# FPMC: a generator for forward physics

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#### Abstract

We present the Forward Physics Monte Carlo (FPMC) designed to simulated central particle production with one or two leading intact protons and some hard scale in the event. The underlying interaction between protons or anti-protons through singlet exchange can manifest itself in many forms. The following production mechanisms are implemented: single diffractive dissociation, double pomeron exchange, and exclusive production due to two-gluon or two-photon exchanges. With increasing beam center-of-mass-energies, the production of new final states become possible at the LHC. The aim of FPMC is to implement these processes in one common framework.

# Program summary

Title of the program: FPMC, version 1.0

Computer: any computer with the FORTRAN 77 or GFORTRAN compiler under the UNIX or Linux operating systems.

Operating system: UNIX; Linux

Programming language used: FORTRAN 77

High speed storage required: < 100 MB

Keywords: Proton-(anti-)proton collisions, diffraction, exclusive production, double pomeron exchange, two photon exchange.

Nature of the physical problem: Proton diffraction at hadron colliders can manifest itself in many forms, and a variety of models exist that attempt to describe it [1, 2, 3, 4, 5, 6, 7]. This program implements some of the more significant ones, enabling the simulation of central particle production through color singlet exchange between interacting protons or anti-protons.

Method of solution: The Monte-Carlo method is used to simulate all elementary  $2 \to 2$  and  $2 \to 1$  processes available in HERWIG. The color singlet exchanges implemented in FPMC are implemented as functions re-weighting the photon flux already present in HERWIG.

Restriction on the complexity of the problem: The program relying extensively on HERWIG, the limitations are the same as in [8].

Typical running time: Approximate times on a 2.5 GHz Dual-Core Intel: 1-60 minutes per 10000 unweighted events, depending on the process under consideration.

Homepage: www.cern.ch/fpmc

### 1 Introduction

In this paper, we present a Forward Physics Monte Carlo (FPMC) [9] generator to simulate inelastic processes occurring in hadron-hadron or collisions in which one or both hadrons stay intact. The focus of FPMC on the other hand is to simulate processes with a large mass produced in the central pseudo-rapidity. This allows to apply perturbative methods to obtain predictions for productions of electroweak boson, di-jets, Higgs boson, dilepton pairs etc. On the contrary, the soft diffractive part of the cross section with in general low- $p_T$  particle production are implemented in other generators.

There are in general two types of processes with leading hadrons distinguished in the diffractive community: exclusive and inclusive. In exclusive events, empty regions in pseudo-rapidity called rapidity gaps separate the intact very forward proton from the central massive object (e.g. di-jets). Exclusivity means that nothing else is produced except the leading protons and the central object. The exclusive processes is due to underlying multi-gluon [6, 7, 10] or two-photon exchanges [2, 3, 4, 5] which we denote here as QCD and QED productions, respectively.

The inclusive processes also exhibit rapidity gaps; however, in addition they contain soft particles accompanying the production of a hard diffractive object and the rapidity gaps are subsequently in general smaller than in the exclusive case. Measurements of these processes have been successfully described by Ingelman-Schlein model [1] which involves exchanges of one or more perturbative pomerons. The pomeron structure is described by the parton distribution functions (PDF) measured in events where rapidity gap or the intact leading proton is observed, mainly at HERA.

Hard diffractive or exclusive physics has been studied in the past at various colliders. Model predictions were obtained using many different generators [11, 12, 13, 14, 15]. This is a first attempt to consolidate predictions involving intact beam particles in the final state into one common framework in order to ease MC prediction for upcoming forward physics program at the LHC.

The paper is organized as follows: A program overview is given in Section 2. The event in information is discussed in Section 3. The main part of the paper is contained in Section 4 where a description of processes that can be studied with FPMC is given. The current work is concluded in Section 5. In the Appendix details concerning the parameter setup to run FPMC are provided.

# 2 Program Overview

The generation of forward processes is implemented inside HERWIG version 6.500 [8]. The original code simulating two-photon exchanges in  $e^+e^-$  collisions is adapted such that the pomeron/gluon is exchanged instead of a photon and a particular proton structure in diffractive events is used in hadron collision in this case. Note that such approach has first been applied in POMWIG [12]. The user selects a particular model of interest by main steering parameter NFLUX . The nature of the process is further specified by parameters TYPEPR to distinguish exclusive/inclusive processes and TYPINC characterized the QED/QCD type of the exchange (see Table 1).

In certain processes which use standard HERWIG non-diffractive matrix elements, the HERWIG process numbering scheme is followed. In addition, new processes have been added for example

for the case of exclusive productions. For all processes simulated with FPMC, the numbering should start with 10000. Adding 10000 to the HERWIG process code IPROC suppresses the underlying event production formation from beam remnants soft scattering. This is equivalent to setting PRSOF=0. For more details see HERWIG manual [8].

In order to prevent interference with the standard HERWIG processes numbering, the FPMC process numbers start from 10000. The standard HERWIG matrix elements are used in some cases. The corresponding process number in FPMC is the process number in HERWIG plus 10000. In this cases, the details of the generation are steered by the same parameters that are used to control the production in HERWIG.

NFLUX	Description
9	QCD factorized model, Pomeron flux [1]
10	QCD factorized model, Reggeon flux [1]
12	QED flux from Cahn, Jackson; $R \sim 1.2A^{\frac{1}{3}}$ [2]
13	QED flux from Drees et al., valid for heavy ions only [3]
14	QED flux in pp collisions, from Papageorgiou [4]
15	QED flux in pp collisions, from Budnev et al. [5]
16	QCD KMR Exclusive model [6]
17	QCD CHIDe Exclusive model [7]
TYPEPR	
INC	Inclusive reaction
EXC	Exclusive reaction (only color-singlet amplitude)
TYPINT	
QED	Photon initiated process
QCD	Gluon/quark initiated process

Table 1: Main switches of the program that select implemented models of the forward physics with leading protons.

# 3 Event Information

The FPMC event information such as for example particle numbering, particle state, kinematics, particle production flow is the same as in original HERWIG and can be found in HERWIG manual [8]. The following changes have been made. Because the implementation of the diffractive inclusive and exclusive processes in hadron-hadron collision is based on two-photon exchanges in  $e^+e^-$  collisions, the event record fixing is done in which the beam electrons are replaced by diffractive protons. Moreover, radiated photons off electrons are replaced by Pomerons/Reggeons where necessary (routine HWFXER). New particle numbers are introduced for Pomeron and Reggeons, ID=990,110, respectively.

### 4 Process Overview

The list of processes and their brief physics description is provided in the following sub-sections. The process numbers are given one. The user is invited to consult the full generator setup summary in Appendix A.

# 4.1 Central Exclusive QED Production - $\gamma\gamma$ Interactions

When an energy of relativistic protons/leptons beams is sufficiently high, a hard process can be initiated by collinear photons emission. Subsequently, a large set of final states can be produced in photon-photon fusion (a photoproduction process with one broken proton can also occur, but this process is not available in FPMC).

The two-photon interactions in  $pp^1$  collisions are described within the Equivalent Photon Approximation (EPA) framework [5]. The cross section is expressed in terms of the photon flux  $f(\omega, q^2)$ . It corresponds to the probability that a proton emits a photon of energy  $\omega$  and momentum transfer  $q^2$ . Since the typical transverse momentum of the photon is very small in two-photon interactions,  $q^2$  dependence of the photon flux can be integrated out and the total cross section can be written as a product of the sub-process  $\gamma\gamma \to X$  cross section and the photon fluxes

$$\frac{d\sigma}{d\Omega} = \int d\omega_1 d\omega_2 \frac{d\sigma_{\gamma\gamma \to X}(W = \sqrt{(4\omega_1\omega_2)})}{d\Omega} f(\omega_1) f(\omega_2). \tag{1}$$

For hadron beams the EPA has better accuracy than the well known Weizsäcker-Williams approximation.

A similar mechanism of two-photon production occurs during heavy ion collisions where the coherent radiation of photons are enhanced by the number of protons, Z, in the nuclei [3, 4]. In this case, however, one has to impose the restriction that the nuclei have an impact parameter greater then  $b_{min} = 2R$ , where R is the nuclear radius. This restriction reduces the cross section substantially [2].

#### 4.1.1 Standard model two-photon processes

Two photon induced exclusive processes are selected using NFLUX=12, 13, 14, 15, 16 and TYPEPR='EXC', TYPINT='QED'.

The following processes are available:

IPROC	Description
16006	$\gamma\gamma \to ll$
16010	$\gamma\gamma \to W^+W^-$

Note that details of the generation such as kinematic ranges are steered by parameters defined in HERWIG for the particular processes numbers IPROC.

<sup>&</sup>lt;sup>1</sup>EPA describes production of photons for any charged particle for which the electromagnetic form factors are known.

### 4.1.2 Beyond standard model two-photon processes

The following beyond Standard Model processes are currently supported:

IPROC	AAANOM	Description
16010	2	$\gamma \gamma \to W^+W^-$ beyond SM
16015	3	$\gamma\gamma \to ZZ$ beyond SM

Two-photon events can be used for studies of a photon coupling to other gauge bosons. FPMC was interfaced with a code produced by CompHEP providing amplitudes of di-boson production  $\gamma\gamma \to WW$  induced by effective Lagrangians due to anomalous couplings between  $\gamma$  and W or Z. In particular, in FPMC one can study the C,P-parity conserving Triple Gauge Coupling (TGC) and Quartic Gauge Coupling (QGC) coupling parameterized by two anomalous parameters and four anomalous quartic parameters (see App. B for complete form of the Lagrangians). The effect of the anomalous Lagrangian can be regulated with a form factor in a dipole form  $\lambda \to \lambda/(1+(s_{\gamma\gamma}/\Lambda_{\rm cutoff})^2)^2$ , where  $s_{\gamma\gamma}$  is the invariant photon-photon center-of-mass and  $\Lambda_{\rm cutoff}$  is a typical scale of the new physics. Parameters are:

Parameter	Type	Default	Description
DKAPPA	float	-	trilinear couping $\Delta \kappa^{\gamma}$ (Eq. (8) in App. B)
LAMBDA	$[\mathrm{GeV^2}]$	-	trilinear couping $\lambda^{\gamma}$
A0W	$[\mathrm{GeV^{-2}}]$	-	quartic coupling $a_0^W/\Lambda$ (Eq. (9) in App. B)
ACW	$[\mathrm{GeV}^{-2}]$	-	quartic coupling $a_C^W/\Lambda$
A0Z	$[\mathrm{GeV^{-2}}]$	-	quartic coupling $a_0^Z/\Lambda$
ACZ	$[\mathrm{GeV}^{-2}]$	-	quartic coupling $a_C^Z/\Lambda$
ANOMCUTOFF	$[GeV^2]$ , -1	-1(OFF)	form factor $\Lambda_{\rm cutoff}$ (see text)

# 4.2 Central exclusive QCD production

Central exclusive processes can occur also via the strong interactions. In analogy to the QED case, one often talks about the Pomeron exchange and  $\mathbb{PP} \to X$  sub-process. However, in reality the calculations are performed in perturbative QCD as a two-gluon exchange. Such a process consists of a hard sub-process  $gg \to X$  and an additional gluon that screens the color. The screening gluon makes the exchange a color singlet.

There are several models of such interactions on the market [6, 7, 10], differing in the treatment of the proton structure, the virtual corrections and the approximations. All models consist of soft re-scattering corrections (the Rapidity Gap Survival Probability) and some of them [6, 16, 17, 18, 19, 20] introduce non-perturbative elements to the calculation.

Currently there are two models of central exclusive production implemented into the FPMC: the KMR (Durham) and the CHIDe (Liege) model.

### 4.2.1 The KMR (Durham) Model

The details of the models can be found in [6]. The model can be chosen by setting NFLUX=16 and TYPEPR='EXC', TYPINT='QCD'. The available sub-processes are:

IPROC	Description
16013	$gg  o gg/qar{q}$
19999	$gg \to H$

The following parameters of the KMR model can be modified in the steering file:

Parameter	Type	Default	Description
Q2CUT	$[GeV^2]$	2.0	Lower limit of luminosity integration
SURV	float	0.03	Rapidity Gap Survival Probability
SCALE	float	1.0	Scales the upper limit in Sudakov formfactor
DELTA	1,2	2	Definition of $\Delta$

### 4.2.2 The CHIDe (Liege) Model

The details of the CHIDe model can be found in [7] and it is set by NFLUX=18 nd TYPEPR='EXC', TYPINT='QCD'. The available subprocesses are:

IPROC	Description
16012	$gg \rightarrow gg$
19999	$gg \to H$

The following parameters of the CHIDe model can be modified in the steering file:

Parameter	Type	Default	Description	
IGLU	$\{1,2,3,4\}$	4	Different impact factor (parameterization of	
		the gluon density)		
LSCALE	float	1.0 Scales the lower limit in Sudakov formfactor		
USCALE	float	1.0	Scales the upper limit in Sudakov formfactor	
SURV	float	0.03	Rapidity Gap Survival Probability	

## 4.3 Inclusive hard diffraction - Pomeron/Reggeon exchange

The implementation of inclusive hard diffractive processes follows the Ingelman-Schlein model of diffraction [1]. The structure of the proton in events with rapidity gaps is modeled by a color singlet Pomeron/Reggeon exchange. We distinguish single diffractive events with single pomeron exchange

$$pp \to p \oplus X + \text{Pomeron remnants} + \text{proton remnants}$$
 (2)

and double Pomeron exchange

$$pp \to p \oplus X \oplus p + \text{Pomeron remnants},$$
 (3)

where  $\oplus$  indicate the presence of the pseudo-rapidity gap.

The diffractive cross section of single diffractive dissociation (SD) is calculated as a convolution of the diffractive structure function and the partonic sub-process cross section

$$d\sigma^{pp\to pX} = \sum_{i} \int f_i^D(x_i, \mu^2, \xi, t) f_j(x_j, \mu^2) d\sigma_{\text{sub}}^{i,j\to X}(x_i, x_j, \mu^2) dx_i dx_j d\xi dt$$
 (4)

where  $x_i$ ,  $x_j$  are the Bjorken-x of the parton coming from Pomeron and proton respectively, and  $\mu^2$  are the renormalization and factorization scales, set equal in the formula above for clarity. Calculation of the double pomeron exchange (DPE) is done along the same line substituting the non-diffractive  $f_j$  distribution by the diffractive  $f_j^D$  one.

Whereas this factorization has been proven to be valid in the *ep* collider, there is an additional suppressing factor for hadron-hadron collisions, so called survival probability factor. At hadron-hadron collider, this suppression arises from soft interaction between the incoming/outgoing hadrons leading to the proton break-up and loss of the event diffractive signature. The factor is believed to be weakly dependent on the particular process.

Measurements at HERA showed that the hadron structure in diffraction can be described in terms of the parton density functions (PDF) in the same way as in non-diffractive case, however in redefined kinematics dependent on the pomeron longitudinal momentum fraction  $\xi$ . This in diffraction commonly used variable is related to the mass of the created diffractive system as  $\xi = M_X^2/s$ , s being the center-of-mass energy of the proton-proton collision. For the structure function, the following factorization has been observed

$$f_i^D(x, \mu^2, \xi, t) = f_{\mathbb{P}/p}(\xi, t) \cdot f_{i/\mathbb{P}}(\beta = x/\xi, \mu^2).$$
 (5)

The production of large diffractive masses is suppressed by the pomeron flux  $f_{\mathbb{P}/p}(\xi,t)$  which approximately behaves as  $\sim 1/\xi$  for not to high diffractive masses (and above a resonance region  $>\sim 1$  GeV). The normalization of the fluxes is conventionally fixed at  $\xi_{\mathbb{P}}=0.003$  such that

$$\xi_{\mathbb{P}} \int_{t_{\text{cut}}}^{t_{\text{min}}} f_{\mathbb{P}/p} \, \mathrm{d}t = 1, \tag{6}$$

where  $|t_{\min}| \simeq m_p^2 x_{\mathbb{P}}^2/(1-x_{\mathbb{P}})$  is the minimum kinematically accessible value of |t|,  $m_p$  is the proton mass and  $|t_{\text{cut}}| = 1.0 \,\text{GeV}^2$  [21]. Note that the same structure function can be assigned to a Reggeon, but the Reggeon contribution is expected to be small at high energy.

The cross section for inclusive DPE processes can schematically be expressed as

$$d\sigma^{\mathrm{pp}\to\mathrm{ppX}} = \sum_{i,j} \int dx_i dx_j \, d\xi_i d\xi_j \, F_{\mathbb{P}/p}(\xi_i) F_{\mathbb{P}/p}(\xi_j) \, f_{i/\mathbb{P}}(x_i,\mu^2) f_{j/\mathbb{P}}(x_j,\mu^2) \, d\hat{\sigma}(ij\to X), \tag{7}$$

where  $F_{\mathbb{P}/p}(\xi)$  is the pomeron flux and  $f_{i/\mathbb{P}}(x,\mu^2)$  parton density in the Pomeron described above.

#### 4.3.1 Implementation

The only difference in the implementation of the single diffractive and double pomeron exchange processes with respect to non-diffractive production already present in HERWIG is the substitution of the proton density function by the proton diffractive structure function in Eq. (5). Some of the diffractive processes which are of interest at the LHC are listed below, but the user can in principle

choose other hard processes defined in HERWIG and run them in the inclusive diffractive mode. The inclusive mode is selected by NFLUX=9, 10 (Reggeon or Pomeron exchange, see Table 1) together with TYPEPR='INC' and TYPINT='QCD'.

Single diffraction/Double pomeron exchange		
IPROC	Description	
11300	$q\bar{q}  o Z/\gamma  o q'\bar{q}'$	
11350	$q\bar{q}  o Z/\gamma  o l\bar{l}$	
11399	$q\bar{q} \to Z/\gamma \to \text{any}$	
11400	$q\bar{q} \to W^{\pm} \to l\nu_l$	
11450	$q\bar{q}  o W^{\pm}  o l\nu_l$	
11499	$q\bar{q} \to W^{\pm} \to \text{any}$	
11500	QCD $2 \rightarrow 2$ parton scattering	
11700	QCD heavy quark production	
12200	QCD direct photon pair production	
16010	$W^+W^-$	

#### 4.3.2 PDF

Parton densities in the Pomeron are selected with the IFIT parameter. H1 fits required both the Pomeron and Reggeon exchanges to be included to describe the data [21], though the Reggeon parton density was assumed to be the PDF of a pion. At high energy, the Pomeron contributions dominate. The production through Pomeron/Reggeons only can be selected via NFLUX=9, 10.

IFIT	PDF set	Reference
101	Official H1 fit B (default)	[21]
100	Official H1 fit A	[21]

### 4.4 Rescattering corrections

The Factorization theorem which, in standard non-diffractive production, allows to use PDF measured in one processes for other theoretical predictions does not hold in diffractive or exclusive processes in hadron-hadron colliders. The factorization breaking suppression is energy dependent; it was measured to be about 0.1 at the Tevatron and is expected to be about 0.03 at the LHC [6, 16, 17, 18, 19, 20]. This correction slightly depends on the type and kinematic of the process. They may modify the angular distribution of scattered final state protons. Several models are therefore included in FPMC: KMR low mass diffractive model and Effective opacity model studied at [22]. The options are

ISOFTM	Description
0	No correction
1	Constant factor [6]
2	KMR low mass diffractive model [22]
3	Effective opacity model [22]

# 5 Conclusions / perspectives

In a relatively simple way, routines of HERWIG are replaced in FPMC to implement wide range of processes with leading intact protons. These can represent signal, background or both at the same time for particular data analysis, and it is therefore important to accommodate all into one framework with the same hadronization model.

Some of these like the Ingelman-Schlein have been already implemented in more modern version of HERWIG (HERWIG++), but for others like the exclusive KMR and CHIDe model, FPMC is the only generator were both are implemented and can thus be clearly compared to each other for the exclusive Higgs or di-jet productions for instance.

We should not forget to mention the importance of two-photon exclusive processes, especially the di-boson anomalous production which when observed can give a strong evidence for beyond standard electroweak symmetry breaking.

Several other processes might be worth of implementing in the future, namely the exclusive QCD production of di-photons or  $\chi_c$ ,  $\chi_b$  or other models for anomalous productions in photon-photon interactions as they will be studied at the LHC.

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## A Manual

### A.1 Usage

FPMC runs as a standalone program. It requires installed CERN libraries, fortran compiler (gfortran/g77), and c++ compiler. The program is compiled with

#### make

Two binary will compile: module and module\_reco. Both modules are designed to be run with a data card that changes the default parameters. In the latter, a simple jet reconstruction algorithm is run and hadron level final states are saved in an ntuple. Several data cards are provided in Datacards/ directory for some standard processes of interest. For example, the WW production via  $\gamma\gamma$  fusion is executed by

./module < Datacards/dataQEDWW

### A.2 Parameters

The main parameters related to the processes with leading intact protons are summarized in Table A.2.

Table 2: Parameters which can be set through data cards.

Parameter	Description	Default
TYPEPR	Select exclusive 'EXC' or inclusive 'INC' production	'EXC'
TYPINT	Switch between QED and QCD process	'QED'
NFLUX	Select flux	15
IPROC	Type of process to generate	11500
MAXEV	Number of events to generate	100
PBEAM1	Type of beam 1 particle	E+
PBEAM2	Type of beam 2 particle	E+
ECMS	CMS energy (in GeV)	14000
HMASS	Higgs mass (GeV)	115
PTMIN	Minimum $p_T$ in hadronic jet production	0
PTMAX	Maximum $p_T$ in hadronic jet production	$10^{8}$
YJMIN	Minimum jet rapidity	-6
YJMAX	Maximum jet rapidity	+6
EEMIN	Minimum dilepton mass in Drell-Yan	10.0
EEMAX	Maximum dilepton mass in Drell-Yan	$10^{8}$
IFITPDF	Diffractive PDF	100
NTNAME	Output ntuple name	'tmpntuple.ntp'
ISOFTM	Soft correction	1
IAION	Atomic number of colliding nuclei	1
IZION	Proton number of colliding nuclei	1
NRN1	1. random number generator initial seed	
NRN2	2. random number generator initial seed	
Q2WWMN	Minimum momentum transfer $(Q^2 =  t )$	0
Q2WWMX	Maximum momentum transfer $(Q^2 =  t )$	4
YWWMIN	Minimum beam momentum loss $(\xi_{min})$	0
YWWMAX	Maximum beam momentum loss $(\xi_{max})$	0.1

### A.2.1 Processes with two leading protons

All processes in this section assume initial generator setup of two electron beams **PBEAM1**='E+' and **PBEAM2**='E+'. They are then internally converted to diffractive protons and appropriate PDF is called in case of double pomeron exchange. In case of exclusive production, the appropriate model for gluon-gluon exchange is used.

Higgs processes					
Process	IPROC	TYPEPR	TYPINC	NFLUX	
Incl. H	11600+ID	INC	QCD	9,10,11	
Excl. H	19900+ID	EXC	QCD	16	
Excl. H	19900+ID	EXC	QED	12,13,14,15	
ID		$= 1, \dots, 6$	$H \to q\bar{q} \text{ (resp. d,u,s,c,b,t)}$		
ID		= 7.8,9	$H \to l^+ l^- \text{ (resp. } e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^-)$		
ID		= 10,11	$H \to W^+W$	$H  o W^+W^-, ZZ$	
ID		= 99	all decay modes		

Dijet processes					
Process	IPROC	TYPEPR	TYPINC	NFLUX	
Incl. dijets	11500	INC	QCD	9,10,11	
Incl. heavy $q\bar{q}$	11700+ID	INC	QCD	9,10,11	
	$ID = 1, \dots, 6$ $gg \rightarrow q\bar{q}$ (resp. d,u,s,			(sp. d,u,s,c,b,t)	
Excl. $q\bar{q}$	16000+ID	EXC	QCD	16, 17	
	$ID = 1, \dots, 6$		$gg \to q\bar{q} \text{ (resp. d,u,s,c,b,t)}$		
	ID = 11		$gg \to q\bar{q}$ (all flavours)		
	ID = 13		$gg \to gg + q\bar{q}$ (all flavours)		
Excl. dijets	16000+ID	EXC	QED	16, 17	
	$ID = 1, \dots, 6$		$gg \to q\bar{q} \text{ (resp. d,u,s,c,b,t)}$		
	ID = 7.8,9		$\gamma \gamma \to l^+ l^- \text{ (resp. } e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^-)$		

$W^+W^-$ , photon and lepton pairs					
Process	IPROC	TYPEPR	TYPINC	NFLUX	
Incl. $W^+W^-$	12800	INC	QCD	9,10,11	
Excl. $W^+W^-$	16010	EXC	QED	15	
Incl. $\gamma\gamma$	12200	INC	QCD	9,10,11	
Excl. $\gamma\gamma$	19800	INC	QCD	16	
Excl. $\gamma\gamma$	19800	EXC	QED	12,13,14,15	
Excl. ll	16006+IL	EXC	QED	12,13,14,15	
Incl. ll	11350	INC	QCD	9,10,11	
Incl. ll	11350+IL	INC	QCD	9,10,11	
	IL = 0,1,2,3		(resp. all fa	milies, $e, \mu, \tau$ )	

## A.2.2 Single diffraction

All processes in this section assume initial setup with one electron beam  ${\bf PBEAM1}={}^{\circ}{\rm P'}$  and  ${\bf PBEAM2}={}^{\circ}{\rm E}+{}^{\circ}$ . The electron is then internally converted to a diffractive proton.

Single diffraction						
Process	IPROC	TYPEPR	TYPINC	NFLUX		
Incl. SD $Z \to q\bar{q}$	11300+IQ	INC	QCD	9,10,11		
$IQ = 0,1,\dots,6$ (resp. all flavours, d,u,s,c,b,t)						
Incl. SD $Z \to l\bar{l}$	11350+IL	INC	QCD	9,10,11		
Incl. SD $Z \to \text{any}$	11399	INC	QCD	9,10,11		
Incl. SD $W^{\pm} \to qq'$	11400+IQ	INC	QCD	9,10,11		
IQ = 0,1,,6 (resp. all flavours, d,u,s,c,b,t)						
Incl. SD $W^{\pm} \to l\nu$	11450+IL	INC	QCD	9,10,11		
	$IL = 0,1,\ldots,$	3	( $l = \text{all families}, e, \mu, \tau$ )			
Incl. SD $W^{\pm} \to \text{any}$	11499	INC	QCD	9,10,11		
Incl. SD dijets	11500	INC	QCD	9,10,11		

# B Anomalous $\gamma\gamma \to WW$ coupling

The amplitude allowing studies of the anomalous coupling of the photon to W boson was generated by CompHEP [23]. For triple gauge boson coupling the following effective Lagrangian was assumed

$$\mathcal{L}/ig_{WW\gamma} = (W^{\dagger}_{\mu\nu}W^{\mu}A^{\nu} - W_{\mu\nu}W^{\dagger\mu}A^{\nu}) + (1 + \Delta\kappa^{\gamma})W^{\dagger}_{\mu}W_{\nu}A^{\mu\nu} + \frac{\lambda^{\gamma}}{M_W^2}W^{\dagger}_{\rho\mu}W^{\mu}_{\nu}A^{\nu\rho}. \tag{8}$$

There,  $g_{WW\gamma} = -e$  is the standard  $WW\gamma$  coupling in the SM and the double-indexed terms are  $V_{\mu\nu} \equiv \partial_{\mu}V_{\nu} - \partial_{\nu}V_{\mu}$ , for  $V^{\mu} = W^{\mu}$ ,  $A^{\mu}$ . The Lagrangian considered contains terms which conserve C,P-parity separately only.

On the other hand, the effective quartic boson coupling was taken to be parameterized by four anomalous parameters  $a_0^W, a_0^Z, a_C^W$ , and  $a_C^Z$ 

$$\mathcal{L}_{6}^{0} = \frac{-e^{2}}{8} \frac{a_{0}^{W}}{\Lambda^{2}} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_{\alpha}^{-} 
- \frac{e^{2}}{16 \cos^{2} \Theta_{W}} \frac{a_{0}^{Z}}{\Lambda^{2}} F_{\mu\nu} F^{\mu\nu} Z^{\alpha} Z_{\alpha}, 
\mathcal{L}_{6}^{C} = \frac{-e^{2}}{16} \frac{a_{C}^{W}}{\Lambda^{2}} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_{\beta}^{-} + W^{-\alpha} W_{\beta}^{+}) 
- \frac{e^{2}}{16 \cos^{2} \Theta_{W}} \frac{a_{C}^{Z}}{\Lambda^{2}} F_{\mu\alpha} F^{\mu\beta} Z^{\alpha} Z_{\beta},$$
(9)

where in addition to the convention already introduced,  $\Lambda$  denotes the energy scale where a new physics is assumed to appear and  $\Theta_W$  is the Weinberg angle. Note that the general parametrization of the  $WW\gamma$  and  $\gamma\gamma WW$  Lagrangians can be found in [24, 25].