Automatic Amplitude Calculation and Event Generation for Collider Physics: GRACE and CompHEP

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Abstract

A brief description of the major issues that modern event generators have to address is presented. New collider physics call for multi-process full fledged event generators for high multiplicity final state processes whose analytic matrix element expressions are usually quite involved. Automatic amplitude generators like GRACE and COMPHEP are geared to produce complete matrix element code and tools for building event generators. Merging, hence generated multi-parton events or even the matrix elements them-selves with the QCD machinery of the parton shower Monte-Carlo packages (PYTHIA, HERWIG or ISAJET) is presented as a practical solution. Matrix element code generators are not limited to the Standard Model and tree level computation. Extended Standard Model Lagrangians have been introduced, including the full minimal supersymmetry model (MSSM). New physics models can be easily probed thanks to the LanHEP symbolic calculation program deriving Feynman rules and couplings directly from the Lagrangian expression. One-loop corrections implemented in the GRACE package are being extensively tested. Recent developments as well as applications to collider physics are discussed

1 Introduction

New physics results in high energy physics research, nowadays, are obtained from a detailed comparison of experimental and simulated data. The event generation is the first link of the event simulation/reconstruction software suite. It is meant to embed all known physics effects taking place when two particles collide including the model dependent hard interaction between elementary partons/leptons. The physics model, hence tested against real data, can be validated or rejected. For a given experiment, a large number of process must be simulated, not only the sought after "signals" but also all "background" processes which may hide or dilute the genuine effects. Higher center of mass energy, larger luminosity, extensions to the Standard Model (SM), all contribute to dramatically increase the number of process calculations as well as the computational complexity and precision of each parton level interaction. At LEP, the basic study of W/Z pair productions has led to the computation of 76 4-fermion final states where some processes had more than 100 diagrams. For upcoming collider physics, orders of magnitude larger computational complexity have to be faced. Supersymmetric model processes exhibit, through their 3 body decay, high multiplicity final state (6-fermion or more) to be computed with precision and for which numerous multi-parton background SM final state must also be evaluated. Initial/final state radiation corrections lead to even more final state partons, helicity/color correlations and mass effects, to more complex matrix elements (ME). At hadron and photon colliders, the initial state particles are composite increasing furthermore the number of elementary processes and leading to the introduction of parton distribution functions. High luminosity, QCD scale dependence and the Higgs production put more constraints on the required computational precision and often 1-loop when not 2-loop corrections must be performed.

1.1 The general automatic approach

The need to automate the various calculation stages all the way to the event generator code is now firmly established. Hopefully automation procedures have been developed since more than ten years [1] and computer programs are now ready to fulfill part of the theorist and experimentalist needs. However, the generalization of these techniques to new physics models and the new experimental computing environment require some deep upgrading when not complete rewritings for a better flexibility and human interface.
A complete automatic approach would mean to cover all the calculation stages from the definition of the group symmetries and particle fields down to the event generation. The major steps would be *(a)* the

introduction of the supersymmetry and soft breaking to obtain the effective Lagrangian, *(b)* the derivation of the Feynman rules and couplings, *(c)* the generation of the matrix element of a given process, *(d)* the cross-section evaluation and *(e)* the construction of the event generator. Step *(a)* is just undergoing a feasibility evaluation. All stages *(b)-(e)* are quite well supported for tree level processes. Step *(b)* is covered by the LanHEP [2] symbolic manipulation program. It produces the input files needed by the matrix element computation system as well as a human readable form in LaTeX for check and documentation (*e.g.* : the QCD Model, figure: 1). Stage *(c-e)* are available in package like GRACE [3], COMPHEP [4] or ALPHA [5].

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                QCD                                 %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
model QCD/2.

parameter        gg= 1.13 : 'Strong coupling'.

vector  G/G: (gluon, color c8, gauge).
spinor  q:(quark, color c3, mass Mq=0.02).

lterm  i*gg*f_SU3*ccghost(G)*G*deriv*ghost(G).

lterm Q*gamma*(i*deriv + gg*lambda*G)*q.

lterm -F**2/4  where
       F=deriv^mu*G^nu^a-deriv^nu*G^mu^a+i*gg*f_SU3^a^b^c*G^mu^b*G^nu^c.
```

LANHEP LATEX OUTPUT

P	aP	Name	Spin	Mass	Width	Color	Comment
$G_{\mu p}$	$G_{\nu q}$	gluon	1	0	0	8	gauge
q_{ap}	Q_{bq}	quark	1/2	Mq	0	3	

Fields in the vertex	Variational derivative of Lagrangian by fields
$G_{\mu p}$ $G_{\nu q}$ $G_{\rho r}$	$gg f_{pqr}\big(p_3^\nu g^{\mu\rho} - p_3^\mu g^{\nu\rho} + p_1^\rho g^{\mu\nu} - p_1^\nu g^{\mu\rho} - p_2^\rho g^{\mu\nu} + p_2^\mu g^{\nu\rho}\big)$
$G.C_p$ $G.c_q$ $G_{\mu r}$	$-gg \cdot p_2^\mu f_{pqr}$
Q_{ap} q_{bq} $G_{\mu r}$	$gg \cdot \gamma^\mu_{ab} \lambda^r_{pq}$
$G_{\mu p}$ $G_{\nu q}$ $G_{\rho r}$ $G_{\sigma s}$	$gg^2\big(g^{\mu\rho}g^{\nu\sigma}f_{pqt}f_{rst} - g^{\mu\sigma}g^{\nu\rho}f_{pqt}f_{rst} + g^{\mu\nu}g^{\rho\sigma}f_{prt}f_{qst}$
	$-g^{\mu\sigma}g^{\nu\rho}f_{prt}f_{qst} + g^{\mu\nu}g^{\rho\sigma}f_{pst}f_{qrt} - g^{\mu\rho}g^{\nu\sigma}f_{pst}f_{qrt}\big)$

Figure 1: QCD model in LanHEP

1.2 Matrix element generation and cross-section computation

From LANHEP output or from hand written equivalent files, the COMPHEP [4] and GRACE [3] packages will generate the Fortran code for the amplitude calculation of any given tree level parton interaction. Two different approaches are followed. In the current version of CompHEP, the diagrams are squared and after some symbolic trace calculation, the matrix element is generated in a quite compact and numerically efficient form. However, the size of the expression increases as the number of diagrams squared introducing some computational limitation (memory and computing time) on the process complexity. GRACE follows the helicity amplitude method where the size of the matrix element remains proportional to the number of diagrams. Finally, the matrix element is integrated over the phase space to produce cross-sections and events can be generated either with their own weight or with a normalized constant weight. This last step is the one which requires most of the attention of the physicist as the multi-dimensional integration algorithm should tame the sharp singularities and reduce the dimension of possible multi-dimensional divergences. Failing to provide the right variable transforms may end up to a non convergent integration or worst, to wrong results. In CompHEP, attempts have been made to perform the appropriate variable transforms, but more developments are needed to fully automate this procedure in particular when dealing with variable particle mass.

1.3 Event generation

An event generator is built from various pieces whose object and nature are quite different. Some are perturbative: the hard scattering matrix element (ME) which can be calculated exactly, the parton shower (PS) which approximate, through the evolution equations, the initial parton conditions and final state jet structure, and some are non-perturbative and probabilistic like the parton distribution in the composite initial particles and the fragmentation of the final partons. The main difficulty in writing event generator programs lies on the consistent matching of those different components. If specific packages implementing all those effects, the so-called parton shower event generator (PSEG) are available (Pythia [6], Herwig [7,8], Isajet [9], a sound interface with multi-parton matrix element remains to be properly implemented.
In SM extensions (SUGRA, GMSB), particle masses and couplings depend on the value given to the model basic parameters in contrast with the SM where they are known from experimental measurements. Several general programs [9–11] have been developed to automate the mass spectrum computation with various level of precision and computation efficiency. MUSE [11] is one of those fast and high precision code interfaced to the GRACE package.

1.4 Pro's and Con's of the automatic approach

The automation of the various steps involved in the full computation of a given process in a given model, beside the simple feasibility issue encountered with the "manual" approach for complex processes, brings additional benefits. It provides a complete calculation including all diagrams without approximation. For example, calculations can be performed which account for fermion mass and helicity correlation. As long as the procedure is well tested, the occurrence of mere calculation mistake is null. Furthermore gauge invariance and gauge independence checks are automatically performed to the highest machine precision. Comparison of the results given by the two independent packages is also a powerful tool for insuring accurate results. Computation involving thousands of Feynman diagrams can be undertaken using this technique.

The price to pay is an heavy load on computer resources. High precision floating point computations are needed to treat the singularity cancellations often found in the multi-dimensional integration. The produced matrix element code is not yet as compact and optimized as the one produced by hand calculations, therefore the cross-section numerical calculation or the event generation is intrinsically longer. In some package based on the symbolic computation of the matrix element, the building of the matrix element code can be quite involved and the complexity of the process can be limited by the computation time and the temporary intermediate storage needed. Even for the purely numerical matrix element code the amount of computer memory needed can over-pass the available physical computer memory slowing down furthermore the integration procedure.

Several improvements are being developed to cope with those issues. Massive parallelism has been implemented for the GRACE system, both for the integration and the event generation part [12]. Graph selection and optional approximation can also be implemented at the code generation level but here an estimate of the actual error introduced is made possible as the full computation is always available. Advanced techniques of multi-dimensional integration and matrix element code optimization are also under development. Finally the steady increase of the performance/price ratio of the computers over these last years give us hope to carry over even the most involved computations.

2 LHC Physics

Let's first illustrate the preceding discussion by listing the major points of concern or pending issues in the development of event generators for the LHC physics. pp and $\gamma\gamma$ colliders are probably the most demanding environment for event generators due to the composite nature of the initial particles. We will therefore go a bit more in detail on each item of this list. Figure 2 shows a typical LHC event and gives some feeling about the complexity of the simulation task.

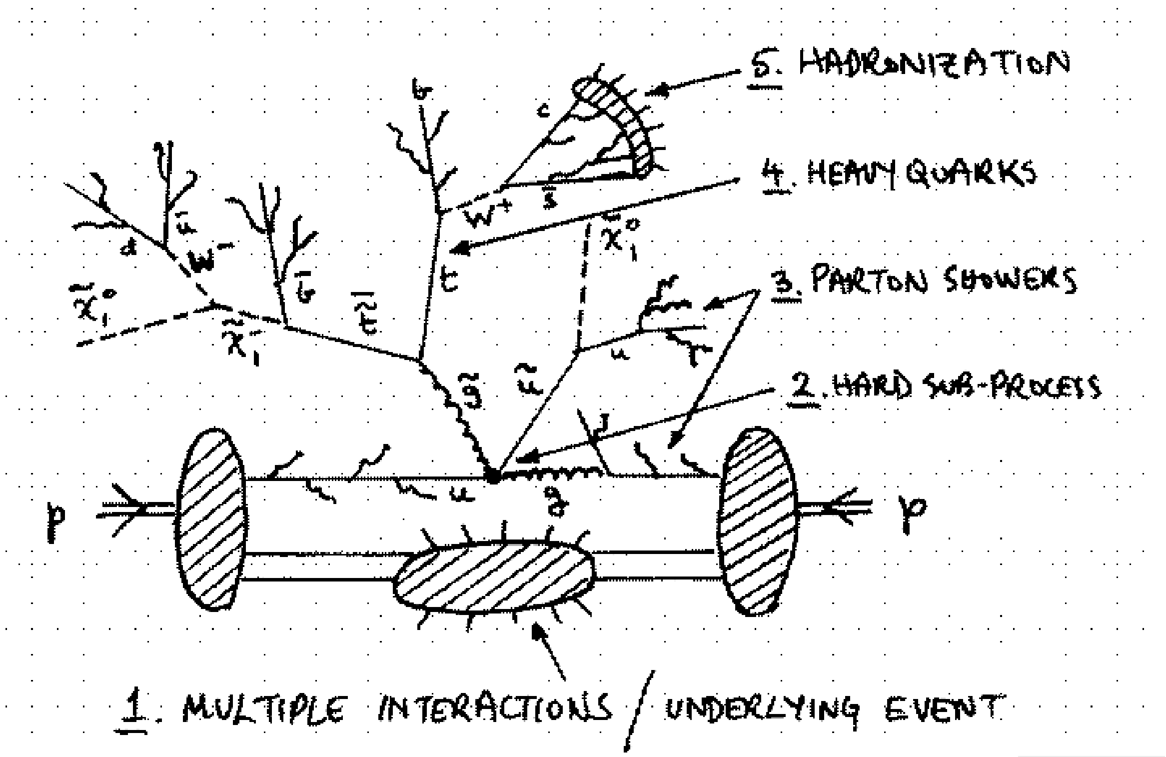

Figure 2: Artistic view of a pp interaction [13]

2.1 Structure functions, parton distributions

The most obvious complication as regarding e^+e^- colliders is the non-elementary status of the proton, the initial state particles. For a given process, it implies the evaluation of several different initial state combinations all contributing to the specified final state. The probability that a proton interacts through a given parton (quarks or gluon) is parameterized by the parton distribution functions depending on two parameters x and Q^2, where x is the proton energy fraction carried by the parton and Q^2 a process dependent energy scale. For the 2 initial partons, the phase-space integration gets 2 additional dimensions (the x of the two partons). The implementation of some parton distributions has already been performed in CompHEP, but it misses the implementation of color/helicity correlations and other initial state effects like ISR and multiple particle interaction.

2.2 Multi-particle final states

2.2.1 Matrix element

PSEG are essentially limited to the simulation of $2 \to 2$ processes[1] based on analytic matrix element expressions. However, the LHC center of mass energy is large enough to open many high multiplicity channels. In addition, new particle searches in the Higgs and Susy sectors require the simulation of $2 \to 4$, $2 \to 6$ or even $2 \to 10$ jet processes[2] for which a precise knowledge of the standard model (SM) background processes is mandatory.

QCD multi-jets events $pp \to n_1$ jets and $pp \to Z/W + n_2$ jets have been computed at lowest order, for $n_1 \leq 6$ assuming all helicity amplitudes give similar contributions (SPHEL approximation) [14] and, using recursion relations [17], for $n_1 \leq 6$ (NJETS [15] and $n_2 \leq 4$ (VECBOS) [16].

In the PSEG, multi-parton final states are mimicked through the PS mechanism based on the leading logarithmic (LL) approximation. It properly describes parton radiations only in the soft and collinear region leading to a crude estimate of the transverse behavior of the event. The remedy for a better multi-parton event generator is two-fold, (*i*) to improve the simulation of the parton shower by introducing ME corrections, (*ii*) to implement the complete multi-parton hard scattering ME process.

The evaluation of ME for multi-particle QCD processes has been reviewed in [18]. A powerful technique is the use of helicity amplitudes in the massless limit [19]. Recent developments in this direction was done in [20] where the Weyl-van-der-Waarden spinor calculus was generalized to the massive fermions. At this level of complexity where so many sub-processes must be calculated, the analytic hand-made approach becomes literally intractable unless stringent approximations are imposed like the narrow width approximation, massless fermions, averaging/summing over initial/final helicity state or selecting only a subset of gauge invariant diagrams.

A more systematic approach is needed: (*i*) to provide all required channels, (*ii*) to allow for a detail study of finite width effects and helicity and color correlations (*iii*) to generate complete ME expressions in order to match the experimental precision. For example, the LHC statistics will allow to measure the top quark mass with accuracy about 1%. This implies that both top quark and W finite widths must be taken into account in the evaluation of the interference between signal and background diagrams.

The automatic Feynman diagram generator packages, largely used for the e^+e^- physics analysis, generate complete and approximation free tree level ME codes, in principle, for any final state multiplicity and with a higher reliability level than hand written procedures[3]. They are gradually upgraded to the pp physics. GRACE [3], MADGRAPH [21], ALPHA [5] and PHACT [22] are based on tree level helicity amplitude algorithms in arbitrary massive gauge theories. The evaluation is purely numerical and the code size scales linearly with the number of external particles. In ALPHA, an iterative algorithm, based on Green functional methods, evaluates the amplitudes for any given Lagrangian and leads to more compact expressions allowing, for example, the generation of $gg/q\bar{q} \to n$ with $n \leq 9$ [23]. The COMPHEP [4] package is based on the squared amplitude technique. Here, the size of the ME code grows exponentially with the number of external particles, but it produces more powerful symbolic expressions. This method has shown good efficiency for the evaluation $2 \to 3, 4$ processes, comparable to the helicity amplitude algorithms. Using COMPHEP the complete calculation of the $Wb\bar{b}$ and $Wb\bar{b}$ + jet for the Tevatron and LHC has allow the study of possible anomalous Wtb couplings [24] (figure 3).

2.2.2 Multi-dimensional Integration

The cross-section computation and the event generation stage are based on the multi-dimensional integration procedure. It needs to be focused to the phase space region where the amplitude is large. The amplitude behavior on those regions can be sharp and multi-variate due to complex singularity patterns. Integration packages including VEGAS [25], BASES/SPRING [26], MILXY [27], FOAM [28] use self-adapting techniques based on *importance* and/or *stratified sampling*. However, a faster integration convergence is obtained by providing the integration algorithm with information on the location and

[1] $n \to m$ represents processes where n initial particle(s) decays or scatter to produce m particles in the final state.

[2] In R-parity non-conserving models

[3] The packages automatically generate checks for gauge invariance and gauge independence.

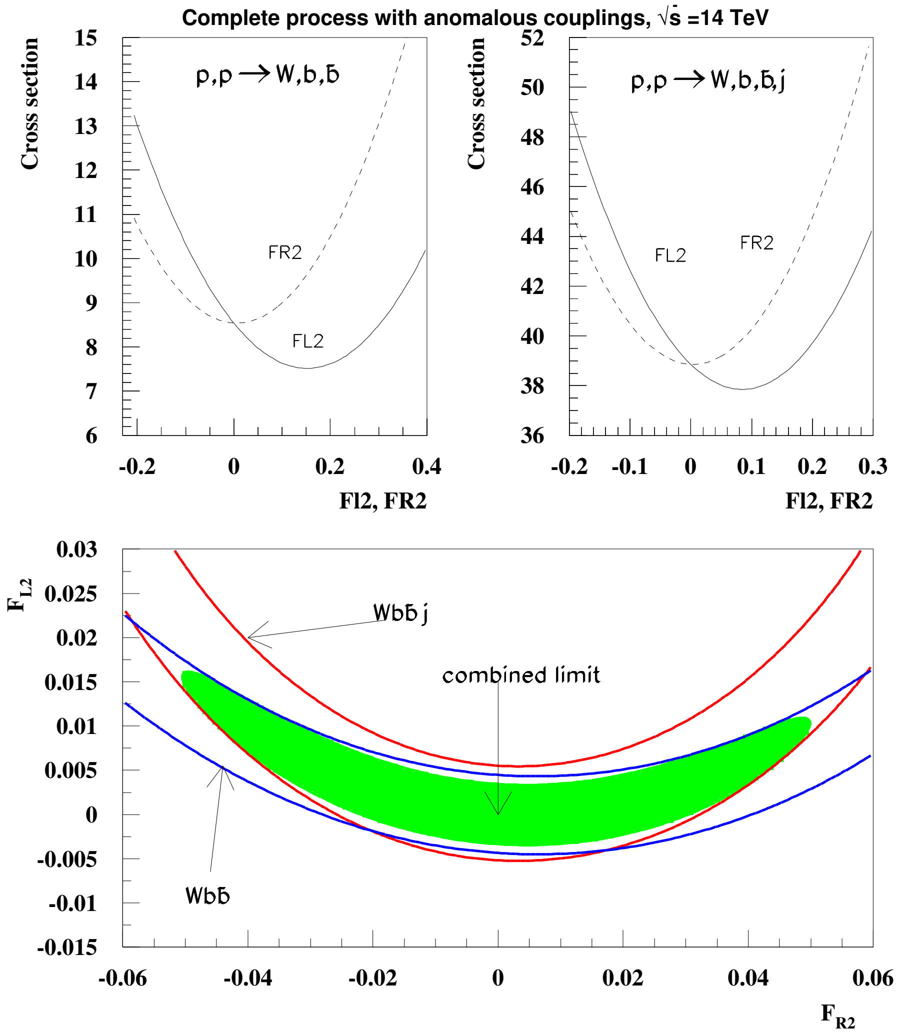

Figure 3: $pp \to Wb\bar{b}$ and $pp \to Wb\bar{b} + jet$ Cross-sections at $\sqrt{s} = 14$ TeV after optimized cuts and corresponding limits on the anomalous couplings F_2^L and F_2^R of the Wtb couplings at LHC (100 fb^{-1}).

behavior of the singularities. This is usually done by the so-called "kinematics" routine performing the mapping of the integration variables to the physics parameters. Not yet fully automated [29], it is aiming by appropriate variable transforms at smoothing the singularities and reducing their dimensionality.

For many important processes, it is impossible to match all singularities within a single set of variable transforms (*e.g.* . $pp \to u\bar{u}d\bar{d}$ with W,Z decays and t-channel singularities). In those cases, one relies on a *multichannel* algorithm [30, 31] where each peaking structure has its own appropriate mapping.

2.2.3 Interface to the PSEG package

The implementation of automatically produced hard process ME in PSEG is a delicate but essential task to benefit from the implementation of the complex QCD machinery reproducing the initial and final states.

The ultimate goal is to embed the full ME with its appropriate kinematics mapping into the kernel of the PSEG through some automated procedure. Although some progress has been achieved toward this end, a simpler approach is to generate parton level event sample using a program dedicated to a given ME, then let them fragment through the parton shower and hadronization scheme of the selected

PSEG. For example, in PYTHIA the routines PYUPIN and PYUPEV are available for the implementation of externally produced event processes. Similar facilities exist or can be implemented in other PSEG. This technique already used by the LHC experiments may raise consistent parameter and parton distribution bookkeeping issues.

2.3 Heavy quark production and parton shower

Keeping the fermion masses at their on-shell value, although making the expressions more complex, is always a good practice to get rid of the propagator pole divergence. At LHC, from a phenomenological point of view, light u,d and s quark masses can be neglected, but heavy c,b and t quark should be implemented not only to reproduce threshold effects, but also for a correct treatment of spin correlation and NLO corrections. Beside the basic t-quark physics studies, the heavy quark event generation plays an important role as the dominant background to the Higgs search ($W/Zb\bar{b}$, $t\bar{t}+2jets$ and $t\bar{t}t\bar{t}$, $b\bar{b}b\bar{b}$, $b\bar{b}t\bar{t}$). Those computations require the use of multi-particle massive ME as developed in the automatic approach.

The simulation of the parton shower developed by a massive quark is similar to the massless case above an angular cut-off of $\theta = m_q/E_q$, while below no radiation is emitted. This is true only in the soft and collinear region, if the physics observable is sensitive to high-p_t effects (*e.g.* top mass reconstruction) full massive radiative heavy quark decay matrix element (i.e. $t \to bWg$) must be embedded in the parton shower code [32, 33]

2.4 Color and helicity implementation

Color and spin effects are important at LHC. Color correlations beside driving the fragmentation of partons lead to color reconnection effects acting on the local event multiplicity. Spin effects in the top physics, for example, provide a useful handle on the nature of the couplings [34].

The procedure to assign helicity and color to the initial/final partons requires similar implementations in an event generator. For $2 \to 2$ processes, the number of possible color flows is small and can be handled easily through an overall factor for the single diagram case and through a slightly more elaborated treatment when dealing with the interference of 2 diagrams with different color flows [35]. For higher multiplicity [36], in the super-symmetric QCD [37] and in the R-parity violated processes [38], the selection of the color final state is more involved. In the helicity amplitude approach, each diagram must be decomposed over a color flow reference base. The cross-sections for all possible color/helicity combinations ($8^{n_g} \times 3^{n_q} \times 2^{n_g+n_q}$) are then evaluated. Adding more final state particles drastically increases the number of cross-section computations.

2.5 NLO, NNLO corrections

In QCD, talking about corrections concerning the next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) contributions is an understatement. Higher order computations are very important not only due to the rather large coupling constant α_s inducing substantial corrections but mainly because they reduce the renormalization and factorization scales dependence (*e.g.* $\sigma_{NLO} = 1.5\ \sigma_{LO}$ for the inclusive channel $pp \to H \to \gamma\gamma + X$, most promising for the light Higgs discovery). Furthermore, analysis or experimental cut dependencies (like y_{min} in jet analysis) are better reproduced when higher order corrections are included. Roughly speaking if one can say that NLO is the first order giving a sensible perturbative result, NNLO can be seen as the error estimate on this result.

In principle, computing NLO matrix elements is straightforward using loop integral reduction techniques, but the number of involved diagrams and their complexity have lead to the development of automatic coding programs like FeynArt/FeynCalc Formcalc/Looptools [39, 40] or GRACE. The latter is geared to provide 1-loop n-body final state ME while, in practice, a maximum of $n = 4$ and further approximations are imposed by computational limitations.

But the main problem lies in the cancellation of soft and collinear infinities present at NLO precision. Fully inclusive computations generate the so-called K-factor as a global scaling factor, but detailed analyzes need phase space dependent corrections. Two techniques have been developed to handle the cancellations: the phase space slicing method [41] and the subtraction scheme [42, 43]. In the former, the cancellation is performed by integration within a given cut-off related to the experimental jet resolution, in the latter the divergent terms are replaced by an approximated analytically integrable expression plus its finite difference with the exact expression. For these two approaches, Monte-Carlo integration techniques are used, allowing for a precise implementation of the experimental cuts. Those programs can be seen as "pseudo-event generators". Phase space points (pseudo-events) after being tested against the cuts have their corresponding weights accumulated to form the observable. Single or multi differential distributions can be built in one go. But two issues prevent the use of these packages as true event generators: *(i)* the handling of negative weighted events and *(ii)* the interface to the LO parton shower and fragmentation stage. No definite scheme currently exists to properly implement LO+NLO processes in a stochastic event generator.

The negative weighted events arise from the virtual corrections canceling the soft and collinear divergences. Several attempts are on trial.

One approach is to treat those events as the usual positive weighted events and to observe the cancellation only after the reconstruction stage where the experimental resolution will have introduced a natural cut-off. This implies the generation, the simulation and the reconstruction of many events which finally cancel, not contributing to the statistical significance and therefore leads to unstable results. More advanced attempts have been based on a re-weighting of event generated by showering from the LO matrix elements [44–49]. Recently, a modified subtraction method is exercised to built NLO event generators [50, 51] by point-by-point cancellation of the singularities. This approach looks quite encouraging although final implementations have not been realized yet.

The second problem is the matching of a NLO ME to the parton shower. A consistent approach would be to interface a NLO ME to next-to-leading log order (NLL) parton shower, but not such algorithm exist yet (see section 2.6) and therefore one has to find the least damaging approach to connect NLO ME and LL PS and final hadronization. Basically the ordered evolution PS variable should be matched to the ME regularization. Remaining double counting effects will be removed by the rejection algorithm for each event topology [50].

2.6 Parton shower

In hadronic collision, the parton showering occurs both in the initial and in the final state. In the latter, the high virtuality partons are evoluted using the DGLAP [52] equations down to quasi-real objects ready to undergo final hadronization. The initial partons selected from the parton distribution functions have a relative energy (x) and virtuality (Q^2) follow a backward evolution [35, 53] will bring back the virtuality down to value compatible with the confinement of partons in a fast hadron (cloud of quasi-real particles). In this process, gluons and quarks are emitted (absorbed in the backward evolution time frame) by quark radiation or gluon splitting. This radiation contributes to the final state multiplicity (beam remnants). In addition, the parton acquires a transverse momentum and the full kinematic of the initial CM of the hard scattering will be uniquely defined.

The parton shower model implemented in the PSEG is essentially a LL approximation, even if some next-to-leading log (NLL) corrections have been added through exact energy-momentum conservation, angular ordering and optimal scale choice for α_S [55]. The dominant logarithmic singularities are resummed in the Sudakov parameters.

As seen in the previous section, the need for a NLL parton shower is high. The problem is that resumming higher order correction breaks one major "raison d'être" of the parton shower: the universality. At leading log level, the hard scattering and the parton showering are 2 independent processes (factorization between the short an the long range) and the success of the PSEG is based on this feature. Incorporating higher order corrections may break universality and each type of hard scattering process may require a specific NLL PS evaluation.

2.7 Multi-parton scattering

Up to now, the Monte Carlo event generators for rare events usually include single scattering processes only. At the LHC we expect, due to unitary bound, multi-parton interactions to give important contributions in several processes [56, 57]. As an example the cross section for the production of four jets with double parton collisions dominates the single scattering process when the minimum of the transverse momenta of the produced jets is $p_{t_{min}} < 20\,\mathrm{GeV}$.

In [56], it has been pointed out that double parton collisions constitute an important source of background to Higgs boson production in the $b\bar{b}$ channel and similar effects are expected in many other processes like production of $W/Z + jets$, $W/Zb\bar{b}$, $b\bar{b} + jets$, etc. It is rather simple to include the double parton scattering in a Monte Carlo. In the hypothesis of no correlation, the double parton inclusive cross section has a simple factorized expression

$$\sigma_D(AB) = \frac{\sigma_A \sigma_B}{\sigma_{eff}} \tag{1}$$

It has been assumed that σ_{eff} is independent on the different species of partons involved, on the c.m. energy of the hadronic collision and on the P_{tmin}. To evaluate the background to Higgs boson production, the value $\sigma_{eff} = 14.5$ mb has therefore been used, as measured by the CDF experiment. The calculation of the process $pp \to W(H \to b\bar{b})$ and of the background $Wb\bar{b}$, in a single and in double collision has been based on the packages MadGraph and HELAS [54] for the computation of matrix elements and on the Vegas routine for the integrations. The calculation of double parton scattering background is easier to perform than the single scattering contribution. In fact the W and $b\bar{b}$ pair are created in two distinct parton interactions and the number of integrations is consequently reduced.

[56] concludes that the double parton interactions are easy to incorporate in to the Monte Carlo and that these interactions are in many cases not negligible and need to be included in every realistic Monte Carlo event generator for LHC.

Finally, it should be noticed that although those computations were performed under the assumption that the initial partons undergoing the scattering were uncorrelated, the multi-parton scattering may provide insights on the dynamical structure of the hadrons [58] and therefore MC should be ready to reproduce transverse parton-parton correlation effects in hadrons.

3 Linear Collider Physics

The linear collider physics requirements are quite similar to what has been achieved for the LEP physics. Beside the beamstrahlung energy correction, all other initial/final state effects have already been implemented for the LEP physics. The matrix element interface to the PSEG is easier than for the pp physics due to the elementary nature of the electrons/positron. All issues related to the multi-parton production, the heavy quark ME, the color/helicity implementation or the parton shower have already been discussed in the preceding section. We will therefore list, here, the main developments made at LEP based on the Grace and the CompHEP packages.

3.1 Initial/final state radiations

Photon radiation from the initial state electron or from the final state parton are included in the event generators by either of two approaches. The structure function approximation simply corrects the particle energy according to the electron structure function. In event generator language, each electron/positron may emit a collinear photon whose energy is the total energy lost by radiation. A more advanced technique is based on the evolution equations from the renormalization group equation already used for the parton shower in QCD [52]. This more precise approximation has been coded in a package called QEDPS [59] and results in the production of n photons each with the proper angular distribution. Another approach leading to similar results has been developed following the YSF [60] technique and implemented in several generator [61].

At linear collider, the beam energy spectrum is degraded by the so-called beamstrahlung effect. Each electron/positron "feels" the electromagnetic field generated by the crossing bunches and may loose energy. This effect is independent from the hard scattering and therefore can be parameterized by an universal beam spectrum determined by the collider parameters only. Independent beamstrahlung packages (*e.g.* [62]) have been developed and interfaced to event generators.

$e^+e^- \to e^-\bar{\nu}_e u\bar{d}$ + ISR

Cuts	$\sqrt{s}(GeV)$		
	190	350	800
(1)Single W	1.055 $\pm$ 0.001	4.803 $\pm$ 0.005	15.97 $\pm$ 0.02
(2)Single W, Mq=0	1.074 $\pm$ 0.001	4.853 $\pm$ 0.005	16.11 $\pm$ 0.1
(1)-(2)/(2)	-1.7%	$-1.\%$	-0.8%

$e^+e^- \to e^-\bar{\nu}_e c\bar{s}$ + ISR

Cuts	$\sqrt{s}(GeV)$		
	190	350	800
(1)Single W	0.958 $\pm$ 0.001	4.585 $\pm$ 0.004	15.51 $\pm$ 0.01
(2)Single W, Mq=0	1.074 $\pm$ 0.001	4.853 $\pm$ 0.005	16.11 $\pm$ 0.1
(1)-(2)/(2)	-10.8%	-5.5%	-3.7%

Table 1: GRC4F: $e^+e^- \to e^-\bar{\nu}_e u\bar{d}$ + ISR and $e^+e^- \to e^-\bar{\nu}_e c\bar{s}$ + ISR parton level cross-sections ($\times 10^{-1} Pb$) for 3 center of mass energies Single W cuts: $E_{u,d} > 3$ GeV, $M_{ud} > 5$ GeV, $\theta_e < 4.43^o$. The last line of each table shows the relative decrease of the cross-section when fermion mass are taken into account.

3.2 4-fermion (γ)

All 4-fermion processes have been generated and assembled in a full fledged event generator (Grc4f [36] based on the GRACE) suitable for the LEP physics. Extensive comparisons have been performed with CompHEP and also with other massless event generator showing that massive matrix element based event generators are better suited for high precision measurement in sensitive phase space region as for the single W physics. Table 1 shows, for different center of mass energies, the fermion mass effects at the hard interaction parton level. An earlier work on radiative 4-fermion $e^+e^- \to e^-\bar{\nu}_e u\bar{d}\gamma$ in comparison with $e^+e^- \to e^-\bar{\nu}_e u\bar{d}, \bar{u}du\bar{d}$ had shown the importance of non-resonant diagrams [63].

3.3 Anomalous quartic couplings at LEP

The full C and P conserving anomalous quartic boson coupling expressions have been given as an input to the LanHEP package. All couplings needed for the LEP2 study of the $e^+e^- \to W^+W^-\gamma, Z\gamma\gamma$ processes were generated and the matrix elements produced by CompHEP. The GRACE kinematics, integration and event generation package did provide all anomalous parameter dependent distributions [64]. Figure 4 shows the sensitivity of the $e^+e^- \to W^+W^-\gamma$ cross-section to some of the 9 anomalous quartic parameters and some parameter correlations.

3.4 Beyond the Standard Model

The MSSM model has been implemented both in GRACE and CompHEP. In addition to the $2 \to 2$ basic and already available processes, all $2 \to 3$ and $2 \to 4$ process matrix elements have been generated and checked. A few of them have been gathered in the Susy23 [65] event generator. Spin effects play an important role in many Susy processes. In chargino pair production [66] strong spin and spin-spin correlations are seen (fig. 5) in the $\phi_{\chi^+}/\phi_{\chi^-}$ (chargino decay plane azimuthal angle) distribution when the full spin effects are included. It shows clearly that the diagonal spin correlation approximation does not reproduce correctly the effect.

3.5 Higher order corrections

Extensive checks are being currently performed on the loop extension of the GRACE package. The introduction of the non-linear gauge provides a sensible check of the results as well as a reduction of the number of effective diagrams. Specific one-loop processes have been reported, $e^+e^- \to t\bar{t}, HZ, WW$ or $WW \to t\bar{t}, ZH \to t\bar{t}, ...$ [67] where some processes have more than 350 diagrams. A detailed study of the radiative correction to $H^+ \to t\bar{b}$ [68] has shown good agreement with partial hand made calculations.

4 Muon Collider Physics

Among the many processes studied for the workshop using the GRACE system, the $Zb\bar{b}$ and $\mu^+\mu^-b\bar{b}$ final states are presented. Figure 6 shows the $b\bar{b}$ invariant mass distributions for $\ell^+\ell^- \to Zb\bar{b}$ where $\ell : e, \mu$. The Z peak is visible in both distributions, but the neutral Higgs peak (H_0, A_0) is only present. as expected, for muon initial states, reflecting the Higgs mass dependent coupling. Figure 7 shows that complete calculations can be carried out even for high multiplicity final state processes $(2 \to 4)$: $\mu^+\mu^- \to \mu^+\mu^-b\bar{b}$ where 556 diagrams are contributing.

5 Standardization and language issues

The availability of several independent event generation packages although aiming at similar scopes is a big advantage for the experimental community. It makes possible comparative checks and leads to a deeper understanding of the various approximations used and implementation dependent issues.

However, one must strongly stress that the definition of a common interface scheme between the event generators and the simulation/analysis experimental packages would be extremely valuable. Such a standardization would cover the following issues: (*i*) parameter naming convention (*ii*) parameter database management (*iii*) event output format (*iv*) event sample database.

Although the standardization scheme can already be exercised on the existing Fortran PSEG, it takes its full meaning with the current transition to the object oriented (OO) methodology. The maintenance issue[4] of those large and complex packages over the long expected lifetime of the LHC experiments is the main reason for using the OO technology, but the built-in object modularity opens the door to a finer grained standardization at least to the level of the interfaces of the main procedures (random number generator, diagram generation, diagram display, matrix element code, integrator, parton shower, fragmentation, structure functions). This would allow the building of event generators using procedures from various origins. Most of the PSEG package developers have endorsed C++ as the language for the future developments. Design and implementation studies are already in progress [69–71].

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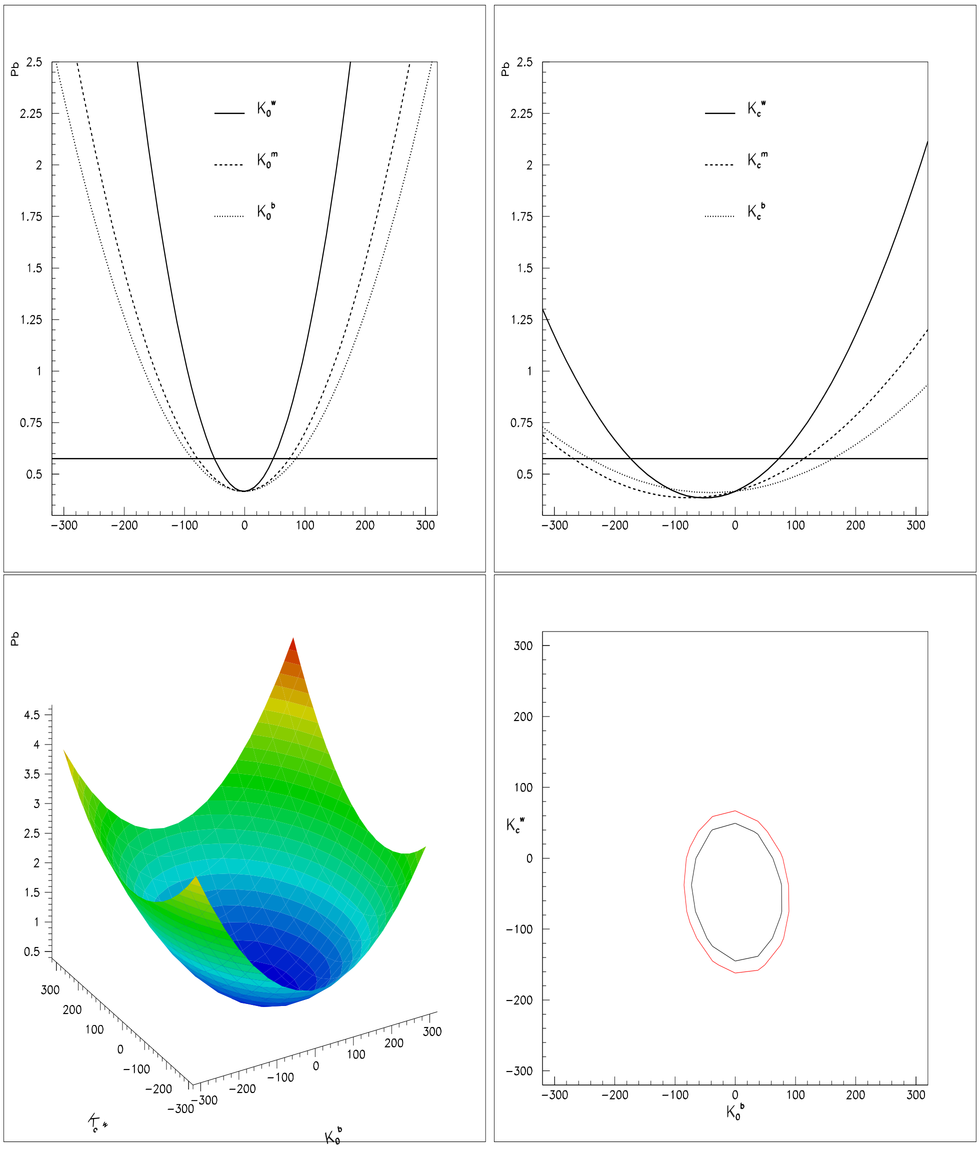


Figure 4: Dependence of the $e^+e^- \to W^+W^-\gamma$ cross section at $\sqrt{s} = 200$ GeV on the anomalous parameters a) k_0, b) k_c, c) bi-dimensional cross-section versus and d) $k^w_{1,2,3}$. For the cuts on the photon refer to the paper. The horizontal line indicates the 3σ increase of the cross section.

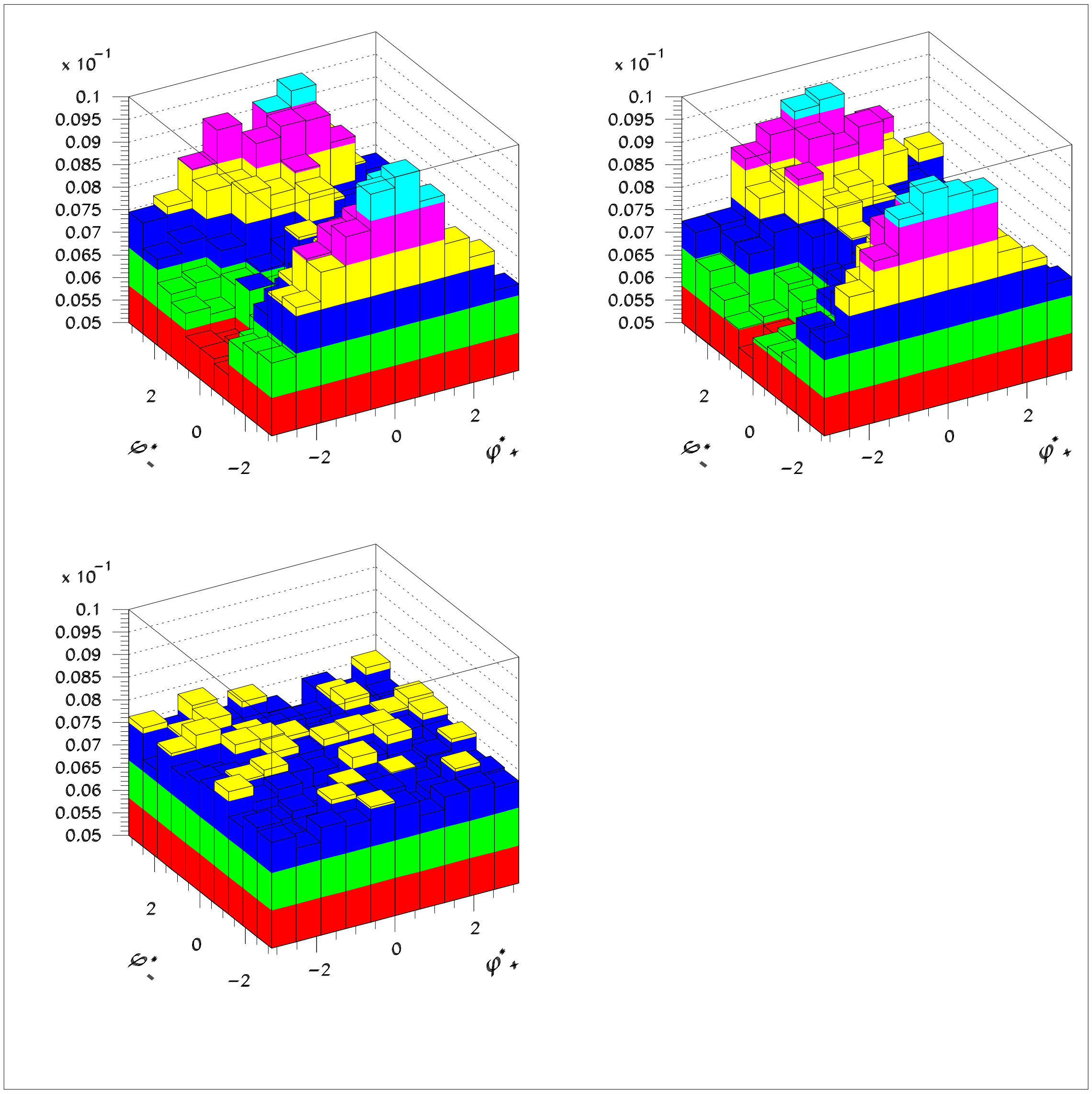
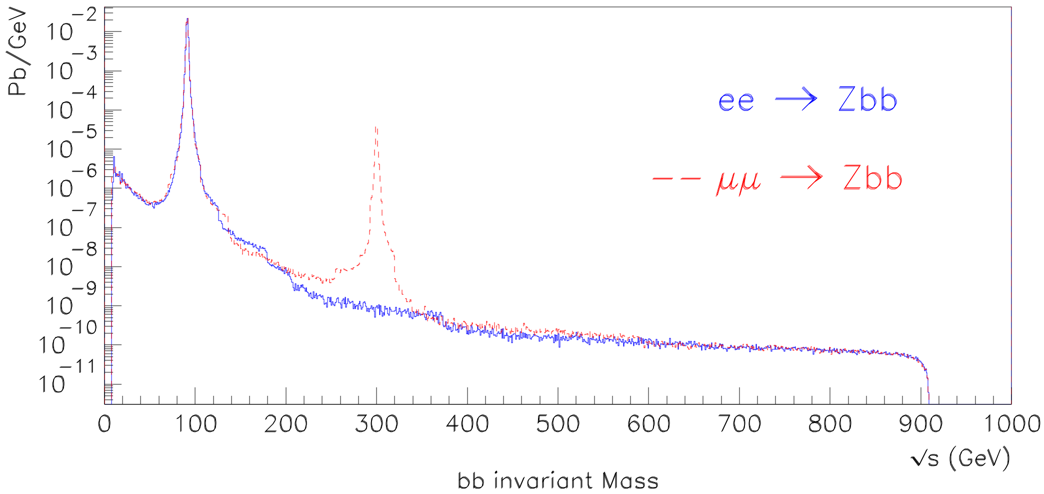


Figure 5: Chargino decay plane Azimuthal angle Correlations (light $\tilde{\nu}_e$, Gaugino type chargino, $\sqrt{s} = 250$ GeV) a) Top-left: Exact calculation of the 54 diagrams, b) Top-Right: Full-spin correlation in the narrow-width approximation c) Bottom-left: Diagonal spin correlation only



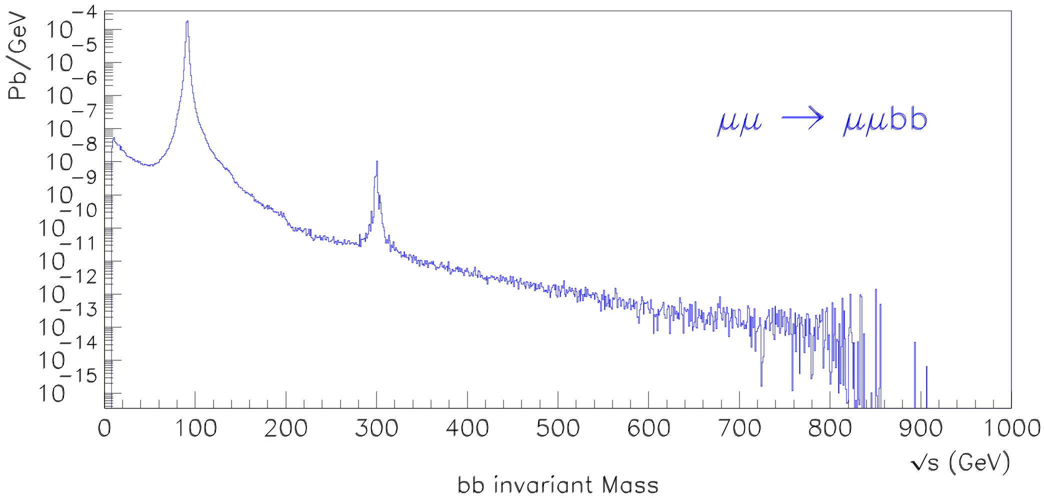


Figure 6: (top): $b\bar{b}$ invariant mass distribution for $\ell^+\ell^- \to Zb\bar{b}$, $\ell : e, \mu$, $\sqrt{s} = 1000$ GeV, $M_{H_0} \simeq M_{A_0} \simeq$ 300 GeV, $M_{h_0} \simeq M_{Z_0}$.

Figure 7: (bottom): $\mu^+\mu^- \to \mu^+\mu^- b\bar{b}$, with, in addition to Fig. 6 settings, $-0.985 \leq \cos\theta_\mu \leq 0.985$.