Introduction to GR@PPA event generators for $pp/p\bar{p}$ collisions

Soushi Tsuno
Department of Physics, Faculty of Science, Okayama University
3-1-1 Tsushima-naka, Okayama 700-8530, Japan

Abstract

We have developed an extended framework, named GR@PPA, of the GRACE system for hadron collisions. The GRACE system is an automatic Feynman diagram calculation system and an event generator based on this diagram calculation. While the original GRACE system assumes that both the initial and final states are well-defined, the GR@PPA framework applies that the initial and final states parton configuration is treated in the Feynman diagram calculation at the same time by putting one more integration variables. As a result, some subprocesses with the same coupling order in hadron-hadron collisions can share an identical "GRACE output code" and can be treated as a single subprocess. This technique simplifies the program code and saves the computing time very much. The constructed event generators would be suitable for the large scale Monte Carlo production in the hadron colliders. In this paper, we discuss this technique, and present some results and performances.

1 Introduction

Since the great success of the Standard Model in the recent decades, there has been no doubt that the gauge theories are capable to describe the interactions between elementary particles. With larger colliding energy available to probe higher energy scattering events, only remained piece of the Standard Model, Higgs boson(s), will be also discovered in the current and future colliders. Besides, a new physics might be opened in this high energy frontier. Among these energy scale, precise predictions by the perturbative calculations is crucial for the signal and background estimations because their event topologies become much complicate with increasing the colliding energy. We have carried on the automatic computation of the Feynman diagrams by GRACE [1] system since we immediately have a huge number of diagram calculation in multi-particle final state processes although we can, in principle, calculate them by hand based on their Lagrangian in perturbation theory.

GRACE has satisfied this requirement at one-loop level [2] in the electroweak interactions as well as at tree level and at the minimal supersymmetric extension of the Standard Model (MSSM) [3]. Those development has been mostly aimed at applications to lepton collisions. The generated codes however are not directly applicable to hadron-collision interactions due to the presence of a parton distribution function (PDF). Also, a certain process in hadron collisions consists of lots of subprocesses by referring incoming partons in PDF or outgoing partons in jets. In current scheme, it leads much time for the diagram calculations. We clearly need an extended framework of the GRACE system for hadron collisions. Early extensions can be seen in [4] and [5].

In order to implement those features specific to hadron collisions, we have developed an extended framework, called GR@PPA (GRace At PP/Anti-p). The primary function of GR@PPA is to determine the initial and final state partons, *i.e.* their flavors and momenta in the incoming partons by referring to a PDF and the final state parton configuration if the process requires jets or decay products from massive bosons. Based on the GRACE output codes, GR@PPA calculates the cross section and generates unweighted parton-level events using BASES/SPRING [6] included in the GRACE system. The GR@PPA framework also includes an interface for a common data format (LHA) [7] with the common interface routines proposed at Les Houches Workshop on 2001[8]. To make the events realistic, the unweighted event data are passed through the showering-MC of PYTHIA [9] or HERWIG [10] which implements the initial- and final-state radiation, hadronization and decays and so forth.

Although the GR@PPA framework is not process-specific and can be applied to any other processes in hadron collisions using the output codes of the GRACE system[1], we also provide some primitive processes packed as a set of matrix element customized for this extension. At the moment, the selected processes are boson(s) plus n jets processes and $t\bar{t}$ plus m jets processes, where n(m) is accounted for up

[1]The extension of GRACE itself to the hadron collisions is under development.

to 4(1) jets. These processes are the most important background processes for the Higgs boson searches or the SUSY particle searches as well as the precise measurements for the understandings of multi-body particle dynamics. Our previous work, four bottom quark production processes (GR@PPA_4b [11]), is also included. The reasons why we also provide the particular processes apart from the benefit of the automatic Feynman diagram calculation by the GRACE system are followings. First, kinematical singularities in each process are cared with a proper treatment. Since the kinematics are optimized to be suitable for well-convergence behavior, one can get high efficiency to generate unweighted events without any care. This is immediately addressed to the program running speed which is critical for the large scale MC production. Second, it is easy to adopt the higher order calculations. In higher order calculations, the calculation procedure is normally process-specific. To avoid the negative weight in cancellation between virtual and loop correction, one requires the phase space points to be positive differential cross section. This feature is so difficult to generalize by the automatic Feynman diagram calculation. Once the customized matrix element for the NLO process is prepared [12], one can simply use it. Third, some extensions are possible only in the modification of the framework. For example, using an ability of C++ language, the GR@PPA generators will work in the C++ environment just by rewriting the framework by C++ but the others are still Fortran. This is minimum changes to wrap the Fortran code produced by the GRACE system. The parton shower algorithm, for example NLL parton shower [13], is also possible to implement by modifying the framework because the parton shower is not a process specific model. Note that the extended GRACE system for hadron collisions will work to provide a set of matrix elements apart from the GR@PPA framework at these point.

In this paper, we describe a symbolic treatment of the diagram calculation adopted in GR@PPA for hadron collisions in the next section. Some benchmark cross sections and program performances are presented in Section 3. Our numerical results were compared with several generators [14, 15, 16, 17]. We got a good agreement with them [18]. Finally, a summary is given in Section 4.

2 Extension of GRACE to $pp/p\bar{p}$ collisions

In hadron-hadron collision, a certain process consists of several incoherent subprocesses according to colliding partons in the hadrons. If the given process has a decay or a jet in the final state, the whole possible combinations of the outgoing partons are also taken into account for. The total cross section is thus expressed as a simple summation of those subprocesses in Eq.(1)

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

where $f_i^a(x_a, Q^2)$ is a PDF of the hadron a (p or $\bar{p}$), which gives the probability to find the parton i with an energy fraction x_a at a 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 a 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. We had mainly 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 [11]. Here, we focus on the later case.

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 both in parton species and their momenta, in order to make the GRACE system applicable to hadron collisions. As already mentioned, a "process" of interest is usually composed of several incoherent subprocesses in hadron interactions. However, in many cases, the difference between the subprocesses is the difference in the quark combination in the initial and/or final states only. 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 subprocess. This technique simplifies the program code and saves the computing time very much.

The number of the combinations taken N out of M flavors allowing to overlap them, in general, is given by ${}_MH_N(\equiv \frac{(N+M-1)!}{N!(M-1)!})$. In case that all parton flavors are considered, $M = 11(u, d, c, s, b, g, \bar{u}, \bar{d}, \bar{c}, \bar{s}, \bar{b})$, then the configuration of the N jets final state has ${}_{11}H_N$ subprocesses if we neglect the conservation by total amount of charges of this subprocess. Clearly we can see that smaller M decreases the number of subprocesses. Unless the flavor difference is taken account in the process, the flavor configurations can be replaced by a generic up-type, down-type parton, and gluon (${}_5H_N \ll {}_{11}H_N$). The base-subprocesses are thus configured only as to have those partons and gluon. The output code of the matrix element from the GRACE system is extended to have a function of input masses and couplings, so that the masses and couplings are interchanged according to the assigned flavors. Note that each base-subprocess covers every possible combination of flavors. The diagram selection in the base-subprocesses thus allows to specify all subprocesses with a proper flavor configuration. In addition, since the Feynman diagrams within the process of Standard Model are symmetry with respect to the momentum (parity) and charge flip of the initial colliding partons in the CM frame of the process, the subprocesses can be reduced more. In Table 1, we list up the number of all possible base-subprocesses contributes in N jets process in $pp(\bar{p})$ collisions together with that of the subprocesses counted for all flavor combinations. The subprocesses are classified according to the difference in the initial-state parton combination. That is, the initial parton combinations in the base-subprocesses are $q_uq_u(\bar{q}_d\bar{q}_d)$, $q_u\bar{q}_d$, $q_ug(\bar{q}_dg)$, q_uq_d, $q_u\bar{q}_u(q_d\bar{q}_d)$, gg, where $q_u(q_d)$ and g is up(down)-type quarks, and gluon, respectively. We take them all positive side.

The integration of Eq.(1) has a weight factor for each subprocess. If a decay products from the resonance particles is separately taken account for the final state partons of N jets configuration, Eq.(2) can be rewritten as

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

where $d\hat{\sigma}^{selected}_{ij\to F}$ is the differential cross section of each subprocess with an input arguments of the masses and couplings. The matrix element is supplied by that of the base-subprocess. Based on the initial and final state parton configuration, the graph selection is applied to this base-subprocess, and masses and couplings are given in the diagram calculation event by event. The $w_{i,j,F}$ is a weight factor for the initial and final state parton configuration, and can be expressed as

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

where an index K and L is the number of W and X bosons, respectively. A PDF is responsible for the weight of the initial state parton configuration, and a squared coupling normalized by that of the base-subprocess is responsible for the weight of the final state parton configuration. Note that the square of the CKM (Cabibbo-Kobayashi-Maskawa) [19] matrix parameter remains after normalization of the coupling of the base-subprocess depending on the number of the W bosons K. If the X boson presents in the Feynman diagrams and decay into F' without interference with the other partons, where F' is a member of the final state particles, then the fraction of the decay is used as the weight factor. The branching ratio and total width may be given by the experimental measured one.

3 Results

The total cross sections estimated by GR@PPA are presented in Table 2 for the single boson plus jets productions and Table 3 for the double bosons plus jets productions, respectively, where all bosons decay into electron and positron (e^+e^-) or electron(positron) and (anti-)electron-neutrino ($e\nu_e$). Both are shown with the cases of Tevatron Run-II ($p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV) and LHC (pp collisions at $\sqrt{s} = 14$ TeV) conditions with CTEQ5L [20] PDF. The renormalization and factorization scales (Q^2) are chosen to be identical, and those values are taken as the squared boson mass for the single boson productions and the summation of squared boson masses for the double bosons productions processes. The cuts are only applied for the final state partons (jets), with the values of $p_T > 8.0$ GeV, $|\eta| < 3.0$, and ΔR > 0.4 for Tevatron, and $p_T > 20$ GeV, $|\eta| < 3.0$, and ΔR > 0.4 for LHC conditions, but no cut is applied for leptons from bosons. The integration accuracy achieved in BASES is fairly better than 1% for all processes with the default settings of the mapping number for the integrations.

The performance of GR@PPA for the W + N jets processes in Tevatron Run-II condition is also summarized in Table 4. Used processor is Intel Xeon 3.4 GHz processor. Tests are performed by two different Fortran compilers: a free software of g77 ver.2.96 and a commercial compiler of Intel Fortran Compiler ver.8.0. The integration time and the generation speed are separately shown. Clearly, the commercial compiler is $\sim$ 2.5 faster than the free compiler, but in both cases, those are not intolerable time for the large scale Monte Carlo production. The generation efficiencies by SPRING are also shown. These are within an order of a few percent for most of the processes. These numbers are exceptionally good for this kind of complicated processes.

4 Summary

We have developed an extended framework, named GR@PPA, of the GRACE system for hadron collisions. We have introduced the scheme to share some subprocesses as a single subprocess. We found that this extension allows us to incorporate the variation in the initial and final states parton configurations into the GRACE system. The results for some processes with multi-parton configurations are presented, and we found that the computing time for the diagram calculations is drastically reduced to be compared with the original GRACE system which assumes that both the initial and final states are well-defined and the integration is performed for every each subprocess. Using this faculty of GR@PPA, we expect that the event generator is suitable not only for a large scale Monte Carlo production at high luminosity hadron colliders of Tevatron or LHC, but also for future NLO calculations which is also composed of lots of subprocesses.

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

Table 1: Number of all possible base-subprocesses contributes in N jets process in $pp(\bar{p})$ collisions together with one of the subprocesses counted for all flavor combinations. The subprocesses are classified according to the difference in the initial-state parton combination.

	N jets	0	1	2	3	4
Tevatron	$W(e\nu_e)$ +	2040(1)	696.0(6)	237.2(3)	77.8(1)	27.12(6)
($\sqrt{s}$ = 1.96 TeV)	$Z(e^+e^-)$ +	1222(2)	174.9(3)	57.8(1)	17.26(3)	7.5(1)
LHC	$W(e\nu_e)$ +	17892(12)	3949(3)	1607(2)	682(2)	316(1)
($\sqrt{s}$ = 14 TeV)	$Z(e^+e^-)$ +	7208(12)	609(1)	278.0(5)	105.1(3)	64.0(4)

Table 2: The total cross section (pb) for the single boson plus jets productions estimated by GR@PPA, where all bosons decay into electron and positron (e^+e^-) or electron(positron) and (anti-)electron-neutrino ($e\nu_e$). Results are presented for the cases of Tevatron Run-II ($p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV) and LHC (pp collisions at $\sqrt{s}$ = 14 TeV) with CTEQ5L. The renormalization and factorization scales are chosen to be identical, and those values are taken as the squared boson mass. The cuts are only applied for the final state partons (jets), with the values of p_T > 8.0 GeV, $|\eta|$ < 3.0, and ΔR > 0.4 for Tevatron, and p_T > 20 GeV, $|\eta|$ < 3.0, and ΔR > 0.4 for LHC conditions, but no cut is applied for leptons from the boson.

	N jets	0	1	2
Tevatron	$W^+(e^+\nu_e)W^-(e^-\bar{\nu_e})$ +	109.1(2)	60.31(9)	31.45(9)
($\sqrt{s} = 1.96$ TeV)	$Z(e^+e^-)Z(e^+e^-)$ +	4.932(7)	2.295(3)	0.895(1)
	$Z(e^+e^-)W(e\nu_e)$ +	17.85(3)	10.40(2)	4.61(1)
LHC	$W^+(e^+\nu_e)W^-(e^-\bar{\nu_e})$ +	1425(4)	906(2)	2680(3)
($\sqrt{s} = 14$ TeV)	$Z(e^+e^-)Z(e^+e^-)$ +	44.89(7)	18.25(3)	9.74(1)
	$Z(e^+e^-)W(e\nu_e)$ +	186.7(3)	449.3(8)	367(1)

Table 3: The total cross section (fb) for the double bosons plus jets productions estimated by GR@PPA, where all bosons decay into electron and positron (e^+e^-) or electron(positron) and (anti-)electron-neutrino ($e\nu_e$). Results are presented for the cases of Tevatron Run-II ($p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV) and LHC (pp collisions at $\sqrt{s} = 14$ TeV) with CTEQ5L. The renormalization and factorization scales are chosen to be identical, and those values are taken as the summation of the squared boson masses. The cuts are only applied for the final state partons (jets), with the values of $p_T > 8.0$ GeV, $|\eta| < 3.0$, and $\Delta\mathrm{R} > 0.4$ for Tevatron, and $p_T > 20$ GeV, $|\eta| < 3.0$, and $\Delta\mathrm{R} > 0.4$ for LHC conditions, but no cut is applied for leptons from the boson.

Process	Fortran Compiler	Integration time (H:M:Sec)	Event Generation speed (events/sec)	Efficiency (%)
$W(e\nu_e)$ + 0 jet	g77	0:0:4.88	43859	69.618
	intel 8.0	0:0:1.80	101010	
$W(e\nu_e)$ + 1 jet	g77	0:0:51.81	13927	19.891
	intel 8.0	0:0:19.15	34364	
$W(e\nu_e)$ + 2 jets	g77	0:38:26.66	708.5	1.731
	intel 8.0	0:13:52.38	1956.5	
$W(e\nu_e)$ + 3 jets	g77	14:03:46.35	17.99	0.283
	intel 8.0	04:57:49.50	51.65	

Table 4: Performance of GR@PPA for the W + N jets processes in Tevatron Run-II condition. Used processor is Intel Xeon 3.4 GHz processor. Tests are performed by two different Fortran compilers: a free software of g77 ver.2.96 and a commercial compiler of Intel Fortran Compiler ver.8.0. The integration time and the generation speed are separately shown. The generation efficiencies by SPRING are also shown.