DIFFVM – A Monte Carlo Generator for Diffractive Processes in ep Scattering.

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Abstract: Diffvm is a Monte Carlo Generator for soft diffractive processes in ep collisions in the framework of Regge phenomenology and the Vector Dominance Model. It includes a detailed simulation of the diffractive dissociation of the proton.

1 Introduction

Diffvm is a Monte Carlo generator which simulates diffractive processes in electron-proton scattering in the framework of Regge phenomenology [1, 2, 3] and the Vector Dominance Model (VDM) [4, 5, 6]. In this approach the electron emits a photon which fluctuates into a virtual vector meson. This vector meson then interacts diffractively, i.e. by pomeron exchange, with the proton. The vector meson as well as the proton may emerge intact from the interaction, or dissociate diffractively. If the vector meson is produced elastically, s-channel helicity conservation (SCHC) is assumed.

Diffvm simulates the following diffractive processes: elastic vector meson production, $ep \to eVp$ and vector meson production with proton dissociation, $ep \to eVN$, as well as single, $ep \to eXp$, and double diffractive dissociation, $ep \to eXN$. Here X and N indicate the states into which the photon and the proton dissociate, respectively. Table 1 defines the kinematic variables relevant to these processes.

The generator features a detailed description of the proton-dissociative final state, including N^* resonance production and the continuum, using a parametrization of proton dissociation data from the reaction $pD \to XD$ [7, 8].

The event generation process is steered by means of control cards, in which the user can fix some parameters and choose among a few options, such as:

- 4-vectors of colliding particles;
- kinematical bounds for the generation of Q^2, y, W and generation mode for Q^2 and y;
- vector meson type and decay channel;
- fragmentation mode for the state N and for the state X;
- VDM model parameters;
- pomeron trajectory.

k	four-momentum of the incident lepton
k'	four-momentum of the scattered lepton
p	four-momentum of the incident proton
p'	four-momentum of the scattered proton
m_{V}	mass of the vector meson
m_{p}	mass of the proton
$q^2 = -Q^2 = (k - k')^2$	4-momentum transfer squared at the lepton vertex
$s = (k + p)^2$	electron–proton CM energy squared
$\nu = \frac{p \cdot q}{m_{\mathrm{p}}}$	photon energy in the proton rest frame
$W = \sqrt{(p + q)^2}$	photon-proton centre–of–mass energy
$x_{BJ} = \frac{Q^2}{2p \cdot q}$	fraction of the beam proton energy carried by the struck quark in the Breit frame
$y = \frac{p \cdot q}{p \cdot k}$	fraction of the beam energy carried by the photon in the proton rest frame
$t = (p - p')^2$	four-momentum transfer squared at the proton vertex
$z = \frac{p \cdot p_{\mathrm{V}}}{p \cdot q}$	fraction of the photon energy carried by the vector meson in the proton rest frame
θ	polar angle of decay particle with respect to the outgoing p direction in the V rest frame
ϕ	angle between the decay plane and the meson production plane in the V rest frame
Φ	angle between the lepton scattering plane and the vector meson production plane (in the proton rest frame)
$\psi = \phi - \Phi$	

Table 1: *Definition of the relevant kinematic variables.*

2 Cross section

The ep inclusive cross section can be written as:

$$\frac{\mathrm{d}^2\sigma_{ep}}{\mathrm{d}y\,\mathrm{d}Q^2} = \Gamma_T\,(y,\,Q^2)\sigma^T_{\gamma^*p}\,(W,\,Q^2) + \Gamma_L\,(y,\,Q^2)\sigma^L_{\gamma^*p}\,(W,\,Q^2), \tag{1}$$

where the symbols $\sigma^T_{\gamma^*p}\,(W,\,Q^2)$ and $\sigma^L_{\gamma^*p}\,(W,\,Q^2)$ indicate the γp cross sections for transversely and longitudinally polarized photons, respectively, and Γ_T and Γ_L are the corresponding flux factors. These factors, as defined in the Hand convention, are given by:

$$\Gamma_T = \frac{\alpha}{2\pi Q^2}\left[\frac{1 + (1 - y)^2}{y} - \frac{2(1 - y)}{y}\frac{Q^2_{\mathrm{min}}}{Q^2}\right], \qquad \Gamma_L = \frac{\alpha}{2\pi Q^2}\frac{2(1 - y)}{y}, \tag{2}$$

where $Q^2_{\mathrm{min}} = m^2_{\mathrm{e}}\frac{y^2}{1-y}$ is the minimum value of Q^2 kinematically allowed.

2.1 Virtual photon generation

DIFFVM can generate the virtual photon using:

- Weizsäcker-Williams Approximation (transversely polarized photons only); alternatively it can generate
- transversely polarized photons (using the first terms in eqs. (1) and (2)); or both
- transversely and longitudinally polarized photons (cf. eq. (2)).

The relation

$$W_{\gamma p}^2 = m_{\rm p}^2 + (sy - Q^2) > W_{\rm min}^2 \tag{3}$$

gives the invariant mass of the γp system. $W_{\rm min}$ represents the minimum CM energy of the γp system kinematically allowed or a user chosen value in the control cards. This threshold determines the minimum value for y:

$$y_{\rm min} = \frac{W_{\rm min}^2 - m_{\rm p}^2}{s}. \tag{4}$$

For each value of y, Q^2 has to satisfy

$$Q^2 > Q_{\rm min}^2. \tag{5}$$

The events generated between the limits just defined (i.e. with Q^2 above $Q_{\rm min}^2$ for a given y and with W above $W_{\rm min}$) are selected by applying the *Hit or Miss Monte Carlo* technique.

2.2 The longitudinal and transverse cross sections

Since according to the VDM the photon transforms into a virtual vector meson before interacting, the cross section for transverse photons of virtuality Q^2 has a propagator term:

$$\sigma_{\gamma *p}^T = \sigma_{\gamma p} \left(\frac{1}{1 + \frac{Q^2}{m_{\rm V}^2}} \right)^2, \tag{6}$$

where $\sigma_{\gamma p}$ is the photon-proton cross section for ρ^0 photoproduction. This is implemented as

$$\sigma_{\gamma *p}^T = \sigma_{\gamma p} \left(\frac{1}{1 + \frac{Q^2}{\Lambda^2}} \right)^2, \tag{7}$$

in DIFFVM, where Λ can be chosen by the user and is set to $m_{\rm V}$ as default.

Since real photons are transversely polarized, the *ep* cross section due to longitudinally polarized photons must vanish in the limit $Q^2 \to 0$. In the Hand convention the longitudinal flux is finite at small Q^2, so that $\sigma_{\gamma *p}^L(Q^2)$ must vanish in this limit.

Therefore it is assumed [12] that:

$$\frac{\sigma_{\gamma *p}^L}{\sigma_{\gamma *p}^T} = R(Q^2) = \xi \frac{Q^2}{m_{\rm V}^2}, \tag{8}$$

where ξ is a constant factor of order 1. In DIFFVM this is parametrized according to

$$R(Q^2) = \frac{\xi \frac{Q^2}{\Lambda^2}}{1 + \chi \xi \frac{Q^2}{\Lambda^2}}, \tag{9}$$

which reduces to

$$R(Q^2) = \xi \frac{Q^2}{m_V^2} \tag{10}$$

for $\Lambda = m_V$ and $\chi = 0$.

The parameter χ is purely phenomenological, with no theoretical justification. If χ is different from 0, then $R(Q^2)$ behaves like $R(Q^2) = \xi \frac{Q^2}{m_V^2}$ for $Q^2 \ll m_V^2$, but only approaches $\frac{1}{\chi}$ for $Q^2 >> m_V^2$, instead of rising indefinitely. The values of ξ and χ are given by the user.

2.3 Diffractive Interaction of the Vector Meson

As already mentioned, DIFFVM is based on the assumption that a virtual vector meson interacts diffractively (i.e. by pomeron exchange) with the beam proton, whereby both particles may be scattered elastically, or may dissociate. The cross sections for these processes are given by Regge theory [1, 2, 3]. DIFFVM only simulates pomeron exchange; the exchange of other Regge trajectories is neglected. Most notably the approximately degenerate ρ, ω, a and f trajectories are neglected.

The pomeron is a Regge trajectory given by $\alpha_{\mathbb{P}}(t) \simeq \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t = 1 + \epsilon + \alpha'_{\mathbb{P}} t$.

In DIFFVM the following values are used for the above parameters:

- $\epsilon = 0.0808$ [13];
- $\alpha'_{\mathbb{P}} = 0.25\ \mathrm{GeV}^{-2}$ [14].

2.4 Elastic Vector Meson Production

DIFFVM simulates the production and decay of the following vector mesons:

ρ^0, ω, ϕ, $\rho(1450)$, $\phi(1680)$, J/ψ, Υ, Υ', Υ''.

The mass of the vector meson is generated following a non–relativistic *Breit-Wigner* distribution. For pomeron exchange, the cross sections for elastic scattering of a vector meson V and a proton at fixed CM energy W and momentum transfer squared $t = p_{\mathbb{P}}^2$ is [8]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{\beta^2_{\mathrm{V}\mathbb{P}}(t)\beta^2_{\mathrm{p}\mathbb{P}}(t)}{16\pi}(W^2)^{2(\alpha_{\mathbb{P}}(t)-1)}, \tag{11}$$

where $\beta^2_{\mathrm{V}\mathbb{P}}(t)$ and $\beta^2_{\mathrm{p}\mathbb{P}}(t)$ are the $\mathbb{P}V$ and $\mathbb{P}p$ coupling constants, respectively.

Different choices for these couplings exist [15, 16], but generally they are well approximated by $\beta^2_{X\mathbb{P}}(t) \simeq \beta^2_{X\mathbb{P}}(0)\, e^{b_X t}$ for small values of $|t|$, resulting in

$$\frac{\mathrm{d}\sigma}{dt} = \frac{\mathrm{d}\sigma}{\mathrm{d}t}|_{t=0,W=W_0} \cdot e^{bt}(\frac{W}{W_0})^{4\epsilon}, \tag{12}$$

with

$$b\,(W) = b\,(W_0) + 4\alpha'_{\mathbb{P}}\,\ln\frac{W}{W_0}. \tag{13}$$

The values for $\sigma\,(W) = \int_{t_{\min}}^{t_{\min}} \frac{\mathrm{d}\sigma}{\mathrm{d}t}\mathrm{d}t$ at $W = W_0$, $b(W_0)$ and W_0 are provided by the user.

2.4.1 Vector Meson Decays

DIFFVM can generate vector mesons made out of light (ρ^0, ω, ϕ and the excited states $\rho^0(1450)$, $\rho^0(1700)$ and $\phi(1680)$) and of heavy quarks (J/ψ, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$). The decays of most of these vector mesons can be performed by JETSET [21]; however, in this case the angular decay distributions are all isotropic.

The excited states $\rho^0(1450)$, $\rho^0(1700)$, $\phi(1680)$ and $\Upsilon(3S)$ are not known in JETSET and their decay is therefore treated by special routines. The program performs the cascade decay of $b\bar{b}$ and $c\bar{c}$ $\Psi(2S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ vector mesons which have a cascade decay channel to another vector meson. The θ distribution for the vector meson decay products is generated according to SCHC. The angles ϕ and ψ are generated according to a flat distribution. The angles θ, ϕ and ψ are defined in table 1.

2.5 Photon Diffractive Dissociation

For diffractive dissociation of the photon (i.e. of the vector meson in the VDM approach) to a state of mass $M_{\mathrm{X}} = \sqrt{(q+p_{\mathbb{P}})^2}$ Regge theory expects

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}t\,\mathrm{d}M^2_{\mathrm{X}}} = \frac{\beta^2_{V\mathbb{P}}(0)\,\beta^2_{p\mathbb{P}}(t) g_{3\mathbb{P}}(t)}{16\pi s^2}\left(\frac{W^2}{M^2_{\mathrm{X}}}\right)^{2\alpha_{\mathbb{P}}(t)} M_{\mathrm{X}}^{2\alpha_{\mathbb{P}}(0)}, \tag{14}$$

where $g_{3\mathbb{P}}(t)$ is the triple pomeron coupling constant, which is usually assumed to be largely independent of t and W^2. The experimental result is [8, 17] $g_{3\mathbb{P}}(t = -0.05\mathrm{GeV}^2) = (0.583 \pm 0.040)\,\mathrm{GeV}^{-1}$ in the limit $s \to \infty$. Using the same approximation as above, one arrives at

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}t\,\mathrm{d}M^2_{\mathrm{X}}} = \left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}t\,\mathrm{d}M^2_{\mathrm{X}}}\right|_{(t=0,W=W_0,M_{\mathrm{X}}=M_0)}\left(\frac{W}{W_0}\right)^{4\epsilon} e^{bt}\left(\frac{M_{\mathrm{X}}}{M_0}\right)^{-2(1+\epsilon)}, \tag{15}$$

with

$$b\,(W, M_{\mathrm{X}}) = b\,(W_0,\, M_0) + 4\alpha'_{\mathbb{P}}\left(\ln\frac{W}{W_0} - \ln\frac{M_{\mathrm{X}}}{M_0}\right). \tag{16}$$

In DIFFVM it is assumed that this relation holds at all values of Q^2 and that the pomeron-photon cross section is constant. The minimum generated value of M_{X} is chosen by the user and is independent of Q^2 and W.

Vector meson dissociation can be simulated either with:

- Jetset [21],

  or assuming

- isotropic phase space decay (cf. 2.6.3), in which the multiplicity of pions is determined assuming KNO scaling [18] (the minimum pion number is 2 due to isospin conservation).

2.6 Proton dissociation

For the generation of the $M_{\rm N}$ spectrum Diffvm uses a parametrization of the experimental data [7, 8] for the mass spectra of diffractively excited hadrons. This spectrum consists of resonance-like structures superimposed on the diffraction dissociation continuum.
The inclusive cross section for diffractive processes, at fixed t, can be parametrized as follows:

$$\frac{d\sigma}{dM_{\rm N}^2} \propto \frac{f(M_{\rm N}^2)}{M_{\rm N}^{2(1+\epsilon)}}, \tag{17}$$

where $f(M_{\rm N}^2)$ is a function of the diffractive mass at the proton vertex accounting for the low mass behaviour, including the resonance states.

Diffvm uses the following parametrization for $f(M_{\rm N}^2)$:

- in the continuum region ($M_{\rm N}^2 \gtrsim 3.6$ GeV^2), $f(M_{\rm N}^2) = 1$; this reproduces the behaviour $\propto \frac{1}{M_{\rm N}^{2(1+\epsilon)}}$ of diffractive dissociation ;

- in the "resonance region" ($M_{\rm N}^2 \lesssim 3.6$ GeV^2), $f(M_{\rm N}^2)$ is the result of a fit to the measured differential cross section, at fixed t, for proton diffractive dissociation on deuterium $pD \to XD$ [8].

The generated diffractive mass, if below 1.9 GeV, is a resonance state, if above 1.9 GeV is a continuum state and may dissociate into a quark-diquark system or decay isotropically (cf. sect. 2.6.1).

For proton dissociation $t_{\rm min}$ can be approximated as:

$$t_{\rm min} \simeq \frac{(m_V^2 + Q^2)(M_{\rm N}^2 - m_{\rm p}^2)}{W^2}. \tag{18}$$

2.6.1 Production and Decay of a Resonance State

For $M_{\rm N}$ values below approximately 2 GeV several resonance-like structures are observed [7, 8]. Since the pomeron trajectory carries the quantum numbers of the vacuum (I = 0, G = P = C = +), only N^{*+} resonances with $J^{\mathcal{P}} = \frac{1}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+, \ldots$ can be produced. These are the $N(1440)$, $N(1520)$, $N(1680)$, and $N(1700)$ (fig.1).

Diffractive states with masses below 1.48 GeV are treated as $N^+(1440)$, for $1.48 < M_{\rm N} < 1.60$ GeV as $N^+(1520)$, and for masses between 1.60 and 1.90 GeV the state is treated as mixture of 50% $N^+(1680)$ and 50% $N^+(1700)$. It is assumed that the N^*'s decay isotropically in their rest frame. The branching ratios used for N^* decays (tab.2) are estimates derived from the numbers given in [9]. All decays with branching ratios below $< 1\%$ or where only upper limits are known are neglected.

Dissociation of the continuum state at the proton vertex, as for the VM vertex, is carried out in either of the following modes:

- JETSET [21];
- isotropic phase space decay into a nucleon + pions, in which the multiplicity of pions is evaluated assuming KNO scaling [18] (see below).

2.6.2 Fragmentation by Jetset (quark-diquark system)

In this mode, DIFFVM splits the proton into a q-qq system, so that quark q (u or d valence quark) couples to the pomeron leaving behind a diquark remnant, either a ud or uu diquark. Due to the possible spin states of the diquark system, 1 for singlets and 3 for triplets, the combinations and probabilities for the quark-diquark system are:

$$q - qq = \begin{cases} u - ud_{\mathrm{spin}=0} & \frac{1}{7} \\ u - ud_{\mathrm{spin}=1} & \frac{3}{7} \\ d - uu_{\mathrm{spin}=1} & \frac{3}{7} \end{cases}$$

The parton q not belonging to the diquark is assigned a fraction x of the 4-vector of the beam proton, while the remnant takes the rest (1-x).

The quantity $x = -\frac{t}{2p_{\mathrm{P}} \cdot p_{\mathrm{I\!P}}}$ is the fraction of momentum of the proton taken by the quark q. The struck quark q', with momentum $\vec{q'} = x \cdot \vec{p}_P + \vec{p}_{\mathrm{I\!P}}$, and the remnant diquark are colour-connected by JETSET [21] in a string.

2.6.3 Isotropic phase space decay

The fragmentation mode for N alternative to JETSET is isotropic phase space decay. The program uses the RAMBO [22] (RAndom MOmentum BOoster) routine to generate phase-space distribution of produced particles. Unlike "hierarchical" procedures of multiparticle systems, in which multiparticle production is represented as a series of two-body decays, resulting in non-uniform phase-space distributions, in this "democratic" procedure all particles are treated equally. Therefore all momenta p_μ^i of particles having mass μ_i are generated isotropically.

Decay mode	$N(1440)$	$N(1520)$	$N(1680)$	$N(1700)$
$N\ \pi$	67%	60%	67%	10%
$\Delta\pi$	25%	20%	11%	35%
$N\ \rho$	0%	20%	11%	20%
$N\ (\pi\pi)^{I=0}_{s\ wave}$	8%	0%	11%	35%

Table 2: *Branching ratios for N^* decays implemented in* DIFFVM.

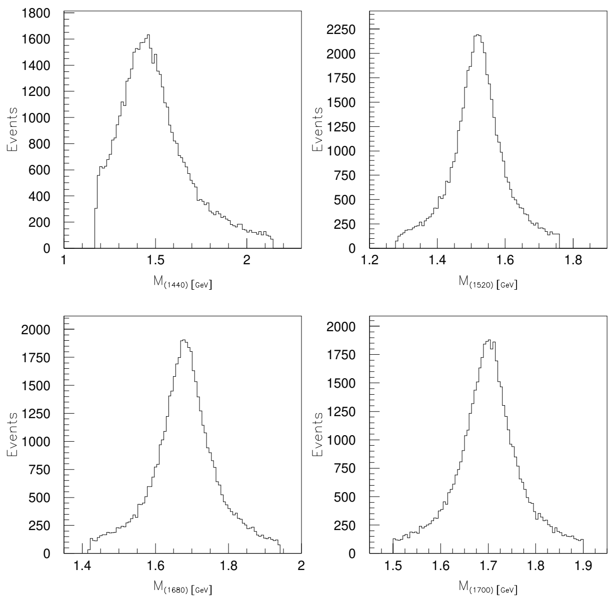

Figure 1: *Mass spectra of the* $N^*(1440)$*,* $N^*(1520)$*,* $N^*(1680)$ *and* $N^*(1700)$ *resonance states as produced by* DIFFVM *.*

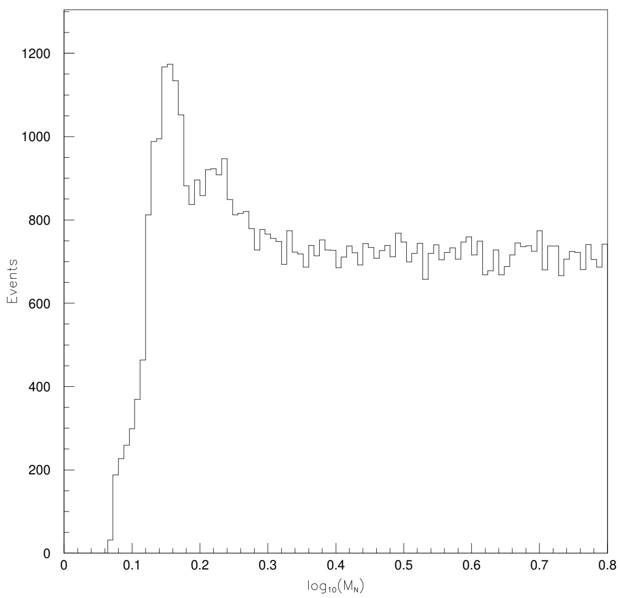

Figure 2: *Distribution of the logarithm of the generated mass* M_{N}*. It is possible to distinguish the transition between the resonance region (diffractive excitation) (*$log(M_{\mathrm{N}}) \sim 0.3$*), starting from the pion production threshold and extending up to about 2 GeV, and the continuum (diffractive dissociation). The first peak appearing in the resonance region (0.16 - 0.18) corresponds to the* $N^*(1440)$ *and* $N^*(1520)$ *states, while the second (0.22 - 0.23) to the* $N^*(1680)$ *and* $N^*(1700)$ *states.*

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