
<td>A</td>
<td>2</td>
<td>2</td>
<td>-1.648</td>
<td>8.569</td>
<td>8.978</td>
</tr>
<tr>
<td>9</td>
<td>g</td>
<td>I</td>
<td>2</td>
<td>21</td>
<td>0.220</td>
<td>1.524</td>
<td>2.027</td>
</tr>
<tr>
<td>10</td>
<td>g</td>
<td>I</td>
<td>2</td>
<td>21</td>
<td>0.383</td>
<td>1.273</td>
<td>3.833</td>
</tr>
<tr>
<td>11</td>
<td>g</td>
<td>I</td>
<td>2</td>
<td>21</td>
<td>0.506</td>
<td>0.921</td>
<td>1.696</td>
</tr>
<tr>
<td>12</td>
<td>g</td>
<td>I</td>
<td>2</td>
<td>21</td>
<td>-0.559</td>
<td>-0.917</td>
<td>51.687</td>
</tr>
<tr>
<td>13</td>
<td>g</td>
<td>I</td>
<td>2</td>
<td>21</td>
<td>0.122</td>
<td>-0.249</td>
<td>75.397</td>
</tr>
<tr>
<td>14</td>
<td>ud_0</td>
<td>V</td>
<td>1</td>
<td>2101</td>
<td>2</td>
<td>0.122</td>
<td>-0.249</td>
</tr>
</tbody>
</table>

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 \( x_R = x_{\text{min}} + R_1 \cdot (x_{\text{max}} - x_{\text{min}}) \) and \( f_R \) with \( f_R = R_1 \cdot f_{\text{max}} \). The integral \( \int_{x_{\text{min}}}^{x_{\text{max}}} f(x)dx \) 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 \( f(x) \) which is much simpler and analytically integrable. Now we generate \( x \) values according to the function \( g(x) \). This is done by the following:

\[
R_1 \int_{x_{\text{min}}}^{x_{\text{max}}} g(x)dx = \int_{x}^{x_{\text{max}}} g(x)dx
\]

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:

\[
R_1 \int_{x_{\text{min}}}^{x_{\text{max}}} g(x)dx = R_1 \log \frac{x_{\text{max}}}{x_{\text{min}}} = \log \frac{x_R}{x_{\text{min}}}
\]
Solving this equation we obtain \( x_R = x_{\text{min}} \left( \frac{x_{\text{max}}}{x_{\text{min}}} \right)^{R_i} \). 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:

\[
\int f(x)dx \simeq \sum_i x_{R_i} f(x_{R_i}) \log \frac{x_{\text{max}}}{x_{\text{min}}}
\]

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 \( f(x) > g(x) \). 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 \( x_1, x_2, \ldots, x_n \) the same procedure is applied.

In \textsc{Rapgap} the \textsc{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 \textsc{Rapgap} the random numbers \( x_i \) are generated with \textsc{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 \( y, Q^2, x_g, x_F, t, \ldots \) 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 \textsc{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 \( F_L^p(x,Q^2) = F_2^p(x,Q^2) - 2xF_T^p(x,Q^2) \):

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

with \( x \) defined as \( x = Q^2/(2P.q) \), \( y = (P.q)/(P.l) \) 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:

\[
F_2^p(x,Q^2) = \sum_f c_f^2 \left( xq_f(x,Q^2) + x\bar{q}_f(x,Q^2) \right)
\]

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 \textsc{Rapgap} (via \textsc{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]:

\[
\frac{d^4\sigma(ep \rightarrow e'XP')}{dydQ^2dxF'dt} = \frac{4\pi\alpha^2}{yQ^4} x F_{D}^{(4)}(x,Q^2;x_F',t) - \frac{y^2}{2} F_{\pi}^{(4)}(x,Q^2;x_F',t)
\]  

(4)

where the diffractive structure functions \( F_{D}^{(4)}(x,Q^2;x_F',t) \) and \( F_{\pi}^{(4)}(x,Q^2;x_F',t) \) are introduced, depending now on four variables, \( x, Q^2 \) defined as above and \( x_F' = (q,p_F')/(q,P) \) and \( t = (P - P') \) 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 \( F_{D}^{(4)} \) by the corresponding \( F_{\pi}^{(4)} \) and \( x_F' \) by \( x_\pi \).

The interpretation of the diffractive structure function \( F_{D}^{(4)} \) 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 \( P \) exchange, where the pomeron has a partonic structure. The structure function \( F_{D}^{(4)} \) is then given as the product of the probability for finding a pomeron \( f_p \) and the structure function \( F_{p}^{(4)} \) of the pomeron:

\[
F_{D}^{(4)}(\beta,Q^2;x_F',t) = f_p(x_F',t)F_{p}^{(4)}(\beta,Q^2)
\]  

(5)

with \( \beta = Q^2/(2q.p_F') \). In analogy to the quark - parton - model of the proton \( \beta \) can be interpreted as the momentum fraction of the total pomeron momentum carried by the struck quark and \( F_{D}^{(4)}(\beta,Q^2) \) 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 \( NPOM=0 \):

\[
f_p(x_F',t) = \frac{\beta^2 F_p(0)}{16\pi} x_F'^{1-2\alpha_F(t)} e^{-b_0|t|}
\]  

(6)

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

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

\[
f_p(x_F',t) = \frac{1}{2} \frac{1}{2.3 x_F'} \left[ 6.38e^{-8|t|} + 0.42e^{-3|t|} \right]
\]  

(7)

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

\[
f_p(x_F',t) = \frac{9\delta^2}{4\pi^2} \left[ F_1(t) \right]^2 x_F'^{1-2\alpha_F(t)}
\]  

(8)

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

\[
F_1(t) = \frac{4m_p^2 - 2.8t}{4m_p^2 - t (1 - t/0.7)^2}
\]  

(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 \( \xi \), 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 

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

- **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 diffusive cross section are given. The calculation of diffusive 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: $\sigma \sim [x_F G_p(x_F, \mu^2)]^2$ with $\mu^2$ the scale explicitly given in the references. The perturbative calculation of $q\bar{q}$ (IPRO=21) and $qg$ (IPRO=20) ([21,25,26]) can be used for light quark and heavy quark production. With $Iqg$ different levels of approximation in the calculation for IPRO=20 can be selected. However it is recommended to use the full calculation with $Iqg=0$.

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 $\frac{d N(x, Q^2)}{dQ^2}$ 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 KMS\(^1\) [32] (IGLU=4, stored in kms.dat), the one of the saturation model by [33] (IGLU=5) and the one of KMR\(^2\) [34] (IGLU=6, stored in kmr.dat).

Due to the different gluon densities different $x_F$ 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:

\[
\begin{align*}
\langle x_F G^D(x_F, \beta) \rangle &= \frac{C_1}{\beta \cdot C_g - \beta + 1} \frac{1}{x_F^\beta} \tag{10}
\end{align*}
\]

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 $1/x_F^\beta$ dependence in contrast to the other models, where at least a $1/x_F^{1+\epsilon}$ 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 $qg$ 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 USDFPR). Here no assumption about factorization is made.

The basic partonic subprocesses available are: $eq \rightarrow e'q'$ (QPM), $eq \rightarrow e'qg$ (QCD-C), $eg \rightarrow e'\bar{q}q$ (BGF), $eg \rightarrow e'\bar{c}\bar{c}$ (BGF), $eg \rightarrow e'\bar{b}\bar{b}$ (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.

\(^1\)A. Stasto kindly provided the program code.

\(^2\)M. Kimber kindly provided the program code.
4.3 Deep Inelastic Scattering including Diffraction and Pion exchange

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

$$F_2(x, Q^2) = F^\text{non-diff}_2(x, Q^2) + F^\text{diff}_2(x, Q^2) + \ldots$$  \hspace{1cm} (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 $F^\text{diff}_2$:

$$F^\text{diff}_2(x, Q^2) = \int F^\text{D(4)}_2(x_F, t; \beta, Q^2) \delta(\beta x_F - x) \, dx_F \, d\beta \, dt$$  \hspace{1cm} (12)

With the knowledge of $F_2$ and $F^\text{diff}_2$ 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 $e - \gamma^\ast - e$ 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 $Q^2 \to 0$. On the other hand parton densities are usually only parameterized down to a fixed value of $Q^2_0$. In order to ensure a well defined small $Q^2$ behavior, an exponential suppression factor is applied: $1 - \exp(-Q_\text{2SUPP} \cdot Q^2)$ with $Q_\text{2SUPP}=3.37$ being the default from HERACLES. Values of $Q_\text{2SUPP}=5$ seems appropriate for parton densities evolved down to $Q^2_0 \sim 1$ GeV$^2$ and $Q_\text{2SUPP}=10$ for $Q^2_0 \sim 0.5$ GeV$^2$.

4.5 Order $\alpha_s$ matrix elements

4.5.1 Order $\alpha_s$ 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 $\alpha_s$.

A more detailed simulation of leading order $\alpha_s$ processes like $\gamma^*g \to q\bar{q} \ (\text{BGF, Fig. 1c.})$ and $\gamma^*q \to qg \ (\text{QCD - Compton, Fig. 1d.})$ 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 $\gamma g \to \gamma q$ is simulated via IPR0 = 16.

A full simulation including QPM - as well as 1st order $\alpha_s$ 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 $\alpha_s$ 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 $\alpha_s$ 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 $\alpha_s$ 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 $\alpha_s$ 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 $F_2^\gamma$ with the quark densities even for relatively large PT2CUT.

4.5.2 NLO and Order $\alpha_s$ 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 ($\alpha_0^s$) and the NLO ($\alpha_s$) 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. 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 $\alpha_s$ 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 $F_2^{\text{charm}}(x,Q^2)$ 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

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

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.

\[\text{3 The implementation of this scheme into RAPGAP was done by S. Schilling.}\]
4.7 QCD processes in hadron-hadron collisions

The hard subprocesses implemented are:

\[
\begin{align*}
gg & \rightarrow q\bar{q} & \text{IRPA}=1 \\
gg & \rightarrow gg & \text{IRPB}=1 \\
qg & \rightarrow qg & \text{IRPC}=1 \\
qg & \rightarrow g\bar{q} & \text{IRPE}=1 \\
qq & \rightarrow gg & \text{IRPD}=1 \\
qq & \rightarrow q\gamma & \text{IRPF}=1 \\
qq & \rightarrow q\gamma & \text{IRPH}=1 \\
qq & \rightarrow g\gamma & \text{IRPI}=1.
\end{align*}
\]

The corresponding color configurations are given in ICOLORA.

4.7.1 Hadron-hadron collisions

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

4.7.2 Resolved Photons in \(\gamma p\) 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 \(\mu^2\) 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 \(\mu^2\) and \(Q^2\): \(x, f(x, \mu^2, Q^2)\) [50–52]. Resolved photon processes can be selected via \text{IPRO=18} for real and virtual photons (depending on \(Q^2_{\text{min}}\)).

Since these processes can only occur for \(\mu^2 > Q^2\), large differences in the cross section are expected when choosing different scales \(\mu^2\), 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 \(qg \rightarrow gg\) 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 \(\mu^2\), 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 \(\pi\) exchange.

4.8 Scales, \(\alpha_s\) and Parton Distribution Functions

In leading order \(\alpha_s\) processes the renormalization scale \(\mu_R\) (\(\alpha_s(\mu_R^2)\)) and factorization scale \(\mu_F\) (\(xf(x, \mu_F^2)\)) 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, \ldots, 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 \(\alpha_s\) 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) \[58\], which is

\[
\mu^2 = \begin{cases} 
\max(|t, u|) & \text{for } \mu^2 < \Lambda_{QCD}^2 \\
\max([-Q^2 - 2q \cdot p_f \cdot 1, -Q^2 - 2q \cdot p_f \cdot z]) & \text{for } \mu^2 = \Lambda_{QCD}^2 \\
\max(1 - z, z) \cdot (\hat{s} + Q^2) & \text{for } \mu^2 > \Lambda_{QCD}^2
\end{cases}
\]

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

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

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

Often $\Lambda_{QCD}$ 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 $\Lambda_{QCD}$ 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 $\Lambda_{QCD}$ 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 $\Lambda_{QCD}$, PARU(112) giving the value of $\Lambda_{QCD}$. The default value is $\Lambda_{QCD}^2 = 0.25$ and MSTU(112)=5. The number of actual open flavors $n_f$ depends on $\mu^2$, and $\alpha_s$ 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 this is done in the fragmentation program 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 $\mu^2$ 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 $J/\psi$ production. Suppose we have a system of a $c\bar{c}$ quark, plus eventually additional gluons in the final state. If the invariant mass $m_x = (q + p_F)^2 < 4 \cdot m_{\gamma p}^2$ then only $J/\psi$ is produced ($\eta_c$ 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 $x_F$ and $\beta$:

\[
x_F = \frac{q \cdot p_F}{q \cdot p} = \frac{Q^2 + m_x^2}{Q^2 + W^2}
\]

\[
\beta = \frac{Q^2}{2 \cdot q \cdot p_F} = \frac{Q^2}{Q^2 + m_x^2}
\]

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

The cross section for vector meson production of course depends crucially on the underlying subprocess. Using the recent parameterization of $F_2^{D(3)}(x_F, \beta, Q^2)$ of the H1 collaboration [15] together with IPRO=12 and
IDIR=0 (which is QPM on a parton in the pomeron) $J/\psi$ 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 $\beta$ dependence of the structure function $F_2^{\Delta(3)}$, since as shown above, changing $Q^2$ is equivalent with changing $\beta$ 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 [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, PYSLI, 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 an 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 ($\gamma^* q_i \rightarrow q_f g_1$) the gluon $g_1$ 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 $P$, 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 $\Delta^{++}$ corresponding to $\pi^0, \pi^+ \text{ or } \pi^-$ 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 alla 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

\[
d\sigma \sim \frac{1}{M^2(1+\epsilon_Y)} \exp (-B_{diss}|t|)
\]

with \( PEPS=\epsilon_Y \) 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 \( d\bar{q}q \) 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.
The quark to which the pomeron couples carries a momentum fraction $\chi$ of the proton's initial momentum. The momenta of the initial quark $q_p$ and the di-quark $d_i - q_p$ are given in the following:

$$q_p \simeq \chi p$$  \hspace{1cm} (25)
$$d_i - q_p \simeq (1 - \chi)p$$  \hspace{1cm} (26)
$$q_p' = q_p - p_{IP} \simeq \chi p - p_{IP}$$  \hspace{1cm} (27)

where $\chi = \frac{q.p}{q.q}$, with $q$ (quark, proton) 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 $\chi$ can be estimated within the resolved pomeron model:

$$\chi = \frac{x_{IP}}{\beta'}$$  \hspace{1cm} (28)

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

For $\beta'$ different probability functions are available:

$$P(\beta') = 2(1 - \beta')$$  \hspace{1cm} (IREM=1), \hspace{1cm} (29)
$$P(\beta') = (a + 1)(1 - \beta')^a$$  \hspace{1cm} (IREM=2), \hspace{1cm} (30)
$$P(\beta') = \frac{N}{\beta'(1 + \frac{N}{\beta'})}$$  \hspace{1cm} (IREM=3) \hspace{1cm} (31)

with $a$ chosen such that $< \beta' > = 1/(a + 2)$ 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 $\mu^2$, a backward evolution according to the DGLAP evolution equations [41–44] will lead to larger initial values of $x$, and smaller $\mu^2$. 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:

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

(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:

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

(33)

$$P_{g \rightarrow gg}(z) = \frac{6}{z(1 - z)}$$

(34)

$$P_{g \rightarrow qg}(z) = \frac{1}{2} (z^2 + (1 - z)^2)$$

(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, a upper cutoff $z_{\text{max}}$ 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 $z_{\text{max}} = \hat{z} = \frac{\mu^2}{2}$ 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 $\epsilon$, 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 $\epsilon$ increases the transverse energy flow, and the data are much better described. The value $z_{\text{max}}$ 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 $\mu^2$ ($\mu^2 = \hat{s}, \hat{p}^2_\perp$) 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 $pp$ 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 $\gamma p$ 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 $\gamma p$) 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 ($\gamma q \to q$) 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:

$$\mu^2 = \max[| -Q^2 - 2q.p_f 1, -Q^2 - 2q.p_f 2|]$$

(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 ($\gamma q \to q$) then the maximum scale for parton showers are calculated as follows: parton showers in the leading order process can go up to $\mu^2 = 4 \cdot p_T^{cut}$ instead of $Q^2$ when no matrix elements are included (with $p_T^{cut} = PT2CUT$ 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 $\alpha_s$.

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 $\min(4p_T^{cut}, W^2)$ 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 standard IS, diffractive scattering and pion exchange is done, if selected via IDISDIF=1.
- **ANALYS**: user analysis subroutine.
- **ALPHAS(RQ)**: give $\alpha_s(\mu)$ with $\mu = RQ$.
- **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 ($\gamma g$ fusion and QCD - Compton) in integration and event generation.
- **FRAG**: generates color string connection for hadronization.
DIFFR1 for diffractive and pion exchange processes $\gamma g \rightarrow q\bar{q}$. 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 $eg \rightarrow e'q\bar{q}$. 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 $eq(q) \rightarrow e'q(q')$. Calls kinematics and phase space routine PARTDF.

DIFFR4 for diffractive and pion exchange processes $eq \rightarrow e'qq$. Calls kinematics and phase space routine PARTDF and matrix element ELEQQF. Both for light and heavy quarks. Using full matrix element for $eg \rightarrow e'q\bar{q}$.

DIS1 for standard inelastic scattering $\gamma p \rightarrow q\bar{q}$. 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 standard inelastic scattering $eg \rightarrow e'q\bar{q}$. 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 standard inelastic scattering $eq(q) \rightarrow e'q(q')$ Calls kinematics and phase space routine PARTDI.

DIS4 for standard inelastic scattering $eq \rightarrow e'qq$. Calls kinematics and phase space routine PARTDI and matrix element ELEQCD. Using full matrix element for $eg \rightarrow e'q\bar{q}$.

ELEQQL matrix element for $\gamma g \rightarrow q\bar{q}$. $q$ stands for light quark.

ELEQQB matrix element for $\gamma g \rightarrow QQ$ including masses. $Q$ stands for heavy quark.

ELEQQF matrix element for $eg \rightarrow e'QQ$ including masses. $Q$ stands for light or heavy quark. Masses of light quarks $m_q = 10 \text{ MeV}$. Masses of light quarks $m_q = 10 \text{ MeV}$.

ELEQCD matrix element for $eq \rightarrow e'q\bar{q}$. Masses of light quarks $m_q = 10 \text{ MeV}$.

ELERES matrix elements for resolved photon processes.

ELEQQ matrix element for exclusive diffractive $q\bar{q}$ production [21, 22].

ELEQQF matrix elements for diffractive $q\bar{q}$ production [74].

DOT(A,B) four vector dot product

DOT(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 standard inelastic scattering processes.

PYSTFU(KF,X,SCALE,XPQ) parton density in particle KF (KF = 2212 for the proton). XPQ= $x f_i(x, \mu^2)$ with $x= x$, SCALE= $\mu^2$. 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= $x f_i(x, \mu^2)$ with $x= x$, SCALE= $\mu^2$.

RUNIGLU(KF,X,KT,P,XPQ) to extract the unintegrated gluon density $x A(x, k_t, \mu)$ for a proton with KF=2212, as a function of $x = x$, $k_t^2 = KT$ and $\mu = \mu$. The gluon density is returned in XPQ(0), where XPQ is an array with XPQ(−6:6).

RAT2DI(KF,X,XMIN,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).

PYREM(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.

PRODIF 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 LSSCALE. 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].

RYSRGA 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].

F2DHV calculation of diffraction for \( N_G = 40 \) [17].

F2BLW calculation of diffraction for \( N_G = 41 \) [21, 22].

F2MD calculation of diffraction for \( N_G = 42 \) [18, 19].

F2MCD calculation of diffraction for \( N_G = 45 \) [35].

\[ \text{USDIFFR}(\text{BETA, SCALE, XPQ, X_POM, T2}) \] user supplied effective diffractive parton density with the fractional momentum \( \text{BETA} = \xi_i \) of the pomeron momentum carried by the parton \( i \), the scale \( \text{SCALE} = \mu \) of the structure function \( XPQ(-6:6) = \xi q(\xi, \mu^2) \), \( X_POM = x_POM \) and \( T2 = t \) (all variables in SINGLE PRECISION).

6.2 Parameter switches

IINT: (D:=0) select integration procedure
\( \quad = 0 \) BASES/SPRING Integration procedure
\( \quad = 1 \) 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: = 180., THEMI = 0) maximum and minimum scattering angle \( \theta \) 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 standard inelastic scattering is done via IDIR, IDISDIF, NG, NPOM described below.
\( \quad = 10: \gamma g \rightarrow q\overline{q} \) using EPA
\( \quad = 11: \gamma g \rightarrow c\overline{c} \) using EPA
\( \quad = 12: e q \rightarrow e' q' \)
\( \quad = 13: e g \rightarrow e'q q' \) using full Matrix Element
\( \quad = 14: e g \rightarrow e'c c' \) using full Matrix Element
\( \quad = 15: e q \rightarrow e'gg \) using full Matrix Element
\( \quad = 16: e q \rightarrow e'g \gamma \) 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 IPRO=12 together with NG=41 and NPOM=41, but technically calculated differently and more efficient.
=30: saturation model for $\gamma^* p \rightarrow q\bar{q}gp$ [74].
=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: $eq \rightarrow e'Q\bar{Q}$

\[Q2SUPP\] (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 standard inelastic scattering
= 0 diffractive and pion exchange processes

\[IDISDIF\] (D=0) choose mixing of standard 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 standard inelastic and diffractive processes.

= 2 mixing of standard 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 $\sin^2 \theta_W$ (/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 $p_T^2$ 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 rapgap.gen

\[IORD:\] (D=1) ordering for initial state P.S.

= 0 no ordering
= 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)
\[=1 \alpha_s \text{ first order with scale } Q^2\]
\[=2 \alpha_s \text{ first order with scale } k_t^2 = (1 - z) \cdot Q^2\]

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 \(qq \rightarrow gg\) switched on(off)

IRPD

=1(0) (D:=1) process \(qq \rightarrow gg\) switched on(off)

IRPE

=1(0) (D:=1) process \(qq \rightarrow q\bar{q}\) 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 \(qq \rightarrow g\gamma\) 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 \(\mu^2 = SCALQ2\) for resolved processes in DIS, can be changed by user (/RESGA).

OMEG2:

(D:=0.01) \(\omega = OMEG2\) suppression factor for virtual resolved photons in the Dress - Godbole model [52].

6.2.6 Parameters for structure functions \(\alpha_s\) 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 \(\alpha_s\)

=0: fixed \(\alpha_s = 0.3\)

=1: running \(\alpha_s(\mu^2)\)

IQ2:

(D: = 5) select scale \(\mu^2\) 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: \(\mu^2 = 4 \cdot m^2 + p_T^2\)

=4: \(\mu^2 = Q^2\)

=5: \(\mu^2 = Q^2 + 4 \cdot p_T^2\)

SCALFA

(D=1) (/SCALF/) factor which the scale \(\mu^2\) used in \(\alpha_s\) and structure function evaluation is multiplied with. For example SCALFA=4 and IQ2=3 means: \(\mu^2 = 4 \cdot m^2 + 4 \cdot p_T^2\), whereas for IQ2=5 the meaning is \(\mu^2 = Q^2 + 4 \cdot p_T^2\).

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

MSTP(56):
MSTP(56) < 10 parameterization from LHAPDFLIB 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: \( xf(x) = 6x(1 - x) \) for gluons. For quarks \( xq(x) = \frac{1}{x}xf_n(x) \)
= u: \( xf_n(x) = (n + 1)(1 - x)^n \) for \( 1 \leq n \leq 5 \) for gluons. For quarks \( xq(x) = \frac{1}{x}xf_n(x) \)
= 10: \( xf(x) = (0.18 + 5.46x)(1 - x) \) only gluons.
= 11: \( xf(x) = \frac{1}{C}C_{F}(1 - x) \) Donnachie Landshoff quark density in pomeron.
= 12: Kniehl, Kohrs, Kramer parton density \[75, 76\] for pomeron including direct coupling.
= 20: parton density for \( \pi^\pm \). IF MSTP(52) < 10 Owens set from PYSTFU is used. IF MSTP(52) > 10 parton density for pion used from LHAPDFLIB [4]

NPOM:
(D: = -10) select pomeron distribution \( f_{p/p}^S \) (/DIFFR/)
= 0: pomeron distribution \( f_{p/p}^S \)
= 1: pomeron distribution \( f_{p/p}^D \)
= 2: pomeron distribution \( f_{p/p}^L \)
= 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 1 (quarks only) (NLO) \[15\]
= -11: H1 fit 2 (quarks and gluons) (NLO) \[15\]
= -12: H1 fit 3 (quarks and gluons peaked at \( z \to 1 \)) (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 \( z \to 1 \)) (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 \( -1, -2, -3, -4, -5, -6 \).
Parameters for the diffractive gluon density in the semi-classical approach of Buchmüller, Hebecker, McDermott [35].

\begin{itemize}
  \item \textbf{C1:} \((D = 1)\) \(C_1 = C_1(\text{BUCHMUE/})\).
  \item \textbf{Cg:} \((D = 1)\) \(C_g = C_g(\text{BUCHMUE/})\).
  \item \textbf{Iqqg} allows different levels of approximation in the matrix element calculation of \(\text{IPRO=20}\). \(\text{Iqqg=0}\) is the full matrix element, \(\text{Iqqg=1,2}\) approximates the matrix element as described in [25].
  \item \textbf{IGLU:} \((D = 1)\) select unintegrated gluon density \(\text{GLUON/})\).
  \item \textbf{IREM:} \((D = 1)\) select momentum distribution of proton dissociation \(\text{PREMNANT/})\).
  \item \textbf{IVM:} \((D = 0)\) select exclusive vector meson production in diffractive scattering \(\text{VMESON/})\).
  \item \textbf{IALMKT:} \((D = 0)\) \(\text{INPU/})\) include primordial \(k_t\) for diffractive processes according to the Aligned Jet Model: \(e^{-5.5k_t}\) for \(\text{IALMKT=1} \) \(\text{INPU/})\).
  \item \textbf{T2MAX:} \((D = 5)\) maximum \(t\) [GeV\(^2\)/c\(^2\)] \(\text{DIFFR/})\).
  \item \textbf{XF:} \((D = 0.9)\) minimum \(X_F\) \(x_F^P = 1 - x_f = 1 - \frac{E'}{E_p}\) \(\text{DIFFR/})\).
\end{itemize}

Parameters for proton dissociation:

\begin{itemize}
  \item \textbf{PEPS:} \((D := 0.0)\) \(\epsilon_Y\) for \(M_Y^2\) spectrum
  \item \textbf{PRN2:} \((D := 4.0)\) \(B_{\text{diss}}\) for \(\exp(-B_{\text{diss}}|t|)\)
\end{itemize}

Parameters for pomeron flux (only for \(\text{NPOM=0,1,2}\)):

\begin{itemize}
  \item \textbf{ALPHP:} \((D := 0.25)\) \(\alpha_P\) [GeV\(^{-2}\)] \(\text{DIFFR/})\).
  \item \textbf{RN2:} \((D := 4.7)\) \(\text{RN2= b_0}\) as defined above \(\text{DIFFR/})\).
  \item \textbf{EPSP:} \((D := 0.085)\) \(\text{EPSP= \epsilon}\) \(\text{DIFFR/})\).
\end{itemize}

### 6.2.8 Accessing information

\begin{itemize}
  \item \textbf{AVGI} \(\text{integrated cross section} \(\text{EFFIC/})\).
  \item \textbf{SD} \(\text{standard deviation of integrated cross section} \(\text{EFFIC/})\).
  \item \textbf{SSS} \(\text{total center of mass energy} s \(\text{PARTON/})\).
  \item \textbf{PBEAM} \(\text{energy momentum vector of beam particles} \(\text{BEAM/})\).
  \item \textbf{KBEAM} \(\text{flavor code of beam particles} \(\text{BEAM/})\).
  \item \textbf{Q2} \(\text{in lepto-production: actual } Q^2\) of \(\gamma \(\text{PARA/})\).
  \item \textbf{YY} \(\text{energy fraction lost by incident electron} \(\text{RAPGKI/})\).
  \item \textbf{XEL} \(\text{energy fraction of parton on electron side} \(\text{RAPGKI/})\).
  \item \textbf{XPR} \(\text{energy fraction of parton on proton side} \(\text{RAPGKI/})\).
  \item \textbf{YMAX,YMIN} \(\text{actual upper and lower limits for } y \(\text{PARAT/})\).
  \item \textbf{Q2MAX,Q2MIN} \(\text{actual upper and lower limits for } Q^2\) of \(\gamma \(\text{PARAT/})\).
  \item \textbf{XMAX,XMIN} \(\text{upper and lower limits for } x \(\text{PARAT/})\).
\end{itemize}
\[ \hat{\rho}^2 \text{ [GeV}^2/c^2] \text{ of parton in hard subprocess } \text{cm} \text{ (/RAPGKI/) system} \]

PT2H

\[ s \text{ [GeV}^2] \text{ of hard subprocess } \text{cm} \text{ (/RAPGKI/) system} \]

SHH

\[ t \text{ [GeV}^2] \text{ for diffractive processes } \text{T2GKI} \text{ (/RAPGKI/) system} \]

T2GKI

\[ x_p = Q^2 \text{ / } 2 \text{p}_i \text{.p}_f = \text{XFGKI} \text{ (/MEINFO/) system} \]

XFGKI

\[ O(\alpha_s) \text{ matrix element information } \text{(/MEINFO/) system} \]

AM(18)

\[ \hat{s} \text{ of hard subprocess } \text{(/PARAT/) system} \]

SHAT

\[ z = \frac{p_i \cdot p_f}{p_i \cdot q} = \text{ZQGKI} \text{ (/MEINFO/) system} \]

ZQGKI

\[ x_p = Q^2 \text{ / } 2 \text{p}_i \text{.q} = \text{XPGKI} \text{ (/MEINFO/) system} \]

XPGKI

\[ \phi = \text{PHIGKI} \text{ azimuthal angle } \text{(/MEINFO/) system} \]

PHIGKI

\[ \text{NIA1, NIA2 position of partons in hard interaction in } \text{LUJETS event record } \text{(/HARD/) system} \]

NIA1, NIA2

\[ \text{NF1, NF2 first and last position final partons/particles of hard interaction in } \text{LUJETS } \text{(/HARD/) system} \]

NF1, NF2

\[ \text{NFT total number of final particles; for } 2 \rightarrow 2 \text{ process } \text{NFT =2} \]

Q2Q

\[ \text{hard scattering scale } \mu^2 \text{ used in } \alpha_s \text{ and structure functions } \text{(/PARAE/) system} \]

ALPHS

\[ \text{actual } \alpha_s \text{ } \text{(/PARAM/) system} \]

PI

\[ \pi \text{ } \text{(/PARAM/) system} \]

ALPH

\[ \text{actual } \alpha_{em} \text{ } \text{(/PARAM/) system} \]

NIN

\[ \text{number of trials for event generation } \text{(/EFFIC/) system} \]

NOUT

\[ \text{number of successful generated events } \text{(/EFFIC/) system} \]

SCAL1, SCAL2

\[ \text{scale for structure function on beam 1 and 2 respectively } \text{(/STRU/) system} \]

XDP1, XPD2

\[ \text{value of parton density on beam 1 and 2 respectively } \text{(/STRU/) system} \]

6.3 List of COMMON blocks

COMMON/BEAM/PBEAM(2, 5), KBEAM(2, 5)

COMMON/BUCMUE/C1, Cg

COMMON/COLCON/ICOLORA, IRESPRO, IRPB, IRPA, IRPC, IRPD, IRPE, IRPF, IRPG

COMMON/DIFFR/T2MAX, XF, ALPHP, RN2, EPSF, QMI, YMI, QMA, YMA, NG, NPOM

COMMON/DISDIF/T2MAX, XF, ALPHP, RN2, EPSF, QMI, YMI, QMA, YMA, NG, NPOM

COMMON/EFFIC/AVGI, SD, NIN, NOUT

COMMON/ELECT/THEM, THEM

COMMON/EWEAK/SIN2W, XMW

COMMON/EWEAK/SINW, XMW

COMMON/EW3C1/KE, KPH, KPA, NFWQ, NFWLCDC

COMMON/MEINFO/ZQGKI, XPGKI, PHIGKI

COMMON/OALPINI/IFULL, IQCDGRID

COMMON/PARAE/Q2, Q2M, Q2MIN, Q2MAX, XMAX, XMIN

COMMON/PARAM/PI, ALPH, IWEI

COMMON/PARAT/AM(18), SHAT, YMAX, XMIN, Q2MAX, Q2MIN, XMAX, XMIN

COMMON/TCEMNT/SSS, CM(4), DBCMS(4)

COMMON/PREMINAT/IEM

COMMON/PTCUT/PT2CUT(100)

COMMON/PYPAIRS/MSTP(200), PARP(200)

PARAMETER (NY = 40, NQ = 20)

COMMON/QCDGRID/IQ(4, NY, QQ(NQ)), \& QPD(NY, NQ), QQDF(NY, NQ), QQBDF(NY, NQ), QQCD(NY, NQ), \& QPM(NY, NQ), QQBPI(NY, NQ), QQBHIP(NY, NQ), QQCDI(NY, NQ), \& QPM(NY, NQ), QQB(NY, NQ), QQBHP(NY, NQ), QQCD(NY, NQ)

PARAMETER (NBQ2 = 20, NBX = 20)

COMMON/RAPERHER/HERPS(6, :), XPQDF(-6: 6, NBX, NBQ2), XPQPF(-6: 6, NBX, NBQ2)

COMMON/RGRDF/XX(NBX), Qxx(NBQ2)

COMMON/R2VAL/F2_DIS(NBX, NBQ2), F2_DIF(NBX, NBQ2), F2_PI(NBX, NBQ2)

COMMON/RAPA/IRPU, IRUNA, IQ2, IRUNAEM, Q2START, W_Q2, OMEG2

COMMON/RAPGKI/YYYY, XEL, XPR, PT2H, SHH, T2GI, XFGKI
7 Example Program

PROGRAM RGMAIN
Implicit None
#include "rgfull.inc"
#include "rgdisdif.inc"
#include "rgluco.inc"
#include "rgludati.inc"
#include "rgpara.inc"
#include "rgpypars.inc"
#include "rdiff.rnc"
#include "rgesq2.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.1e10.) then
      c    write(6,*),*** time limit reached. time left = ',timeleft
      c    goto 123
      c endif
      CALL EVENT
C--- user analysis routine
   CALL ANALYS
C--- user analysis routine (hztool)
   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)
   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 version:
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, CERNLIB 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 interface 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 interface 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 executable using HZTOOL
./configure --disable-shared --prefix=install-path hzexe=yes

if you want to create an executable 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 executable 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 consitency with PYTHIA using LHAPDF
* nhera mode changed to run with standard lhapdf
* 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 IPRO=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 IPRO=30

* Version 3.1012
* pion exchange for neutrons added
* ARIADNE now for all IPRO available (also for IPRO=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 treatement 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 qgq 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 draprn (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)
* *::>
  eleeres charge for top corrected
* *::>
  VERSION  2.08/05  30/03/2000 17.28.20

29
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 DJANGOH

>::> 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 qgq)
* *:
* VERSION 2.06/41 22/07/98 10.23.45
* QCDGRID speeded up by usage of grid for wmax
* *:
* VERSION 2.06/41 15/07/98 22.50.21
* heracles fl included
* *:
* VERSION 2.06/38 26/06/98 22.30.23
* Bug in intrinsic k_t for resolved photons corrected (PYREM)
* *:
* VERSION 2.06/36 26/06/98 22.30.23
* resolved photon BFKL qq -> qq added acc. Cox/Forshaw hep-ph9806056
* *:
* VERSION 2.06/34 17/06/98 23.08.14
* writing grid file for pdf's included --> faster when same param.
* processes IPRO=21 included qq 2gluon exchange
* processes IPRO=20 included qg 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 qgq 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 qgq 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.....
weighting for diffr. with \( ng>0 \) improved

bug in arexec for diffractive events corrected

QCDMIX corrected when using grid

bug in lmeps for QED radiation fixed

Subroutine EVENT changed so that 1200(nrad) and 12 give same results for diffraction

lots of changes in PYSSPA for res. photons needed
rearranged switches to be more transparent.... included option for angular ordering in PYSSPA

bug in small mass collapsing for charm in LMEPS corrected

2nd attempt to IPS in resolved photon

first attempt to IPS in resolved photon

NFLAV added to f2md

IPRO=15 PHIGKI changed to region 0 - 2\( \pi \)

bug NIA1 used in AREXEC corrected

check on IDISDIF in rapgap improved....

bug corrected: mixing F2 and F2D for \( NG<0 \)

initial particle code for res. gamma corrected

initial parton for resolved gamma in LMEPS corrected

mismatch in dimensions in XXI and Q2I in rapgap cured

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 IPR0 = 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

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*::> VERSION 2.04/00 23/12/96 13.56.36
* charged current interactions (W exchange) included

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*::> 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 IPRD=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
* IPRD = 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 IPRD=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

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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 PYREMN

::> 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 pyrems

::> 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
initial and final state parton shower included
a la LEPTO.
mixing of lowest order and higher order QCD possible
also DIS and DIFF possible via IDIR=1 ==> DIS
   IDIR=0 ==> DIF

Heracles interface added

include process IPRO=100
gamma + pomeron --> rho + pomeron

YMAX and Q2MAX cuts implemented

now also cut on Minimum scattering angle of electron
THEMI included

CMZ version of RAPGAP
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