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Hard diffractive scattering in high energy ep collisions and the Monte Carlo Generator RAPGAP

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Abstract

The program RAPGAP generates events in ep collisions where the electron is scattered on a pomeron $\mathbb{P}$ coupled to the proton p. A gap in rapidity between the fast moving proton and the remaining hadronic system is observed. The program is applicable to photoproduction ($Q^2 \simeq 0$) as well as deep inelastic scattering ($Q^2 > 0$). Different types of hard interaction processes such as $\gamma^* q \to q'$ and $\gamma g \to q\bar{q}$ for light and heavy quarks are included. Several options for the parametrisation of the pomeron and its parton density are available within the program. The hadronisation is performed using the LUND string fragmentation model. The Monte Carlo implementaion is described and some phenomenological consequences are discussed.

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1 Tabular Summary

program name	RAPGAP
version	1.0
date of lastest version	Dec. 1993
author	Hannes Jung (F36HJU at DSYIBM.DESY.DE)
program size	$\sim$ 3000 lines of code
input files needed	none
computer types	any with standard Fortran 77, tested on IBM MVS, VAX
other programs called	JETSET 7.3
	ARIADNE 4
	DIVON 4 (CERN Library)
initial parton shower	ARIADNE
hard sub-processes included	$\gamma g \to q\bar{q}$
	$\gamma g \to c\bar{c}$
	$eg \to e'q\bar{q}$
	$eg \to e'c\bar{c}$
	$eq \to e'q'$
final parton shower	ARIADNE
fragmentation model	LUND string
initial QED radiation	none

2 Introduction

The basic partonic processes in inelastic lepton nucleon scattering $ep \to e'X$ are shown in Fig. 1. When a quark or a gluon is scattered off the proton, it leaves behind a colored remnant because the struck parton itself carries color. In the final state all colored partons have to combine somehow to give colorless hadrons which can be observed. Thus there are color strings between the partons of the hard interaction and the remnant of the proton. This model of inelastic lepton nucleon scattering we call here *standard IS* instead of DIS because it applies also for photoproduction.

However there is a fraction of events in inelastic lepton nucleon scattering observed at HERA [1, 2] which show a large gap in rapidity between the fast moving proton and the rest of the hadronic particles (the same type of events are well known from $p\bar{p}$ sacttering [3]). These events cannot be explained by *standard IS* because the color strings mentioned above will result in particles filling the region between the partons of the hard interaction and the remnant of the proton.

If, however, the proton emits a colorless object [2] , like a pomeron (which may be thought of as a simple two gluon state with zero net color), there is obviously no color flow from the proton, which stays intact or becomes a low mass state, to the other final state particles. The

[2] Also other color neutral particles, like π's, can couple to the proton. Such processes will be included in the next version of RAPGAP

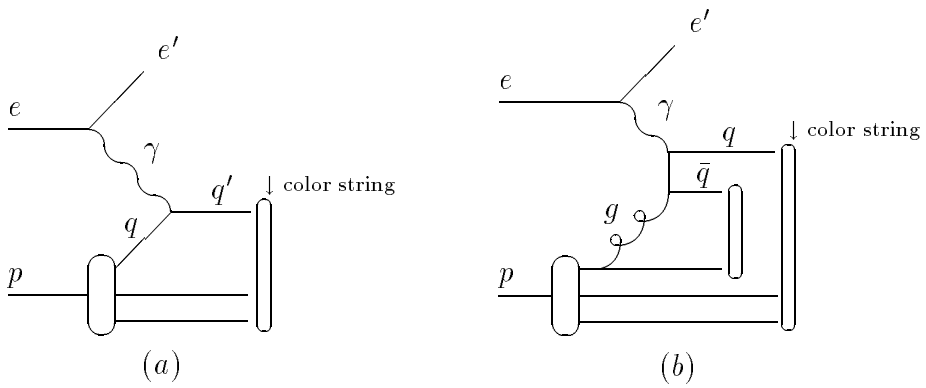

Figure 1: Basic processes for inelastic lepton nucleon scattering. *a*. shows the lowest order process. *b*. shows the $O(\alpha_{em}\alpha_s)$ for gamma gluon fusion. Indicated is the color flow when a colored parton is scattered off the proton directly.

particles resulting from the hard interaction are separated in rapidity from the fast moving proton independent of the detailed nature of the hard interaction.

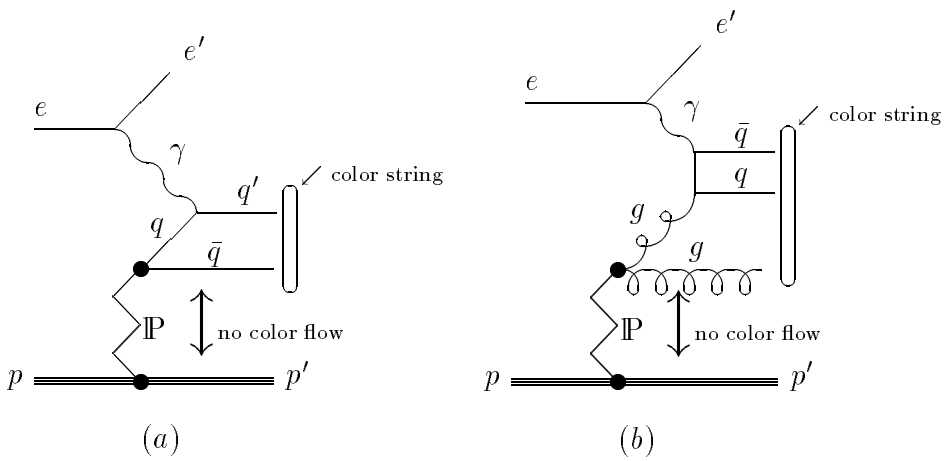

Figure 2: Basic processes for inelastic lepton scattering on a pomeron. *a*. shows the lowest order process. *b*. shows the $O(\alpha_{em}\alpha_s)$ for gamma gluon fusion. Since the pomeron is a color neutral object there is no color flow between the diffractively scattered proton and the particles of the hard interaction. A gap in rapidity is observed between the fast moving proton and the other particles.

Here we follow the idea of Ingelman and Schlein [4] that the proton couples to a (spacelike)

pomeron $\mathbb{P}$ and this pomeron consists of partons. Now the photon coupling to the incoming lepton interacts with partons of the pomeron instead of interacting with partons of the proton directly as in the usual model of *standard IS*. These processes are shown in Fig. 2.

Provided that we know the probability $f_{p\,\mathbb{P}}$ for finding a pomeron $\mathbb{P}$ inside the proton and that we know the parton density $f_{\mathbb{P}\,\mathrm{p_i}}$ inside the pomeron, the calculation of the cross section for such processes is straightforward:

$$d\sigma(ep \to e'Xp') = f_{p\,\mathbb{P}} \cdot f_{\mathbb{P}\,\mathrm{p_i}} \cdot d\sigma(ep_i \to e'X) \tag{1}$$

where $d\sigma(ep_i \to e'X)$ is the partonic cross section for scattering an electron scattering on a parton p_i. This process now depends on whether the pomeron has mainly a quark or a gluon structure.

3 Physics Input and Monte Carlo Implementation

The program described here is valid for all Q^2, i.e. for deep inelastic scattering as well as for photoproduction ($Q^2 \sim 0$). The full matrix elements and the correct treatment of the (virtual) photon are implemented. All different options described in this paper are available in the program RAPGAP. Resolved photon processes in photoproduction are not available in the present version of the program.

3.1 Kinematics

Here we give the main kinematic relations for processes of the type $e + p \to e' + X + p'$ where p' is a proton or a low mass diffractive state and X describes the final state including all particles except the scattered electron e'. Let l, P be the momenta of the electron and proton respectively, p_γ the momentum of the interacting photon and $y = \frac{P.p_\gamma}{P.l}$ its fractional energy (if the lepton scattering angle is small), x the fractional momentum of the beam momentum carried by the parton p_1 and P' the momentum of the scattered proton p'. Then the following relations hold:

$$\begin{aligned} s &= (l+P)^2 \simeq 2l.P && (2)\\ W^2 &= (p_\gamma + P)^2 \simeq -Q^2 + ys && (3)\\ \hat{s} &= (p_\gamma + p_1)^2 = -Q^2 + 2p_\gamma.p_1 \simeq -Q^2 + yxs && (4) \end{aligned}$$

where $p_\gamma^2 = -Q^2$ and $p_1^2 = 0$ and the "$\simeq$" sign indicates that the masses m_e, m_p are neglected.

In the case of $\gamma^* q \to q'$ we simply have $\hat{s} = m_q^2 = 0$ and obtain the usual formula for Bjorken x_{Bj} with $x = x_{Bj} = \frac{Q^2}{2P.p_\gamma}$ whereas in case of $\gamma\, g$ fusion we have $x = x_g = \frac{\hat{s}+Q^2}{2P.p_\gamma} \geq x_{Bj}$.

The invariant mass of the hadronic final state X (without the final state proton p') is given by:

$$\begin{aligned} m_X^2 &= (p_\gamma + P - P')^2 && (5)\\ &= -Q^2 + t + 2p_\gamma p_{I\!P} = -Q^2 + rys + t && (6)\\ &= \left(\sum_i p_i\right)^2 && (7) \end{aligned}$$

with $t = (P - P')^2 = p_{I\!P}^2$, $p_{I\!P} = P - P'$, $r = 1 - x_p$ being the momentum fraction carried by the pomeron, $x_p = P'/P$ and the sum in the last equation runs over all particles except the scattered electron e' and the scattered proton p'. When t is small we obtain for photoproduction ($Q^2 \sim 0$) the same formula for r as in hadroproduction: $r \simeq m_X^2/W^2$.

Thus having fixed the momenta of the interacting partons, the "hard" subprocess $\gamma(p_\gamma) + q(p_1) \to q'(p_2)$ or $\gamma(p_\gamma) + g(p_1) \to q(p_2) + \bar{q}(p_3)$ with $p_2^2 = m_q^2$ and $p_3^2 = m_{\bar{q}}^2$ can be generated according to the matrix element and the available phase space.

Kinematic arguments now lead to upper and lower limits on y:

$$y_{max;min} = \frac{s + W_0^2 \pm \sqrt{(s - W_0^2)^2 - 4m_e^2 W_0^2}}{2(s + m_e^2)} \tag{8}$$

with $W_0^2 = (m_q + m_{\bar{q}} + m_p)^2 - m_p^2$ for γg fusion and $W_0^2 = (m_q + m_p)^2 - m_p^2$ for quark scattering. Lower and upper limits for Q^2 are:

$$\frac{m_e^2 y^2}{(1-y)} \leq Q^2 \leq ys - W_0^2 \tag{9}$$

and for x:

$$\frac{(m_q + m_{\bar{q}})^2 + Q^2}{ys} \leq x \leq 1 \tag{10}$$

In the MC implementation we start generating y, Q^2 and x with an approximated $1/y$, $1/Q^2$ and $1/x$ spectrum. The integration of the multidimensional cross section is performed with the DIVON package [5], which after integration also allows the generation of unweighted events according to the actual cross section.

3.2 Physics Subprocesses

In the case of $e\,q$ scattering (see Fig. 2a) the partonic cross section is:

$$\frac{d\sigma(eq \to e'q')}{dy\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[1 + (1-y)^2\right] \tag{11}$$

where only transverse photons are considered.

In photon gluon fusion (see Fig. 2b) a pair of light or heavy quarks can be produced. For this process both the full matrix element for $e\ g \to e' q\bar{q}$ [6] and the Equivalent Photon Approximation described in the next section together with the matrix element for $\gamma^* g \to q\bar{q}$ are implemented. For simplicity we give here only the cross section for photon gluon fusion into light quarks ($m_q = 0$):

$$\frac{d\sigma}{dy\, dQ^2\, d\hat{t}} = \frac{dN}{dy\, dQ^2} \frac{d\hat{\sigma}}{d\hat{t}} \tag{12}$$

with $\frac{dN}{dy\, dQ^2}$ given by EPA and $\hat{\sigma}$ being the cross section for $\gamma^* g \to q\bar{q}$ (for transverse photons):

$$\frac{d\hat{\sigma}}{d\hat{t}} = \frac{\pi}{(\hat{s}+Q^2)^2}(e_q^2 \alpha \alpha_s) \left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} - \frac{2\hat{s}Q^2}{\hat{t}\hat{u}} \right) \tag{13}$$

with $\hat{s}, \hat{u}, \hat{t}$ being the usual Mandelstam variables in the hard subprocess. Note that $\hat{t}$ corresponds to the hard subprocess and is not the same as $t = (P - P')^2$.

In the case of light quark production a cut on the invariant mass $\hat{s}$ or on the transverse momentum $\hat{p}_t$ of one of the quarks has to be introduced in order to avoid collinear divergencies. This cut is not needed in the case of heavy quark production where the masses are included in the matrix element.

3.3 Equivalent Photon Approximation

In leptoproduction in general the cross section can be factorised into a (virtual) photon density and the cross sections σ_L and σ_T for longitudinal and transverse polarised photons. When the contribution of longitudinal photons is neglected we can write the leptoproduction cross section:

$$d\,\sigma_{lp \to l' X}(s) = \frac{dN}{dy\, dQ^2} \sigma_T(y\, s) \tag{14}$$

where $\frac{dN}{dy\, dQ^2}$ is the equivalent photon approximation and σ_T the photoproduction cross section for transverse photons at a reduced CM energy of ys. The photon spectrum is given by:

$$\frac{dN}{dy\ dQ^2} = \frac{\alpha}{\pi} \left((1 - y - \frac{y^2}{2}) \frac{1}{y\ Q^2} - \frac{m_e y}{Q^4} \right) \tag{15}$$

where the last term is a correction to the well known Weizsäcker Williams approximation when factors of the order of $\frac{m_e}{Q^2}$ are kept [7].

One should note that with the formula given in eq.(15) the photon has a finite virtuality $Q^2 = -q^2 = (l - l')^2$ thus leading to a nonvanishing scattering angle of the scattered lepton.

3.4 $p - \mathbb{P}$ Vertex

The probability for finding a pomeron $\mathbb{P}$ with energy fraction r and virtuality $t = (P - P')^2 = p_{\mathbb{P}}^2$ in a proton can be calculated in Regge theory. A detailed discussion can be found in [8]. Here

only the part relevant for the pomeron probability distribution is reviewed. The cross section for single diffractive scattering via pomeron exchange for a process $A + B \to C + X$ with C being a diffractive state can be written as:

$$\begin{aligned} \frac{d\sigma^{diff}}{dt\ dr} &= \frac{1}{16\pi}|\beta_{B\,\mathbb{P}}(t)|^2 r^{1-2\alpha_{\mathbb{P}}(t)}\sigma_{tot}(A\mathbb{P}) \\ &= \frac{1}{16\pi}|\beta_{B\,\mathbb{P}}(t)|^2\ \frac{1}{r^{1+2\epsilon}}\ e^{-2\alpha'_{\mathbb{P}} ln(1/r)|t|}\ \sigma_{tot}(A\mathbb{P}) \end{aligned} \tag{16}$$

with $\sigma_{tot}(A\mathbb{P})$ being the cross section for scattering particle A with pomeron $\mathbb{P}$ and $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t$ with $\alpha_{\mathbb{P}}(0) = 1 + \epsilon$ and $\alpha'_{\mathbb{P}} = 0.25$. The parameter $\epsilon = 0.085$ describes the rise in the total cross section observed in $p\bar{p}$ and recently in γp [9, 10] scattering experiments.

With the ansatz

$$\beta_{p\,\mathbb{P}}(t) = \beta_{p\,\mathbb{P}}(0) e^{-\frac{1}{2}R_N^2|t|} \tag{17}$$

$\beta(0)$ can be related to the $p\,p$ cross section via:

$$\sigma_{tot}(pp) = \beta^2_{p\mathbb{P}}(0) \simeq 40\text{mb} \tag{18}$$

and we get

$$\beta_{p\,\mathbb{P}}(0) = 6.3\text{mb}^{1/2} \simeq 10\text{GeV}^{-1} \tag{19}$$

At small $r \leq 0.01$ a slowly changing slope parameter b of the logarithmic t dependence is obtained from pp scattering (for example in [11]) with $b \simeq 6.5$. This slope b can be related to eq.(16) and eq.(17):

$$e^{-b|t|} = e^{-(R_N^2 + 2\alpha'_{\mathbb{P}} ln(1/r))|t|)} \tag{20}$$

with $R_N^2 = 4.7\ \text{GeV}^{-2}$. One should note that this forward slope of the t dependence is correlated with r.

By $f_{p\mathbb{P}}(t, r)$ we denote the probability density that the proton (p) splits into a proton (p') and a Pomeron ($\mathbb{P}$) with momentum fraction r of the momentum of the incoming proton (p). This density depends on the momentum transfer $t = (p - p')^2$. $f_{p\mathbb{P}}(t, r)$ is given by Berger et al. [8] and Streng [12] (with label S for further reference):

$$f^S_{p\,\mathbb{P}}(t, r) = \frac{\beta^2_{p\mathbb{P}}(t)}{16\pi} r^{1-2\alpha_{\mathbb{P}}(t)} \tag{21}$$

In addition to the above description of $f_{p\,\mathbb{P}}(t, r)$ other parametrisations exist. Ingelman and Schlein [4, 15] (label IS) deduce $f_{p\,\mathbb{P}}(t, r)$ from a fit to measured data. They use the Regge picture only for the normalisation. They obtain

$$f^{IS}_{p\,\mathbb{P}}(t, r) = \frac{1}{2.3}\frac{1}{r}\left[6.38e^{-8|t|} + 0.424e^{-3|t|}\right] \tag{22}$$

Donnachie and Landshoff [13] (label DL) use Regge theory together with an elastic form factor for the proton and obtain:

$$\begin{aligned} f^{DL}_{p\,\mathbb{P}}(t, r) &= \frac{9\delta^2}{4\pi^2}\ \frac{4m_p^2 - 2.8t}{4m_p^2 - t}\ \frac{1}{(1 - t/0.7)^2}\ r^{1-2\alpha_{\mathbb{P}}(t)} \\ &= \frac{9\delta^2}{4\pi^2}\ \frac{4m_p^2 - 2.8t}{4m_p^2 - t}\ \frac{1}{(1 - t/0.7)^2}\ \frac{1}{r^{1+2\epsilon}}\ e^{-2\alpha'_{\mathbb{P}} ln(1/r)|t|} \end{aligned} \tag{23}$$

where $\alpha_{I\!P}(t)$ is given by the formula above and $\delta^2 = 3.5$ GeV^{-2}.

A comparison between the different parametrisations of the t dependence is shown in table 1 and in Fig. 3. There is a factor of ~ 2 difference between $f^S_{p\,I\!P}(t,r)$ and the other two parametrisations. This differences are reflected in the normalisation of the total cross section.

$\int_{r_{min}}^{r_{max}} f_{p\,I\!P}(t,r)drdt$				
	$\lvert t\rvert < 1$ GeV			
	$r_{max} = 0.01$	$r_{max} = 0.05$	$r_{max} = 0.1$	$r_{max} = 1.0$
$\int f^S_{p\,I\!P} drdt$	3.7	4.6	5.0	6.0
$\int f^{IS}_{p\,I\!P} drdt$	1.9	2.5	2.8	3.7
$\int f^{DL}_{p\,I\!P} drdt$	2.2	2.9	3.1	4.0

Table 1: The integral of $\int f_{p\,I\!P}(t,r)drdt$ for the different parametrisations mentioned in the text as a function of r_{max} ($r_{min} = 10^{-4}$ is appropriate for HERA energies). In the calculation we took $\alpha'_{I\!P} = 0.25$ and $\epsilon = 0.085$. $f_{p\,I\!P}$ is labelled with S for the Streng type pomeron eq.(21), IS for the Ingelman Schlein eq.(22) and with DL for the Donnachie Landshoff type pomeron eq.(23) parametisation. The differences between the different parametrisations show the uncertainty in overall normalisation.

3.5 Pomeron structure function

So far very little is known about the structure of the pomeron. Measurements of hard diffractive scattering have been performed [3], but it is still an open question whether the pomeron consists mainly of gluons [4, 8, 12] or of quarks [13]. It is also unclear whether the partons in the pomeron fulfill the momentum sum rule:

$$\int_0^1 \sum_i x f_{I\!P\ \mathrm{Pi}}(x) = 1 \tag{24}$$

If the pomeron is made from gluons, one can derive two extreme initial gluon densities obeying the momentum sum rule (eq.(24)) :

$$xG_0(x) = 6x(1-x) \tag{25}$$

if the pomeron is made of 2 gluons or

$$xG_5(x) = 6(1-x)^5 \tag{26}$$

if the gluons in the pomeron are as soft as in the proton. Berger et al. [8] suggest the following form:

$$xG(x) = [0.18 + 5.46x]\,(1-x) \tag{27}$$

If the pomeron is a two quark system (assuming that only $u\bar{u}$ and $d\bar{d}$ contribute), the quark densities look as follows:

$$xq_0(x) = \frac{6}{4}x(1-x) \tag{28}$$

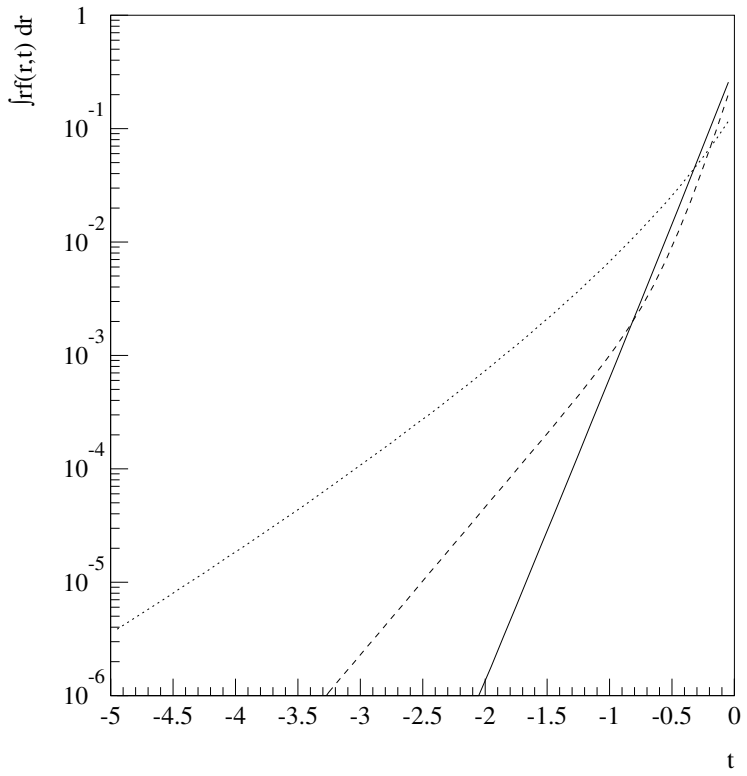

Figure 3: t dependence of the three different parametrisations for $\int r f_{p\,\mathbb{P}} dr$. The full line shows the Streng type pomeron eq.(21), the dashed line the Ingelman Schlein eq.(22) and the dotted line the Donnachie Landshoff type pomeron eq.(23). The effective t slope for the Streng and Donnachie Landshoff type pomeron is obtained by integrating $r f_{p\,\mathbb{P}}$ over r with $0.1 < r < 10^{-4}$.

where the factor $1/4$ follows from the summation over quark flavors and the requirement of eq.(24).

Donnachie and Landshoff [13] use a different approach. They assume only quark densities ($u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ with half strength) in the pomeron and use the normalisation obtained from the proton quark densities:

$$xq(x) = \frac{1}{3} C\pi x(1-x) \tag{29}$$

with $C = 0.23$. After summation over the quark flavors the quark density becomes $\sum_i xq^i(x) = \frac{5}{3} C\pi x(1-x)$ and it differs from the above one in eq.(28) $\sum_i xq_0^i(x) = 6x(1-x)$ by a factor of ~ 7.5 in normalisation.

In addition to these theoretical uncertainties there is also a uncertainty in the Q^2 evolution of the parton densities. Calculations have been performed recently using DGLAP and GLR/MQ

equations. Depending whether DGLAP or GLR is used the results are very different and especially saturation effects play an important role. This is shown explicitely in [14, 15].

3.6 Fragmentation and Remnant Treatment

Higher order gluon emission is simulated with the Color Dipole Model (ARIADNE) [16] and the hadronisation is performed using the LUND string fragmentation model [17].

In *standard IS* a parton carrying color is removed from the proton and a colored proton remnant is left. This remnant together with the colored partons of the hard interaction must form a color singlet state (see Fig. 1). This color string generates a particle flow between the proton remnant and the partons of the hard scattering.

In diffractive scattering the proton stays intact or becomes a low mass diffractive state, here simply denoted by p' [3]. Because of the emission of the color neutral pomeron there is no color connection between the diffractively scattered proton p' and the other particles. When a quark (antiquark) is removed from the pomeron a antiquark (quark) of same flavor but with the corresponding anticolor is left (Fig. 2a). This remnant is connected via the color string to the scattered quark (antiquark). When a gluon is removed from the pomeron $\mathbb{P}$ a color octet remnant is left, here treated as a single gluon. This pomeron remnant together with the $q\bar{q}$ of the hard interaction forms the color singlet state (Fig. 2b).

Even with higher order gluon emission the color strings stay as described above. Only when a gluon splits into $q\bar{q}$ the color flow is broken.

4 Inelastic and Hard Diffractive Scattering

In Fig. 4 we show $\frac{d\sigma}{d\eta_{max}}$ for the process $ep \to e'Xp'$ at HERA energies for 30 GeV electrons on 820 GeV protons. η_{max} is the maximum rapidity of any of the produced particles in the hadronic final state except the scattered proton p'. In Fig. 4(a) the prediction is shown for a purely gluonic pomeron (the full line corresponds to $xG_0(x)$ and the dashed line to $xG_5(x)$). In Fig. 4(b) the prediction for a pomeron with quark content is shown. In both cases a clear gap in rapidity is observed between the scattered proton at $\eta \simeq 7.5$ and the rest of the particles. In addition in both figures the prediction from *standard IS* (simulated with LEPTO 6.1 [18]) is shown with the dotted line. It can be seen that the prediction of events with a large rapidity gap η_{max} is very different for *standard IS* and diffractive scattering and even the predictions from quark or gluon content of the pomeron differ in the η_{max} distribution.

The cross section of inelastic hard diffractive scattering is only a special part of the usual inelastic process. This can be understood since the initial gluon and sea quark distributions for the proton satisfy either constraints from Regge theory, i.e. that the total cross section

[3] In RAPGAP 1.0 the low mass diffractive state is always taken to be a simple proton. No diffractive dissociation of the proton is included yet.

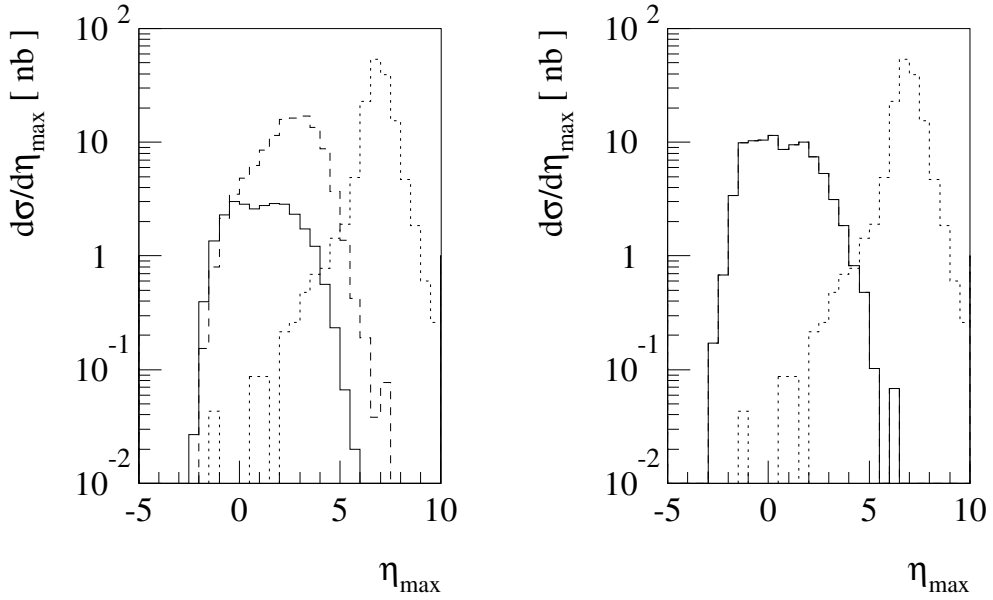

Figure 4: Rapidity distribution for diffractive and *standard IS* scattering with $Q^2 > 4$ GeV^2, $y > 0.1$ and $m_X > 4$ GeV at HERA energies. $(a.)$ $\frac{d\sigma}{d\eta_{max}}$ for $\gamma g \to q\bar{q}$. The full line shows the prediction for G_0, the dashed line for G_5 and the dotted line shows the prediction for *standard IS*(LEPTO 6.1). $(b.)$ $\frac{d\sigma}{d\eta_{max}}$ for $eq \to q$. The full line is the prediction with xq_0 and the dotted line the prediction for *standard IS*(LEPTO 6.1). For diffractive scattering $f_{p\,\mathbb{P}}^{S}$ is used.

for small x becomes constant due to pomeron exchange, or they satisfy constraints from the Lipatov pomeron resulting in $xG(x) \sim 1/\sqrt{x}$ for small x. That means that diffractive scattering is already included in the usual structure function parametrisations. Therefore the cross section of diffractive scattering must not be added to the usual one of inelastic scattering. However diffractive scattering is not included in the simulation of the hadronic final state in *standard IS* Monte Carlo models.

The inelastic lepton nucleon cross section is uniquely defined in terms of x and Q^2. Therefore a complete description of the hadronic final state might be obtained as follows: By comparison of the x and Q^2 distributions of *standard IS* and diffractive events, the fraction of diffractive events for given x and Q^2 can be determined. By replacing this fraction of events in the *standard IS* sample by the corresponding diffractive events a complete event sample is obtained.

5 Description of the program components

The main routines are:

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 some histograms are filled.
ALPHAS(RQ)	give $\alpha_s(\mu)$ with μ =RQ.
PARTI	initial particle and parton momenta are given.
DFUN	interface to FXN1
FXN1	calls routines for selected processes: DIFFR1, DIFFR2, DIFFR3,
CUTG(IPRO)	cuts for process IPRO in integration and event generation.
FRAG	color flow for diffractive processes.
DIFFR1	$\gamma g_{I\!P} \rightarrow q\bar{q}$. calls kinematics and phase space routine PARTDF and matrix element ELEQQL and ELEQQB. Both for light and heavy quarks. Using Equivalent Photon approximation and $\gamma g \rightarrow q\bar{q}$ matrix element.
DIFFR2	$eg_{I\!P} \rightarrow e'q\bar{q}$. calls kinematics and phase space routine PARTDF and matrix element ELEQQF. Both for light and heavy quarks. Using full matrix element for $eg \rightarrow e'q\bar{q}$.
DIFFR3	$eq(\bar{q}) \rightarrow e'q'(\bar{q}')$ calls kinematics and phase space routine PARTDF
ELEQQL	matrix element for $\gamma g \rightarrow q\bar{q}$. q stands for light quark.
ELEQQB	matrix element for $\gamma g \rightarrow Q\bar{Q}$ including masses. Q stands for heavy quark.
ELEQQF	matrix element for $eg \rightarrow e'Q\bar{Q}$ including masses. Q stands for light or heavy quark. Masses of light quarks m_q = 10 MeV.
DOT(A,B)	A.B four vector dot product
DOT1(I,J)	four vector dot product of vectors I and J in LUJETS common.
BOOK	histogram booking
DVNOPT	changing options for DIVON
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 processes.
RASTFU(KF,X,SCALE,XPQ)	parton density in particle KF (KF = 100 is included for the pomeron) and $XPQ = xf_i(x,\mu^2)$ with $X = x$, $SCALE = \mu^2$.
RAT2DI(KF,X,XMAX,TMIN,T,WTDIST)	$T = t$ and $X = r$ dependent probability distribution for radiating a parton KF from the proton. (KF = 100 for the pomeron).
USPOM(R,T)	user supplied pomeron probability distribution with energy fraction $R = r$ and virtuality $T = t$.
USGLU(X,SCALE)	user supplied parton density of pomeron with the fractional momentum X of the pomeron momentum carried by the gluon and the scale SCALE for structure function evolution.

COMMON/RAPA /IPRO,IRUNA,IQ2

Parameters:

IPRO: select process to be generated
=10: $\gamma g_{\mathbb{P}} \to q\bar{q}$ using EPA
=11: $\gamma g_{\mathbb{P}} \to c\bar{c}$ using EPA
=12: $eq_{\mathbb{P}} \to e'q'$
=13: $eg_{\mathbb{P}} \to e'q\bar{q}$ using full Matrix Element
=14: $eg_{\mathbb{P}} \to e'c\bar{c}$ using full Matrix Element
The program RAPGAP is not able to produce mixed event samples of different processes.

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

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

COMMON/PTCUT/ PT2CUT(20)

Parameters:

PT2CUT(IPRO) : minimum $\hat{p}_\perp^2$ for process IPRO. Must be used for generation of light quarks in processes IPRO=10 and IPRO=13. (D=1.0)

COMMON/RAPGKI/ YY,XEL,XPR,PT2H,SHH

Parameters:

YY : energy fraction lost by incident electron
XEL : energy fraction of parton on electron side
XPR : energy fraction of parton on proton side
PT2H : $\hat{p}_\perp^2$ [GeV$^2/c^2$] of parton in hard subprocess cm system
SHH : invariant mass $\hat{s}$ [GeV^2] of hard subprocess

COMMON/INPU /PLEPIN,PPIN,NFRAG,ILEPTO,IFPS

Parameters:

PLEPIN : momentum p [GeV/c] of incoming electron (D=$-$30.)
PIN : momentum p [GeV/c] of incoming proton (D=820.)
NFRAG : switch for fragmentation
= 0 off
= 1 on (D)
ILEPTO : Not used at present.
IFPS : switch parton shower
= 0 off
= 10 gluon radiation according to ARIADNE.

COMMON/DIFFR/T2MAX,XF,ALPHP,RN2,EPSP,QMI,YMI,NG,NPOM

Parameters:

T2MAX : maximum t [GeV$^2/c^2$] for diffractive process (D=20)

XF : minimum $x_f = \frac{E_p}{E_{p'}}$ (D=0.9)

ALPHP : $\alpha_{\mathbb{P}}$ [GeV^{-2}] (D=0.25)

RN2 : R_N^2 as defined above (D=4.7)

EPSP : ϵ (D=0.085)

QMI : Minimum Q^2 to be generated

YMI : Minimum y to be generated

NG : select pomeron structure function $xG(x)$ gives gluon density. Quark densities fulfilling momentum sum rule are $xq(x) = \frac{1}{4}xG(x)$ when only two quark flavors contribute with equal strenght.
=0: $xG_0(x) = 6x(1-x)$ (D)
=n: $xG_n(x) = (n+1)(1-x)^n$ for $1 \leq n \leq 5$
=10: $xG(x) = (0.18 + 5.46x)(1-x)$
=11: $xq(x) = \frac{1}{3}C\pi x(1-x)$ Donnachie Landshoff quark density in pomeron.
< 0: user supplied structure function via function USGLU(X,SCALE) with X = $E_g/E_{\mathbb{P}}$ and SCALE=μ^2 the scale for sctructure function evolution

NPOM : select pomeron distribution $f_{p/\mathbb{P}}$
=0: pomeron distribution $f^S_{p/\mathbb{P}}$
=1: pomeron distribution $f^{IS}_{p/\mathbb{P}}$
=2: pomeron distribution $f^{DL}_{p/\mathbb{P}}$
< 0: user supplied pomeron distribution via function USPOM(X,T2) with X = $E_{\mathbb{P}}/E_p$ and T2 = $(p-p')^2$

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

Parameters:

SSS overall s

CM boost vector to overall center of mass system

DBCMS boost vector to hard scattering center of mass system

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

Parameters:

PBEAM energy momentum vector of beam particles

KBEAM flavour code of beam partciles

COMMON/LUCO /KE,KP,KPH,KGL,KPA

Parameters:

particle codes for internal use.

COMMON/HARD/ NIA1,NIR1,NIA2,NIR2,NF1,NF2,NFT

Parameters:

NIA1,NIA2 position of partons in hard interaction in LUJETS event record

NF1,NF2 first and last position final partons/particles of hard interaction in LUJETS

NIR1,NIR2 first and last position of remnant for internal use only

NFT total number of final particles; for $2 \to 2$ process NFT=2

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

Parameters:

AM	masses of final state particles of hard interaction
SHAT	$\hat{s}$ of hard subprocess
YMAX,YMIN	actual upper and lower limits for y;
Q2MAX,Q2MIN	actual upper and lower limits for Q^2 of γ.
XMAX,XMIN	upper and lower limits for x.

COMMON /PARAE/Q2,Q2Q,PCM(4,18)

Parameters:

Q2	in leptoproduction: actual Q^2 of γ.
Q2Q	hard scattering scale μ^2 used in α_s and structure functions
PCM	particle momenta (in double precision) in hard interaction in CM- frame for internal use only

COMMON /PARAM/ ALPHS,PI,ALPH,IWEI

Parameters:

ALPHS	actual α_s
PI	π
ALPH	α_{em}
IWEI	= 1 unweighted event generation. = 0 weighted events during integration procedure

COMMON/EFFIC/AVGI,SD,NIN,NOUT

Parameters:

AVGI	integrated cross section
SD	standard deviation of integrated cross section
NIN	number of trials for event generation
NOUT	number of successful generated events

COMMON/STRU/ SCAL1,XPD1,SCAL2,XPD2

Parameters:

SCAL1,SCAL2	scale for structure function on beam
XDP1,XPD2	value of parton density on beam

6 Example Program

```
      PROGRAM RGMAIN
C---initialise JETSET 7.3 parameters
      REAL * 4 PLEPIN,PPIN
      INTEGER KE,KP,KPH,KGL,KPA,NFRAG,IFPS
      INTEGER NIA1,NIR1,NIA2,NIR2,NF1,NF2,NFT
```

```
      COMMON/LUCO  /KE,KP,KPH,KGL,KPA
      COMMON/INPU  /PLEPIN,PPIN,NFRAG,ILEPTO,IFPS
      COMMON/HARD/ NIA1,NIR1,NIA2,NIR2,NF1,NF2,NFT
      REAL * 8 ALPHS,PI,ALPH,PT2CUT
      INTEGER IRUNA,IQ2,IWEI
      COMMON /PARAM/ ALPHS,PI,ALPH,IWEI
      INTEGER IPRO
      COMMON/RAPA /IPRO,IRUNA,IQ2
      COMMON/PTCUT/ PT2CUT(20)
      INTEGER NG,NPOM
      REAL * 8 T2MAX,XF,ALPHP,RN2,EPSP,QMI,YMI
      COMMON/DIFFR/T2MAX,XF,ALPHP,RN2,EPSP,QMI,YMI,NG,NPOM
C     initialize random number generator
      ISEED = 213123
      CALL H1RNIN(ISEED)
C---initialise RAPGAP parameters
         CALL GRAINI
C-- change standard parameters
C*********************************************************************
C     1ST INCOMING PARTICLE  (KE=11 ELECTRON)
C     1ST INCOMING PARTICLE  (KE=22 PHOTON)
      KE =  11
c      KE =  22
C     LEPTON MOMENTIM (D=-30)
      PLEPIN = -30.
C*********************************************************************
C     2ND INCOMING PARTICLE (KP = 2212 PROTON)
      KP = 2212
C     proton momentum (D=820)
      PPIN   = 820.
C*********************************************************************
C     PARTON SHOWER OFF/ON (D=10)
C     (off = 0, ARIADNE = 10)
      IFPS   = 10
C*********************************************************************
C     fragmentation on/off (D=1)
      NFRAG  = 0
C*********************************************************************
C     fixed/running alpha_s (D=1)
      IRUNA  = 1
C*********************************************************************
C      scale for alpha_s
C      1:  q2 = m**2
C      2:  q2 = shat
C      3:  q2 = m**2 + pt**2
```

```
C      4:  q2 = Q2
       IQ2    = 4
C*********************************************************************
C     select process to be generated
       IPRO   = 13
C*********************************************************************
C  Processes gamma gluon fusion using EPA and gamma glu Martix Element
C    10: gamma pommeron_gluon --> q qbar (light quarks:u,d,s)
C    11:  gamma pommeron_gluon --> Q Qbar (charm quarks)
C
C*********************************************************************
C  Process e q --> e' q'
C    12:  e q --> e' q'
C*********************************************************************
C  Processes gamma gluon fusion using full e glu Matrix Element
C    13:  e pommeron_gluon --> e' q qbar (light quarks:u,d,s)
C    14:  e pommeron_gluon --> e' Q Qbar (charm quarks)
C
C*********************************************************************
C    parameters for pomeron distribution
C     gluon density in pomeron (D=0)
       NG   =  0
C select pomeron distribution
C     (D=0) (0 = Streng, 1 = Ingelman/Schlein, 2 = Donnachie Landshoff)
       NPOM = 0
C epsilon for rising of x Section in Streng and DL pomeron distribution
       EPSP = 0.085
       RN2  = 4.7
       ALPHP = 0.25
C cut of x_f
       XF  = 0.9
c Maximum -t allowed in generation
       T2MAX = 1.
C Minimum Q^2 of electron to be generated
       QMI = 8.d0
C Minimum y of electron to be generated
       YMI=0.1d0
C pt^2_hat cut for light quark Matrix Elements
       PT2CUT(10)=1.
       PT2CUT(13)=1.
C*********************************************************************
C Initialize ARIADNE
          CALL ARINIT('RAPGAP')
C--- CALCULATE X SECTION
          CALL RAPGAP
```

```
C--- print x section
         CALL RAEND(1)
C--- event generation
         DO 5 I=1,5000
         CALL EVENT
  5      CONTINUE
C---PRINT NR OF GENERATED EVENTS
         CALL RAEND(20)
         STOP
         END
```

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