GR@PPA 2.7 event generator for $pp/p\bar{p}$ collisions

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Abstract

The GR@PPA event generator has been updated to version 2.7. This distribution provides event generators for V (W or Z) + jets (≤ 4 jets), VV + jets (≤ 2 jets) and QCD multi-jet (≤ 4 jets) production processes at pp and $p\bar{p}$ collisions, in addition to the four bottom quark productions implemented in our previous work (GR@PPA_4b). Also included are the top-pair and top-pair + jet production processes, where the correlation between the decay products are fully reproduced at the tree level. Namely, processes up to seven-body productions can be simulated, based on ordinary Feynman diagram calculations at the tree level. In this version, the GR@PPA framework and the process dependent matrix-element routines are separately provided. This makes it easier to add further new processes, and allows users to make a choice of processes to implement. This version also has several new features to handle complicated multi-body production processes. A systematic way to combine many subprocesses to a single base-subprocess has been introduced, and a new method has been adopted to calculate the color factors of complicated QCD processes. They speed up the calculation significantly.

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1 Introduction

The great success of the Standard Model in recent decades leaves no doubt that gauge theories are capable of describing the interactions between elementary particles. Precise perturbative calculations based on gauge theories will become a crucial portion as larger collision energies are available to probe higher energy phenomena. For instance, the Higgs boson(s) and new particles predicted by theories beyond the Standard Model are the most important subjects to study in the current and future hadron collider experiments. They frequently decay to final states including multiple hadron jets, which predominant QCD interactions can easily imitate. A precise evaluation of these backgrounds is, therefore, necessary in order to accomplish a reliable measurement. However, once we try to do that using perturbative gauge theories, we immediately encounter a huge number of processes to evaluate. It is often too large to calculate by hand.

We have been carrying on automatic computations of Feynman diagrams by using the GRACE system [1]. GRACE is capable of calculations at the one-loop level [2] as well as at the tree level in the standard electroweak theory, and at the tree level in the minimal supersymmetric extension of the Standard Model (MSSM) [3]. It can also be applied to QCD interactions. However, since the development has been mostly aimed at applications to lepton collisions, it is not directly applicable to hadron-collision interactions, mainly due to the necessity to include the parton distribution function (PDF). Besides, processes in hadron collisions usually consist of lots of subprocesses. They are desired to be combined into a single process.

In order to implement those features specific to hadron collisions, we have developed an extended framework, called GR@PPA (GRace At PP/Anti-p). Early developments can be seen in our previous reports [4, 5]. The primary function of GR@PPA is to determine the initial and final state partons, *i.e.*, their flavors and momenta of the incoming partons by referring to a PDF, and those of the final state partons for jets or decay products. Based on the GRACE output codes, GR@PPA calculates the cross section and generates unweighted parton-level events using BASES/SPRING [6]. The GR@PPA framework also includes an interface to the LHA common data format [7]. The final steps of the event generation, *i.e.*, the initial- and final-state radiation, hadronization, decay and so forth, are done by passing the unweighted partonic events to PYTHIA [8] or HERWIG [9].

Although the GR@PPA framework is not process-specific, we provide it as an event generator package including matrix elements for some selected processes. At the moment (version 2.7), the included processes are the weak boson(s) plus N jets and $t\bar{t}$ plus N jets productions as well as the pure QCD N jets productions, where $N \leq 4$. These processes are the most important backgrounds in the Higgs boson and SUSY particle studies, and also useful to understand multi-body particle dynamics in precise measurements. Our previous work, the four bottom quark production (GR@PPA_4b [10]), is also included.

The reasons why we provide particular processes apart from the benefit of the automatic calculation by GRACE are the following; First, kinematical singularities in each process must be cared with a proper treatment. One can get a high efficiency to generate

unweighted events since the kinematics are already well optimized. This is immediately addressed to the program running speed. It is critical for large scale MC productions. Second, it will be easier to adopt higher order calculations. Once the customized matrix element for an NLO process is prepared [11], users will be able to simply use it without any detailed care. Third, some different extensions are possible only by the modification of the framework. For example, GR@PPA generators can be extended to work under the C++ environment just by rewriting the framework in C++. The parton shower algorithm, *e.g.* the NLL parton shower [12], will also be possible to implement by modifying the framework.

We describe a symbolic treatment of the parton flavor in the diagram calculation in the next section. The feature of GR@PPA and its running are given in section 3. Some benchmark cross sections and program performances are presented in Sections 4 and 5, respectively. Finally, a summary is given in Section 6. We provide a list of supported processes and a summary of benchmark test conditions in Appendices.

2 New features in the extension of GRACE to $pp/p\bar{p}$ collisions

In hadron-hadron collisions, a certain process of interest usually consists of several incoherent subprocesses. The total cross section is thus expressed as a summation of the subprocesses as

$$\sigma = \sum_{i,j,F} \int dx_1 \int dx_2 \int d\hat{\Phi}_F f_i^1(x_1, Q^2) f_j^2(x_2, Q^2) \frac{d\hat{\sigma}_{ij\to F}(\hat{s})}{d\hat{\Phi}_F}, \tag{1}$$

where $f_i^a(x_a, Q^2)$ is the PDF of the hadron a (p or $\bar{p}$), which gives the probability to find the parton i with the energy fraction x_a at the probing virtuality of Q^2. The differential cross section $d\hat{\sigma}_{ij\to F}(\hat{s})/d\hat{\Phi}_F$ describes the parton-level hard interaction producing the final-state F from the collision of partons, i and j, where $\hat{s}$ is the square of the total initial 4-momentum. The sum is taken over all relevant combinations of i, j and F.

The original GRACE system assumes that both the initial and final states are well-defined. Hence, it can be applied to evaluating $d\hat{\sigma}_{ij\to F}(\hat{s})/d\hat{\Phi}_F$ and its integration over the final-state phase space $\hat{\Phi}_F$ only. An adequate extension is necessary to take into account the variation of the initial and final states. We have made two sorts of development in GR@PPA, — applying PDF in the phase space integration and sharing several subprocesses as a single base-subprocess. The former is described in our previous paper [10]. Here, we focus on the later. As already mentioned, a "process" of interest is usually composed of several incoherent subprocesses in hadron interactions. In many cases, the difference between the subprocesses is only in the quark combination in the initial and/or final states. The matrix element of these subprocesses is frequently identical, or the difference is only in a few coupling parameters and/or masses. In such cases, it is

convenient to add one more integration/differentiation variable to replace the summation in Eq. (1) with an integration. As a result, these subprocesses can share an identical "GRACE output code" and can be treated as a single base-subprocess. This modification drastically saves the program running time and simplifies the program coding.

The number of combinations to take N out of M flavors, allowing an overlap, is given by ${}_MH_N(\equiv \frac{(N+M-1)!}{N!(M-1)!})$. In case that all parton flavors up to the b-quark are considered, M is equal to $11(u, d, c, s, b, g, \bar{u}, \bar{d}, \bar{c}, \bar{s}, \bar{b})$. The configuration of the N jets final state has ${}_{11}H_N$ subprocesses. Clearly a smaller M decreases the number of subprocesses. Since the diagram structure is invariant against the quark (anti-quark) flavor exchange in QCD, the invariance is preserved by introducing generic up-type and down-type quarks even if the electroweak interaction is included. The base-subprocesses can be configured using these generic quarks. Then, the number of configurations is reduced to ${}_5H_N \ll {}_{11}H_N$. The output code of the matrix element from the GRACE has been so modified that the masses and couplings can be treated as input variables. The number of combinations has been further reduced using symmetries in the Standard Model such as the invariance in the charge and parity conjugate. In Table 1 we list up the number of base-subprocesses for the N jets production process in $pp(\bar{p})$ collisions, to be compared with the total number of subprocesses that they cover. The initial colliding partons in the base-subprocesses in Table 1 are composed of $q_uq_u(\bar{q}_d\bar{q}_d)$, $q_u\bar{q}_d$, $q_ug(q_dg)$, q_uq_d, $q_u\bar{q}_u(q_d\bar{q}_d)$ and gg, where $q_u(q_d)$ and g are the up(down)-type quark, and the gluon, respectively.

Equation (2) can be rewritten in term of the base-subprocess using a weight factor to treat the initial and final state parton configuration as

$$\sigma = \sum_{i,j,F} \int dx_1 \int dx_2 \int d\hat{\Phi}_F \; w_{ijF} \; \frac{d\hat{\sigma}^{\rm selected}_{ij\to F}(\hat{s}; m, \alpha)}{d\hat{\Phi}_F}, \tag{2}$$

where $d\hat{\sigma}^{\rm selected}_{ij\to F}$ is the differential cross section of the base-subprocess with input arguments of masses and couplings. The coefficient w_{ijF} is the weight factor for the chosen configuration. An appropriate subprocess is selected in event by event based on the flavor configuration decided by the weight factor. Since the QCD interactions are identical for any configuration in the subprocess, the weight factor is composed of PDF and the CKM (Cabibbo-Kobayashi-Maskawa) [13] matrix as

$$w_{ijF} = f_i^1(x_1, Q^2) f_j^2(x_2, Q^2) |V_{\rm CKM}|^{2K} \{{\rm Br}(X \to F') \times \Gamma^X_{\rm tot}\}^L \; , \tag{3}$$

where L is the number of X bosons (W or Z). The probability of the decay final state F' can be handled in terms of the branching ratio, if the interference with the other partons is ignored. The branching ratio and the total width can be given by the experimentally measured ones. The flavor configuration is determined by the $|V_{\rm CKM}|^{2K}$, where K is the number of W bosons in the process.

We have to define a certain QCD color base representation in order to calculate the color factor of the interaction. In addition, PS programs usually require the information of color connection between partons in the event. The color bases should be so defined

that the required connection information can be easily derived. In our previous works [14] we adopted such a definition that all color bases are composed of the SU(3) triplets. Namely, gluons are decomposed to a pair of quark and anti-quark. This definition includes color-singlet components which are not well interpreted for the hadronization. Besides, this leads to a large number of color bases for complicated processes consisting of many partons.

In the present version of GR@PPA we have adopted a different definition. We use a chain of a quark, n gluons ($n = 0, 1, 2, ...$) and an anti-quark as fundamental components. The color bases are given by products of such chains, and "glueballs" having no quark at the ends. This definition fits to the requirement of the LHA event interface [7]. In the event generation, one of the possible color bases is chosen in proportion to their squared amplitudes in order to determine the color connection. The interference is ignored (*i.e.*, a large N_c approximation) as usual, since no reasonable way is known to include it. Of course, the interference is taken into account in the cross section evaluation. Compared to our previous definition, this definition significantly reduces the number of color bases for complicated processes. For instance, it is reduced from 24 to 14[1] for processes having two quark pairs and two gluons (*e.g.*, $gg \to q\bar{q}q\bar{q}$). This reduction results in a faster calculation of the color factor and the color connection.

N jets (α_s^N)	base-subproc.	subproc. w/ all flavors
2	8	176
3	9	276
4	14	891

Table 1: Number of base-subprocesses for the N jet production process in $pp(\bar{p})$ collisions to be compared with the total number of subprocesses that they cover. The subprocesses can be classified according to the difference in the initial-state parton combination, and further classified by accounting for the charge and parity symmetries in the jet flavors.

3 Program running

3.1 Distribution package

The distribution package of the GR@PPA event generator consists of two part, the framework and the matrix elements. The framework contains a CHANEL library, a BASES/SPRING package, and a kinematics library. The CHANEL library is a set of subroutines to calculate diagram elements: vertices, propagators and external legs. BASES/SPRING is a multi-dimensional general-purpose Monte Carlo integration and event-generation program set. The kinematics library converts the random numbers given by BASES/SPRING

[1] Among 14 combinations, two color factors produce zero amplitudes at tree level.

to a set of kinematical variables for the matrix element calculation, and converts the returned matrix element to the differential cross section. These routines are common to all processes. On the other hand, the matrix elements, generated by GRACE with some modifications for hadron collisions, are process dependent. They are supplied as separate packages.

The program running of GR@PPA generator is totally controlled by the subroutine `GRCPYGEN`. In the initialization, `GRCPYGEN` calls BASES to evaluate the total cross section for the given process, while it calls SPRING in the event generation cycle. The calling sequence of `GRCPYGEN` is as follows:

```
CALL GRCPYGEN(CBEAM, IGSUB, MODE, SIGMA),
```

where the input arguments are

`CBEAM (CHARACTER)` : '`PP`' for pp collisions and '`PAP`' for $p\bar{p}$ collisions
`IGSUB (INTEGER)` : process number
`MODE (INTEGER)` : = 1 for calling BASES, and 0 for calling SPRING,

and the output is

`SIGMA (REAL*8)` : integrated cross section.

The argument `CBEAM` is dummy when `MODE` = 0. A unique number `IGSUB` is assigned to every physics process as listed in Appendix A. The output `SIGMA` is always equal to the integrated cross section of the process specified by `IGSUB`. The generated event is stored in the LHA common block [7].

The distribution package is arranged for the use on Unix systems. However, since the structure is rather simple, we expect that the program can be compiled and executed on other platforms without serious difficulties. The package for the GR@PPA framework is composed of the following files and directories:

`Config.perl` : a script to configure the setup,
`Makefile` : `Makefile` for the setup,
`README` : a file describing how to set up the programs,
`VERSION-2.76` : a note for this version,
`proc.list` : a list of the processes supported in this version,
`basesv5.1/` : BASES/SPRING (version 5.1) source codes,
`chanel/` : CHANEL source codes,
`grckinem/` : source codes of kinematics,
`example/` : source codes of example programs,
`inc/` : `INCLUDE` files,
`lib/` : the directory to store object libraries; initially empty.

The `proc.list` contains all process names and the corresponding process identification numbers `IGSUB`. It also includes keywords for the processes used to configure the matrix elements.

The matrix element packages are separately given. They need to be installed in the GR@PPA framework directory. We provide several packages. Users can choose any of them according to their needs. Each matrix element package is composed of the following directories:

`xxx` : a set of matrix elements,
`diagram` : Feynman diagrams used in the calculation of this process,

where `xxx` is a process group name. For example, the matrix elements for top quark production processes (with or without extra jets) are all placed under the `top` directory.

3.2 How to install

The programs can be downloaded from

`URL: http://atlas.kek.jp/physics/nlo-wg/grappa.html` .

The first task for the setup is to run the configuration script `Config.perl`. Next, users have to edit the file `Makefile` to specify the paths to the libraries to be linked, such as PYTHIA, HERWIG and CERNLIB. Those parts to be edited can be found at the top of the `Makefile`. Users may also edit the `inc/define.h` file to select a PDF library. Currently, PDFLIB in CERNLIB [15], LHAPDF [16], and PYTHIA built-in PDFs are supported. The standalone CTEQ6 [17] routine is also included for the default use. In the case for using PDFLIB, edit one of the lines in `inc/define.h` as

```
#define PDFLIB CERNPDFLIB .
```

As an example we show an instruction to install the W+1jet and W+2jets production processes in the GR@PPA framework. After downloading the framework package and the two matrix element packages, unpack them as

```
tar xzvf GR@PPA-2.76.tgz
cd GR@PPA-2.76
tar xzvf ../matrix_w1j_v1.03.tgz
tar xzvf ../matrix_w2j_v1.03.tgz .
```

By these commands, the `wjets` directory is created and under it two directories, `w1j` and `w2j`, are created. Then, configure the matrix elements and the compiling environment in `Config.perl`, and execute it as

```
Config.perl .
```

This creates the `Makefile` according to the present matrix-element installation. Users have to edit the `Makefile` to specify further details, such as particular compiler options and paths to external libraries. Now, users can create the matrix element libraries and the framework libraries. Type the commands as follows:

```
make w1j
make w2j
make kinem
make integ .
```

Note that, because the kinematics codes are modified according to the selected matrix elements, the kinematics library must be created after making the matrix element libraries. Users must repeat the above sequence again when they add new matrix elements. The created libraries are installed in the `lib/` directory by executing the command,

```
make install .
```

The example programs are given for the standalone use, and PYTHIA- and HERWIG-interfacing. The command

```
make example
```

sets up these examples in the `example/` directory.

3.3 Initialization and customization

Although the execution of GR@PPA is controlled by the subroutine `GRCPYGEN`, the detailed behavior depends on some parameters in common blocks and conditions defined in some subprograms. The subroutine `GRCINIT` initializes all related parameters to the default values. Users can change them after calling `GRCINIT` as described in the following.

The parameter that is necessary to be given by users is `GRCECM`, which specifies the cm energy of the beam collision in GeV. Optionally, users can define some phase-space cuts in the laboratory frame: `GPTCUT`, `GETACUT` and `GRCONCUT`. These parameters define the minimum p_T in GeV, the largest pseudorapidity in the absolute value and the minimum separation in ΔR, respectively. These cuts are applied to all produced jets except for those from weak boson decays. The separation (ΔR) is defined for every pair of jets as

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}, \tag{4}$$

where $\Delta\phi$ and $\Delta\eta$ are the separation in the azimuthal angle and the pseudorapidity, respectively. The arrays `GRCPTCUT`, `GRCETACUT` and `GRCRCONCUT` can separately set certain phase-space cuts for each final state particle.

Additionally, the subroutine `GRCUSRCUT` provides a framework to apply customized cuts referring to detailed properties such as four-momenta of the particles. Some useful functions are available there. If the events are acceptable `IUSRCUT = 0` should be returned, while `IUSRCUT = 1` for the rejection. Since those cuts are applied at the integration stage,

a high event generation efficiency can be achieved in the event generation. The selection can be applied even for the particle flavor. This feature is useful for a parton flavor selection in the jet production. A concrete example can be found in Appendix B.

The arrays `IGWMOD` and `IGZMOD` specify the decay mode of the W and Z bosons, respectively. If the value is equal to 1, the corresponding decay channel is activated; if the number is equal to 0, the channel is disabled. `IWIDCOR` is an option for the decay width correction for the W and Z bosons. The theoretically calculated values are used if `IWIDCOR = 1`, while the experimentally measured ones can be used if `IWIDCOR = 2`. If `IWIDCOR = 2`, the cross section is weighted by using the measured branching ratio as

$$\sigma(X \to f\bar{f}) \;=\; \sigma_{\rm calc}\,\frac{\Gamma^{\rm tot}_{\rm exp}}{\Gamma^{\rm part}_{\rm calc}}\,{\rm Br}_{\rm exp}(X \to f\bar{f}) \quad , \tag{5}$$

where $\sigma_{\rm calc}$ is the calculated cross section using the given total decay width $\Gamma^{\rm tot}_{\rm exp}$, $\Gamma^{\rm part}_{\rm calc}$ is the partial decay width theoretically calculated, and ${\rm Br}_{\rm exp}(X \to f\bar{f})$ is the branching ratio experimentally measured. ${\rm Br}_{\rm exp}(X \to f\bar{f})$ must be given in the arrays `GRCWBR` and `GRCZBR` for the W and Z bosons, respectively.

The array `IGJFLV` determines the active flavor of jets in the final state except for those from W and Z boson decays. If `IGJFLV(I) = 1`, the corresponding flavor I (d, u, s, c, b, t, g for $I = 1, 2, ..., 7$) is activated, while it is disabled if `IGJFLV(I) = 0`. Regardless that they are disabled by the `IGJFLV` flags, those flavors are occasionally produced if the diagram structure requires them. For example, consider the case that the u flavor in the PDF is activated and the $qg \to qg$ base-subprocess is chosen in the QCD 2 jets production. In this case, if g is activated, the $ug \to ug$ subprocess is activated even if u is disabled by `IGJFLV`. If both u and g are disabled, this subprocess itself is disabled. That is, the events are accepted if either of the activated flavors by `IGJFLV` has to appear in the final state. The jet flavor can also be controlled by changing the CKM parameter `GRCCKM` if the process includes intermediate W bosons.

Further detailed parameters, such as particle masses, decay widths and couplings, are accessible in the subroutine `SETMAS`. The mass and the total decay width of the weak bosons can be manually controlled there. GR@PPA does not give any constraint to these parameters. However, the electroweak parameters are characterized by only three (plus Higgs mass) parameters.[2] The setting for dependent parameters are ignored and their values are recalculated according to the choice of the scheme given by the parameter `IGAUGE`. The G_μ scheme is taken as the default, where all the parameters are given by the set of following parameters:

$$(G_F,\; M_W,\; M_Z)\;. \tag{6}$$

Here, G_F is the Fermi constant, M_W and M_Z are masses of W and Z bosons, respectively.

The other process-specific parameters are defined in the subroutine `GRCPAR`. Users can choose different conditions for different processes. The variable `ICOUP` determines the energy scale (Q^2) for calculating the coupling strengths, $\alpha_{\rm em}$ and α_s, in the matrix element

[2] Additionally, a gauge invariance also demands fermion masses in the Yukawa sector.

calculation (renormalization scale). The selectable choices are prepared (see Table 2). The variable `IFACT` determines Q^2 for PDF (factorization scale). The definition is the same as `ICOUP`. The same choice as `ICOUP` is taken if `IFACT` is not explicitly given. As an option, users can apply their own definitions of these energy scales, by setting `ICOUP = 6` and/or `IFACT = 6` and editing the subroutine `GRCUSRSETQ`. An example is attached to `grcpar.F`. The number of flavors used in the coupling calculation and PDF is given in `INPFL`. The flavor is ordered as u, d, c, s and b. The extrapolation to the top quark in the coupling formula and PDF is not taken into account at the moment.

The integer variable `IBSWRT` controls whether BASES should be called in the initialization or not. The task of BASES is to optimize the integration grids and, after that, store the optimized results in a "BASES table". The execution of BASES consumes much CPU time because a precise evaluation is necessary for an efficient event generation by SPRING. It is not necessary to repeat the execution for identical conditions. A previously optimized result ("BASES table") is reused if `IBSWRT = 1`. It should be noted that, once the parameters which affects the estimated result of the integration are changed, the "condition" is no longer identical and BASES has to be re-executed. The parameter `NCALL` specifies the number of sampling points in each step of the iterative grid optimization in BASES. The larger this number is, the better the conversion would be. However, it takes longer in the CPU time. The optimized values are preset in `grcpar.F`. The character variable `GRCFILE` gives the "BASES table" file name[3]. A new file must be specified if `IBSWRT = 0`, while an existing file must be specified if `IBSWRT = 1`.

The parameters described in this subsection are summarized in Table 2.

3.4 BASES integration

In the output of GR@PPA, users should pay appropriate attention to the print out from BASES, especially when they apply tight cuts. Since each subprocess is composed of many coherent diagrams, it is not practicable to take all singularities into account in the "kinematics" definitions. Some very minor ones are ignored in GR@PPA. A combination of very tight cuts may enhance the relative contribution of ignored singularities. In such cases, it is likely to happen that, in the BASES iteration, the estimated total cross section jumps (increases) to a value unreasonably different from the previous estimation and, accordingly, the estimated error increases. Users should consider that they must be in such a trouble if they find a jump of, for instance, more than three times the previous error. The results are unreliable in the phase-space region defined by such cuts. The instructive integration accuracy is 0.5% or better for every iteration. Users should change the parameter `NCALL` to a larger value if this accuracy is not achieved.

[3]BASES actually creates two files having extensions of .data and .result, respectively, added to the name given by `GRCFILE`. The former is the "BASES table", while the latter is a readable summary of the BASES execution.

Parameter	Description
GRCECM	CM energy of the beam collision in GeV. (D=14000.)
CBEAM	'PP' for pp collisions and 'PAP' for $p\bar{p}$ collisions. (D='PP')
IGSUB	Process number. See Table 7.
MODE	Mode selection for GRCPYGEN: = 1 for calling BASES, and 0 for calling SPRING.
GPTCUT	Minimum p_T cut in GeV for jets except for those from weak boson decays. (D=20.GeV)
GRCPTCUT(8)	Minimum p_T cut in GeV for each final state particle. (D=0.GeV)
GETACUT	Largest pseudorapidity cut in the absolute value for jets except for those from weak boson decays.(D=3.)
GRCETACUT(8)	Largest pseudorapidity cut for each final state particle. (D=10.)
GRCONCUT	Minimum separation cut in ΔR ($= \sqrt{\Delta\phi^2 + \Delta\eta^2}$) for jets except for those from weak boson decays.(D=0.4)
GRCRCONCUT(8)	Minimum separation cut in ΔR ($= \sqrt{\Delta\phi^2 + \Delta\eta^2}$) for each final state particle. (D=0.)
IGWMOD(20)	Decay mode for W boson: = 1 to activate, and 0 to deactivate.
IGZMOD(16)	Decay mode for Z boson : = 1 to activate, and 0 to deactivate.
IWIDCOR	Width correction for W and Z. (D=1)
GRCWBR(20)	Branching ratio for W. It is used only when IWIDCOR=2.
GRCZBR(16)	Branching ratio for Z. It is used only when IWIDCOR=2.
IGJFLV(7)	Flag for the jet flavor of jets except for those from weak boson decays: = 1 to activate, and 0 to deactivate.
IGRCGEF	Photon interference in Z production processes is included if set to 1, ignored if 0. (D=1)
GRCCKM(3,3)	CKM parameters.
IGAUGE	Choice of electroweak parameters. The G_μ scheme is used as the default. (D=1)
ICOUP	Choice of the renormalization scale. = 1 : $\sqrt{\hat{s}}$ of the hard interaction. = 2 : average of squared transverse mass ($< m_T^2 >$). = 3 : total squared transverse mass ($\sum m_T^2$). = 4 : maximum squared transverse mass ($max\ m_T^2$). = 5 : fixed value. Set GRCQ in GeV. = 6 : user defined scale. Set GRCQ in the subroutine GRCUSRSETQ.
IFACT	Choice of the factorization scale. (D=0) The definition is the same as ICOUP. If IFACT = 0, the same value as the renormalization scale is used. In case IFACT = 5 or 6, set GRCFAQ in GeV.
GRCFILE	Output file name for the BASES integration.
IBSWRT	Mode selection for BASES integration: = 0 for calling the BASES integration, and 1 for skipping. (D=0) If IBSWRT = 1, the file defined in GRCFILE is used.
NCALL	Number of sampling points in each step of the iterative grid optimization in BASES.
INPFL	Number of flavors used in the coupling calculation and PDF. (D=5)

Table 2: Parameters in GR@PPA.

4 Processes

4.1 $V + N$ jets

The process identification number `IGSUB` is assigned to be $100 \sim 104$ and $110 \sim 114$ for W and Z production processes with 0 up to 4 jets. The matrix elements (ME) include the boson decays into two fermions, so that the decay properties are correctly reproduced at the tree level. Heavy quarks such as bottom and top quarks can also be included as the jets as well as the lighter quarks and the gluon. Since the quark mixing in the couplings with W boson is treated up to the third generation, single and triple heavy quark productions are allowed in the multi-jet configuration, in addition to the pair production from the gluon splitting. In $Z + N$ jets processes, the Z/γ^* interference can be taken into account in the ME calculations. The interference between decay fermions and those from other sources is ignored.

The benchmark cross sections of the $V + N$ jets production processes for the Tevatron Run II and the LHC conditions are presented in Table 3, where the quark flavors are included up to the b quark. We also present the benchmark cross sections for the case having at least one b quark, and having a $t\bar{t}$ pair in the final state. The results are in good agreement with those from other generators [18, 19, 20, 21, 22]. The detailed parameters used in these calculations are described in Appendix B.

	Tevatron Run-II		LHC	
N jets	$W(e\nu_e)$	$Z(e^+e^-)$	$W(e\nu_e)$	$Z(e^+e^-)$
0	$1.576(2)\times10^{3}$	$1.598(3)\times10^{2}$	$1.116(2)\times10^{4}$	$9.57(3)\times10^{2}$
1	$1.852(3)\times10^{2}$	$1.829(4)\times10^{1}$	$2.854(5)\times10^{3}$	$2.614(7)\times10^{2}$
2	$3.461(7)\times10^{1}$	3.485(6)	$1.143(3)\times10^{3}$	$1.082(2)\times10^{2}$
3	6.29(2)	$6.35(2)\times10^{-1}$	$4.82(1)\times10^{2}$	$4.53(1)\times10^{1}$
4	1.201(5)	$1.173(3)\times10^{-1}$	$2.19(1)\times10^{2}$	$2.045(5)\times10^{1}$
2 (≥ 1 b)	$3.260(6)\times10^{-1}$	$9.24(2)\times10^{-2}$	2.720(7)	8.68(2)
3 (≥ 1 b)	$1.019(2)\times10^{-1}$	$2.266(5)\times10^{-2}$	4.305(9)	3.740(7)
4 (≥ 1 b)	$2.947(8)\times10^{-2}$	$3.817(5)\times10^{-3}$	3.90(3)	$9.47(2)\times10^{-1}$
$t\bar{t}+0$	$5.269(9)\times10^{-4}$	$2.248(3)\times10^{-4}$	$3.774(7)\times10^{-2}$	$2.682(6)\times10^{-2}$
$t\bar{t}+1$	$1.357(2)\times10^{-4}$	$6.302(9)\times10^{-5}$	$4.98(2)\times10^{-2}$	$3.59(1)\times10^{-2}$
$t\bar{t}+2$	$6.86(1)\times10^{-5}$	$5.707(5)\times10^{-7}$	$6.52(2)\times10^{-2}$	$1.156(2)\times10^{-2}$

Table 3: Benchmark cross section (pb) for $V + N$ jets processes. Results are presented for the Tevatron Run II and the LHC cases. The detailed parameters used in the calculations are described in Appendix B.

4.2 $VV + N$ jets

The number `IGSUB` is assigned to be $120 \sim 122$ for the WW production processes, $130 \sim 132$ for the WZ production processes, and $140 \sim 142$ for the ZZ production processes. The matrix elements (ME) include the boson decays into two fermions, so that the decay

properties such as the spin correlation between two bosons is correctly reproduced at the tree level, while the interference between the fermions from different bosons and those from other sources is ignored. The Z/γ^* interference can be taken into account in the ME calculations. Heavy quarks (b and t) can also be included in the jets.

The benchmark cross sections for the Tevatron Run II and the LHC conditions are presented in Table 4. We also present the results for the case having at least one b quark, and having a $t\bar{t}$ pair in the final state. The detailed parameters are described in Appendix B.

	Tevatron Run-II		
N jets	WW	WZ	ZZ
0	$7.91(2)\times10^{-2}$	$6.06(1)\times10^{-3}$	$1.541(3)\times10^{-3}$
1	$1.986(5)\times10^{-2}$	$2.013(4)\times10^{-3}$	$3.721(6)\times10^{-4}$
2	$4.77(1)\times10^{-3}$	$5.16(2)\times10^{-4}$	$7.698(9)\times10^{-5}$
2 (≥ 1 b)	$1.582(2)\times10^{-4}$	$6.00(2)\times10^{-6}$	$1.629(3)\times10^{-6}$
$t\bar{t}$ + 0	$5.504(5)\times10^{-7}$	$5.065(7)\times10^{-8}$	$8.871(9)\times10^{-9}$

	LHC		
N jets	WW	WZ	ZZ
0	1.339(5)	$4.64(1)\times10^{-2}$	$1.080(2)\times10^{-2}$
1	1.071(3)	$1.873(4)\times10^{-1}$	$6.06(1)\times10^{-3}$
2	$9.41(2)\times10^{-1}$	$1.536(4)\times10^{-1}$	$3.419(5)\times10^{-3}$
2 (≥ 1 b)	$7.36(1)\times10^{-2}$	$1.164(3)\times10^{-4}$	$1.887(8)\times10^{-4}$
$t\bar{t}$ + 0	$7.432(9)\times10^{-4}$	$1.213(2)\times10^{-5}$	$3.040(5)\times10^{-6}$

Table 4: Benchmark cross section (pb) for VV + N jets processes. Results are presented for the Tevatron Run II and the LHC cases. The detailed parameters used in the calculations are described in Appendix B.

4.3 $b\bar{b}b\bar{b}$

We provide the $b\bar{b}b\bar{b}$ production processes which have been developed in our previous work [10] as a separate matrix element package. The process identification number is 160 for the Higgs production associated with bottom quarks ($Y_b^2\alpha_s^2$), 161 for the Z/γ^* mediated process ($\alpha_s^2\alpha_{\rm em}^2$), 162 for the pure QCD process (α_s^4), 163 for the HZ production ($Y_b^2\alpha_{\rm em}^2$), and 164 for the Z pair mediated process ($\alpha_{\rm em}^4$), where the SM Higgs boson is assumed for the Higgs production.

4.4 $t\bar{t}$ + N jets

Aside from the QCD multi-jets processes, we provide top pair production processes. In these processes, the whole decay chain of the top quark is included in the diagram calculation, so that the spin correlation in the top decay is fully reproduced. In addition

to the $t\bar{t}$ production (6-body ME), we also provide the $t\bar{t}$ + 1 jet (7-body ME) process. This process may give an insight for the 7-body kinematics including the top decay. The process number is assigned to be 170 for $t\bar{t}$, and 171 for $t\bar{t}$ + 1 jet. Possible anomalous couplings in the top decay and its production will be included in the ME calculation in a future version. They will be provided as an update set of the matrix elements.

4.5 N jets

The QCD multi-jets processes are provided with the process identification numbers from 182 to 184 for 2, 3 and 4 jets, respectively. The electroweak interaction is ignored in these processes. Heavy flavors such as bottom and top quarks can be produced by appropriately setting `IGJFLV`.

The benchmark cross sections of the QCD N jets processes are presented in Table 5. We also present the results for heavy flavor production processes. These results are in good agreement with those from other generators [18, 19, 20, 21, 22]. It should be noted that the result for the $b\bar{b}b\bar{b}$ production is the same as that for the process `IGSUB = 162`. The detailed parameter setting is described in Appendix B.

	Tevatron Run-II	LHC
N jets	QCD jets (α_s^N)	QCD jets (α_s^N)
2	$1.853(5)\times10^{7}$	$4.355(8)\times10^{8}$
3	$6.88(3)\times10^{5}$	$3.326(7)\times10^{7}$
4	$8.82(3)\times10^{4}$	$7.94(1)\times10^{6}$
$bbbb$	5.70(1)	$8.42(2)\times10^{2}$
$b\bar{b}t\bar{t}$	$7.46(2)\times10^{-3}$	3.796(8)
$t\bar{t}t\bar{t}$	$5.809(4)\times10^{-6}$	$2.322(5)\times10^{-2}$

Table 5: Benchmark cross section (pb) for QCD multi-jets processes. Results are presented for the Tevatron Run-II and the LHC cases. The detailed parameters used in the calculations are described in Appendix B.

5 Performance

The computation performance of GR@PPA for the $W + N$ jets processes in the Tevatron Run-II condition is summarized in Table 6. The tests have been performed using Intel Pentium 4 3.4 GHz CPU and two different Fortran compilers: a free software, g77 in gcc 2.96, and a commercial compiler, Intel Fortran Compiler version 8.0. The integration time and the generation speed are separately shown. Clearly, the commercial compiler is about 2.5 times faster than the free compiler. However, in both cases, the time is not intolerable for large scale Monte Carlo productions. The generation efficiencies of SPRING, shown in the table, are exceptionally good for this kind of complicated processes.

The result for the $W + 4$ jets is not shown in the table, since it consumes too long CPU time to run as a single process. A parallel computing is indispensable for practical uses. A parallel computing employing MPI (Message Passing Interface) is supported in BASES. The benchmark result in Table 3 has been obtained by using a PC farm having 12 Intel Pentium 4 3.2 GHz CPUs with Intel Fortran Compiler version 7.0. The integration time is 23 hours fully using these CPUs. The event generation speed is 0.11 events/sec with the generation efficiency of 0.1%. Though SPRING does not support parallel computing, users can parallelize the event generation by hand by changing the starting random number seed. The parallel computing has also been applied to the $W +$ 3 jets production. The integration time has been reduced to 24 minutes from 5 hours for the single-process computing on the same platform. The scalability is quite good. Those users who want to apply the parallel computing should contact the author[4].

Process	Fortran Compiler	Integration time (H:M:Sec)	Event Generation speed (events/sec)	Efficiency (%)
$W(e\nu_e) + 0$ jet	g77	00 : 00 : 05	43859	69.6
	intel 8.0	00 : 00 : 02	101010	
$W(e\nu_e) + 1$ jet	g77	00 : 00 : 52	13927	19.9
	intel 8.0	00 : 00 : 19	34364	
$W(e\nu_e) + 2$ jets	g77	00 : 38 : 27	709	1.7
	intel 8.0	00 : 13 : 52	1957	
$W(e\nu_e) + 3$ jets	g77	14 : 03 : 46	18	0.3
	intel 8.0	04 : 57 : 50	52	

Table 6: Performance of GR@PPA for the $W + N$ jets processes in the Tevatron Run-II condition. The tests have been performed using Intel Pentium 4 3.4 GHz CPU and two different Fortran compilers: g77 version 2.96, and Intel Fortran Compiler version 8.0. The integration time and the generation speed are separately shown.

6 Summary

The GR@PPA event generator has been updated to version 2.7. In this version, the extensions have been mostly applied to deal with the flavor configuration in the initial and final state by sharing several subprocesses into the single subprocess. This allows us to incorporate the variation in the initial and final states parton configurations such as the multi-jets production processes. A new method has been also adopted to calculate the color factors of complicated QCD processes. Those implementations are able to speed up the diagram calculation for multi-jet production processes significantly.

The distribution of this version is composed of two separate packages: the framework and the matrix element for the processes. The framework consists of some process-independent elements such as integration packages and kinematic libraries. The matrix

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element provides a set of the matrix elements used in the GR@PPA event generator. Currently, we provide the matrix element packages for V (W or Z) + jets ($\leq$ 4 jets), VV + jets ($\leq$ 2 jets) and QCD multi-jet ($\leq$ 4 jets) production processes at the tree level for pp and $p\bar{p}$ collisions, where the jet flavor includes up to top quark. The four bottom quark productions implemented in our previous work (GR@PPA_4b) are also included. In addition, we provide the top-pair and top-pair + jet production processes, where the correlation between the decay products are fully reproduced at the tree level. Namely, processes up to seven-body productions can be simulated, based on ordinary Feynman diagram calculations.

The GR@PPA event generator takes advantages that further extensions are easily applicable in the GR@PPA framework. Once NLO processes or non-Standard Model processes are given as a matrix element package, users will be able to simply use them without any detailed care. An extended framework to include the parton shower is also possible. They may be available in a future release or by a release of the new matrix element packages. The GR@PPA event generator will be suitable not only for a large scale Monte Carlo production for high luminosity hadron collisions at Tevatron and LHC, but also for future NLO calculations to be composed of lots of subprocesses.

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A Processes in GR@PPA

All physics processes are recognized by unique process numbers `IGSUB` listed in Table 7. The second column in the table is the order of coupling constants for the process. The parameter Y_b is the Yukawa coupling of the b quark. The third column shows the command paramter for compiling the ME. The parameter name is the same as the directory name of the process. The forth column is the process descriptions. Each process consists of several base-subprocesses. The symbol "f" denotes the fermion from boson decays. The decay fermions except for those in the $b\bar{b}b\bar{b}$ processes do not interfere with other partons.

IGSUB	Coupling order	Command parameter	Process description
100	$\alpha_{\rm em}^2$	w0j	$pp(\bar{p}) \to W(2f) + 0$ jet $(+X)$
101	$\alpha_{\rm em}^2\alpha_s$	w1j	$pp(\bar{p}) \to W(2f) + 1$ jet $(+X)$
102	$\alpha_{\rm em}^2\alpha_s^2$	w2j	$pp(\bar{p}) \to W(2f) + 2$ jets $(+X)$
103	$\alpha_{\rm em}^2\alpha_s^3$	w3j	$pp(\bar{p}) \to W(2f) + 3$ jets $(+X)$
104	$\alpha_{\rm em}^2\alpha_s^4$	w4j	$pp(\bar{p}) \to W(2f) + 4$ jets $(+X)$
110	$\alpha_{\rm em}^2$	z0j	$pp(\bar{p}) \to Z/\gamma^*(2f) + 0$ jet $(+X)$
111	$\alpha_{\rm em}^2\alpha_s$	z1j	$pp(\bar{p}) \to Z/\gamma^*(2f) + 1$ jet $(+X)$
112	$\alpha_{\rm em}^2\alpha_s^2$	z2j	$pp(\bar{p}) \to Z/\gamma^*(2f) + 2$ jets $(+X)$
113	$\alpha_{\rm em}^2\alpha_s^3$	z3j	$pp(\bar{p}) \to Z/\gamma^*(2f) + 3$ jets $(+X)$
114	$\alpha_{\rm em}^2\alpha_s^4$	z4j	$pp(\bar{p}) \to Z/\gamma^*(2f) + 4$ jets $(+X)$
120	$\alpha_{\rm em}^4$	ww0j	$pp(\bar{p}) \to W^+(2f)W^-(2f') + 0$ jet $(+X)$
121	$\alpha_{\rm em}^4\alpha_s$	ww1j	$pp(\bar{p}) \to W^+(2f)W^-(2f') + 1$ jet $(+X)$
122	$\alpha_{\rm em}^4\alpha_s^2$	ww2j	$pp(\bar{p}) \to W^+(2f)W^-(2f') + 2$ jets $(+X)$
130	$\alpha_{\rm em}^4$	zw0j	$pp(\bar{p}) \to Z/\gamma^*(2f)W(2f') + 0$ jet $(+X)$
131	$\alpha_{\rm em}^4\alpha_s$	zw1j	$pp(\bar{p}) \to Z/\gamma^*(2f)W(2f') + 1$ jet $(+X)$
132	$\alpha_{\rm em}^4\alpha_s^2$	zw2j	$pp(\bar{p}) \to Z/\gamma^*(2f)W(2f') + 2$ jets $(+X)$
140	$\alpha_{\rm em}^4$	zz0j	$pp(\bar{p}) \to Z/\gamma^*(2f)Z/\gamma^*(2f') + 0$ jet $(+X)$
141	$\alpha_{\rm em}^4\alpha_s$	zz1j	$pp(\bar{p}) \to Z/\gamma^*(2f)Z/\gamma^*(2f') + 1$ jet $(+X)$
142	$\alpha_{\rm em}^4\alpha_s^2$	zz2j	$pp(\bar{p}) \to Z/\gamma^*(2f)Z/\gamma^*(2f') + 2$ jets $(+X)$
160	$Y_b^2\alpha_s^2$	b4hbb	$pp(\bar{p}) \to h_0(b\bar{b}) + b\bar{b}$ $(+X)$
161	$\alpha_{\rm em}^2\alpha_s^2$	b4zbb	$pp(\bar{p}) \to Z/\gamma^*(b\bar{b}) + b\bar{b}$ $(+X)$
162	α_s^4	b4qcd	$pp(\bar{p}) \to b\bar{b}b\bar{b}$ $(+X)$
163	$Y_b^2\alpha_{\rm em}^2$	b4hz	$pp(\bar{p}) \to h_0(b\bar{b}) + Z/\gamma^*(b\bar{b})$ $(+X)$
164	$\alpha_{\rm em}^4$	b4zz	$pp(\bar{p}) \to Z/\gamma^*(b\bar{b}) + Z/\gamma^*(b\bar{b})$ $(+X)$
170	$\alpha_{\rm em}^4\alpha_s^2$	tt6bdy	$pp(\bar{p}) \to tt \to 6f$ $(+X)$
171	$\alpha_{\rm em}^4\alpha_s^3$	ttj7bdy	$pp(\bar{p}) \to t\bar{t} + 1$ jet $\to 6f + 1$ jet $(+X)$
182	α_s^2	qcd2j	$pp(\bar{p}) \to 2$ jets $(+X)$
183	α_s^3	qcd3j	$pp(\bar{p}) \to 3$ jets $(+X)$
184	α_s^4	qcd4j	$pp(\bar{p}) \to 4$ jets $(+X)$

Table 7: Processes included in GR@PPA, version 2.7.

B Parameters

The kinematical cuts and other parameters used in the benchmark tests in Section 4 are as follows:

Beams :

The benchmark tests have been carried out for the Tevatron Run II ($p\bar{p}$) and the LHC (pp) conditions with the center-of-mass energies of

$$\sqrt{s} \;=\; \begin{cases} 1.96 & \text{TeV} & p\bar{p} & \text{(Tevatron Run II)}, \\ 14 & \text{TeV} & pp & \text{(LHC)}. \end{cases} \tag{7}$$

Electroweak parameters :

The G_μ scheme is adopted with the parameter set of

$$(G_F,\; M_W,\; M_Z) \;=\; (1.16639 \times 10^{-5}\ \text{GeV}^{-2},\; 80.419\ \text{GeV},\; 91.188\ \text{GeV}) \quad , \tag{8}$$

where G_F is the Fermi constant, M_W [23] and M_Z [23] are the masses of the W and Z bosons, respectively. This set leads to the other parameters as

$$\alpha_{\text{em}} \;=\; 1/132.51 \quad , \quad \sin^2\theta_W \;=\; 0.2222 \quad .$$

Boson width and decay :

The W boson is forced to decay to a pair of an electron and a neutrino, and the Z boson to an electron-positron pair. In diboson production processes, the interference between electrons (neutrinos) from two bosons is ignored. We use fixed decay widths for W, Z and the top quark as

$$\Gamma_W \;=\; 2.048 \quad \text{GeV}, \qquad \Gamma_Z \;=\; 2.446 \quad \text{GeV}, \qquad \Gamma_t \;=\; 1.508 \quad \text{GeV}. \tag{9}$$

CKM parameters :

We use the following CKM parameters:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \;=\; \begin{pmatrix} |V_{ud}| = 0.9752 & |V_{us}| = 0.2210 & |V_{ub}| = 0.0054 \\ |V_{cd}| = 0.2210 & |V_{cs}| = 0.9743 & |V_{cb}| = 0.0419 \\ |V_{td}| = 0.0054 & |V_{ts}| = 0.0419 & |V_{tb}| = 0.9991 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad . \tag{10}$$

The phase of CKM matrix is neglected.

Fermion masses :

Following values are use for the masses of heavy quarks

$$m_c = 1.5\ \text{GeV} \quad m_b = 4.7\ \text{GeV} \quad m_t = 174.3\ \text{GeV} \quad . \tag{11}$$

The other quarks (u,d,s) are assumed to be massless. The electron and neutrino masses are also neglected.

Proton Distribution Function :

We use CTEQ6L [17] containing 5 flavors for PDF. The corresponding strong coupling constant is $\alpha_s(M_Z^2) = 0.1180$.

Energy scale :

The renormalization and factorization scales (Q) are always chosen to be identical and fixed to the Z boson mass as

$$Q \;=\; \mu_F \;=\; \mu_R \;=\; m_Z \;=\; 91.188 \quad \text{GeV}. \tag{12}$$

Kinematical cuts :

The following kinematical cuts are applied to avoid infrared/collinear singularities,

$$p_T \;\geq\; 20\,\text{GeV}\,, \quad |\eta| \;\leq\; 3.0\,, \quad \Delta R \;\geq\; 0.4 \quad . \tag{13}$$

These cuts are applied to the jets (u, d, c, s, b and g) and electrons, while no cut is done to top quarks and neutrinos.

Flavor selection :

In some tests of heavy flavor productions, a particular jet flavor is selected in the integration. This is done in the subroutine `GRCUSRCUT`. The following is an example to select those events having two top quarks in the final state:

```
ITOP = 0                ! counter of the number of top-quark in jets.
DO I = 1,NJET           ! loop over n jets.
   IF (IABS(GRCKFCD(I)).EQ.6) ITOP = ITOP + 1  ! number of top qaurks.
ENDDO
IF (ITOP.NE.2) IUSRCUT = 1   ! reject this event.
```

References

[1] Minami-Tateya Group, GRACE manual, KEK Report 92-19 (1993);
F. Yuasa *et al.*, Automatic computation of cross sections in HEP: Status of GRACE system, *Prog. Theor. Phys. Suppl.* **138** (2000) 18 [hep-ph/0007053]

[2] G. Belanger *et al.*, GRACE at ONE-LOOP: Automatic calculation of 1-loop diagrams in electroweak theory with gauge parameter independence checks, hep-ph/0308080.

[3] J. Fujimoto *et al.*, GRACE/SUSY: Automatic generation of tree amplitudes in the minimal supersymmetric standard model, *Comput. Phys. Commun.* **153** (2003) 106 [hep-ph/0208036].

[4] T. Abe, GRAPE-Dilepton (Version 1.1): A generator for dilepton production in e p collisions, *Comput. Phys. Commun.* **136** (2001) 126 [hep-ph/0012029].

[5] K. Sato *et al.*, Integration of GRACE and PYTHIA, Proc. VII International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT 2000), P.C. Bhat and M. Kasemann, AIP Conference Proceedings **583** 214 (2001) [hep-ph/0104237].

[6] S. Kawabata, A NEW MONTE CARLO EVENT GENERATOR FOR HIGH-ENERGY PHYSICS, *Comput. Phys. Commun.* **41** (1986) 127;
S. Kawabata, A New version of the multidimensional integration and event generation package BASES/SPRING, *Comput. Phys. Commun.* **88** (1995) 309.

[7] E. Boos *et al.*, Generic User Process Interface for Event Generators, hep-ph/0109068.

[8] T. Sjöstrand, *et al.*, High-energy-physics event generation with PYTHIA 6.1, *Comput. Phys. Commun.* **135** (2001) 238 [hep-ph/0010017].

[9] G. Corcella, I.G. Knowles, G. Marchesini, S. Moretti, K. Odagiri, P. Richardson, M.H. Seymour and B.R. Webber, HERWIG 6: An event generator for hadron emission reactions with interfering gluons (including supersymmetric processes), *J. High Energy Phys.* **01** (2001) 010 [hep-ph/0011363]; hep-ph/0210213.

[10] S. Tsuno *et al.*, GR@PPA_4b: A four bottom quark production event generator for $pp/p\bar{p}$ collisions, *Comput. Phys. Commun.* **151** (2003) 216 [hep-ph/0204222].

[11] Y. Kurihara *et al.*, QCD event generators with next-to-leading order matrix-elements and parton showers, *Nucl. Phys.* **B 654** (2003) 301 [hep-ph/0212216].

[12] H. Tanaka, T. Sugiura and Y. Wakabayashi, Factorization algorithm for parton showers beyond the leading logarithmic order of QCD, *Prog. Theor. Phys. Suppl.* **114** (2005) 477 [hep-ph/0510185];
H. Tanaka, Initial state parton evolution beyond the leading logarithmic order of QCD, *Prog. Theor. Phys. Suppl.* **110** (2003) 963;
T. Munehisa, J. Fujimoto, Y. Kurihara and Y. Shimizu, A QED shower including the next-to-leading logarithm correction in e^+e^- annihilation, *Prog. Theor. Phys. Suppl.* **103** (2000) 587 [hep-ph/9912392].

[13] N. Cabbibo, *Phys. Rev. Lett.* **10** (1961) 531;
M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49** (1973) 652.

[14] J. Fujimoto *et al.*, grc4f v1.1: a Four-fermion Event Generator for e^+e^- Collisions, *Comput. Phys. Commun.* **100** (1997) 128 [hep-ph/9605312].

[15] H. Plothow-Besch, PDFLIB: A Library of all available parton density functions of the nucleon, the pion and the photon and the corresponding alpha-s calculations, *Comput. Phys. Commun.* **75** (396) 1993.

[16] W. Giele, *et al*.., The QCD/SM working group: Summary report, Les Houches 2001, Physics at TeV colliders 275 [hep-ph/0204316];
See www document, http://hepforge.cedar.ac.uk/lhapdf/ .

[17] CTEQ Collab.,H.L. Lai *et al*.., Global QCD analysis of parton structure of the nucleon: CTEQ5 parton distributions, *Eur. Phys. J.* **C 12** (2000) 375 [hep-ph/9903282].

[18] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A.D. Polosa, ALPGEN, a generator for hard multiparton processes in hadronic collisions, *J. High Energy Phys.* **07** (2003) 001 [hep-ph/0206293].

[19] F. Maltoni and T. Stelzer, MadEvent: Automatic event generation with MadGraph, *J. High Energy Phys.* **02** (2003) 027 [hep-ph/0208156].

[20] E. Boos *et al*., CompHEP 4.4: Automatic computation from Lagrangians to events, *Nucl. Instrum. Meth.* **534** (2004) 250 [hep-ph/0403113].

[21] F. Krauss, R. Kuhn and G. Soff, AMEGIC++ 1.0: A matrix element generator in C++, *J. High Energy Phys.* **02** (2002) 044 [hep-ph/0109036];
A. Schälicke, F. Krauss, R. Kuhn and G. Soff, Implementing initial state radiation for lepton induced processes in AMEGIC++, *J. High Energy Phys.* **12** (2002) 013 [hep-ph/0203259].

[22] C.G. Papadopoulos, PHEGAS: A phase space generator for automatic cross-section computation, *Comput. Phys. Commun.* **137** (2001) 247 [hep-ph/0007335].

[23] S. Eidelman *et al*., Review of particle physics, *Phys. Lett.* **B 592** (2004) 1.