Automatic Generation of Tree Level Helicity Amplitudes

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Abstract

The program MadGraph is presented which automatically generates postscript Feynman diagrams and Fortran code to calculate arbitrary tree level helicity amplitudes by calling HELAS[1] subroutines. The program is written in Fortran and is available in Unix and VMS versions. MadGraph currently includes standard model interactions of QCD and QFD, but is easily modified to include additional models such as supersymmetry.

1. Introduction

Calculating tree level processes is fundamental to a large fraction of phenomenology done today. Although results for most interesting tree level processes exist in the literature, it is often desirable to be able to reproduce these calculations in order to investigate the process from another perspective or perhaps even with just a different set of parton distribution functions. In principle reproducing these calculations is trivial, in practice it can take weeks or even months to generate and debug code for $2 \rightarrow 3$ or $2 \rightarrow 4$ processes. Recently, several programs have been introduced to facilitate coding...
tree level processes. Some are based on symbolic manipulation packages such as Mathematica, Maple, and Reduce. These packages include HIP[2], FeynArts[3], FeynCalc[4], and Tracer[5]. They greatly aid in calculating matrix elements using traditional trace techniques. For processes with more than 5 external particles, the results of trace methods are often rather cumbersome so helicity amplitude techniques are used. Helicity amplitude methods sum the diagrams before squaring, which results in the complexity growing linearly with the number of diagrams rather than quadratically as it does using trace techniques. Another advantage of helicity methods is that a program can easily be modified to decay the final state particles. Packages such as HELAS[1] and GRACE[6] use this technique. While all of the above programs are useful in the area for which they were designed, none allow the general user to specify the initial and final state particles to produce helicity amplitude code which the user can read and modify or simply incorporate into a Monte-Carlo. MadGraph was written to fulfill this function.

A MadGraph user specifies the initial state and final state particles, and the desired order in QCD and QFD. MadGraph then generates a Fortran function which calls HELAS routines to calculate the amplitude. This function can then be linked with a generic Monte-Carlo driver with the appropriate cuts and graphing options as well as the HELAS library. The result is a program which calculates the process of interest while reducing the programming time from days to minutes. MadGraph can generate the Feynman diagrams and HELAS calls for hundreds of diagrams in seconds. The color factors sometimes require a couple of minutes for complicated QCD processes. The code which is produced is not designed for optimal speed, but is easy to read and debug. As an example the process $e^- + e^- \rightarrow e^- + e^- + Z$ runs on a DECstation 5000 with about 100 events/second. BRS invariance and Lorentz invariance are easy to verify using HELAS. More elusive errors are in overall factors. To help minimize these errors MadGraph automatically includes factors for the interchange of fermions and for averaging over initial state colors. Summing and averaging over helicity states can either be done automatically by the MadGraph generated function, or by the user in their Monte-Carlo.
2. Generating HELAS Calls

MadGraph divides the problem of generating helicity amplitudes into four main parts. First, all distinct tree level topologies are generated. Second, particles are inserted into these topologies to produce all of the Feynman diagrams for the specified process. Third, the color and symmetry factors associated with each diagram are calculated. Finally, the HELAS code for the diagrams is generated.

The topologies are generated using a very simple recursive formula. The program begins with the one possible topology for a process with three external legs. By adding an additional leg in turn to the legs of the three topology, and to the three point vertex, the four topologies for four external particles are generated. The twenty five topologies for five external particles are generated by adding one external leg to each of the lines and three vertices of the four particle topologies. This process is continued to generate topologies for six, or seven external particles. Currently, the program is limited to seven external particles to limit memory use. In principle the process can be continued to any number of particles desired.

Once the topologies have been generated, the external legs are assigned to the particles which were requested by the user. From here, each vertex which has only one unspecified line is checked to determine if the current model allows such a vertex, and if so what particle the unspecified line must correspond to. If more than one particle is possible, this is noted, and the second choice is tried later. The process is continued until either all of the lines are specified and the graph is stored, or a vertex is reached for which there is no possible coupling in the specified model and the graph is discarded. All of the graphs which are stored are then checked to assure they are of the correct order in the appropriate coupling constants. The advantage of this scheme is twofold. First, it is extremely fast. Hundreds of diagrams can be generated in a fraction of a second. Second, it is extremely easy to add new models. All that is necessary is to specify the allowed vertices.

The symmetry factor for the interchange of two identical fermions is determined by following all of the fermion lines and seeing which external particles are attached by a line. Then one combination is assigned to be the positive orientation. All other graphs will be compared to this positive orientation to determine how many permutations are required to get from one configuration to the other. Each permutation results in a factor of -1. The color
factors are determined by first assigning the appropriate color matrix at each vertex, and then applying the completeness relations for the Gell-Mann matrices as color lines are summed over. This part of the program, along with diagonalizing the color matrix, consumes the most time.

Generating the HELAS code for each diagram completes the process. The design of HELAS is similar to that of the MadGraph topology algorithm. External wave functions are generated first and then the vertices with only one leg left uncalculated are used to calculate the wave function for that leg. The process is continued until all of the legs are calculated and the last vertex gives the amplitude for the graph. MadGraph simply looks at the vertices and depending on what types of particles are in the vertex, it writes out an appropriate HELAS call. The produced code is essentially a large ‘if then’ block which has each possible vertex as a case. The code is optimized by making sure that no redundant calls are made. For instance, if external legs one and two are combined to form a propagator in several different graphs, the propagator wave function is calculated only once, and that result is then used in all the future graphs which require it. Although simple, this optimization often reduces the output code by a factor of two or more.

3. Feynman Diagrams

Because it is often desirable to look at Feynman diagrams for the process being calculated, MadGraph generates a postscript file with these diagrams and the amplitude they correspond to in the code. In principle, graph generation should be trivial once all of the particles and vertices are determined. However, determining an esthetic arrangement of the vertices and particles requires some thought. The algorithm used in MadGraph minimizes the sum of the length squared of the lines. This does not always produce perfectly symmetric diagrams, however it is a fairly easy procedure to implement and the diagrams are adequate for research purposes. For each four-gluon vertex there are actually three identical graphs rather than just one. This is necessary to account for the three different color factors in a single four gluon vertex.
4. Examples

The best way to understand the program is to look at some examples. In this section, explicit examples will show what MadGraph is capable of performing. A general understanding of the HELAS package will be useful since it will allow the user to understand the function generated by MadGraph. If you are unfamiliar with this package, it will suffice to realize that given a particular set of particle momenta, HELAS returns a complex number which is the amplitude for each Feynman diagram. These amplitudes are then summed and squared to give the matrix element squared. In an effort to maintain uniformity, MadGraph asks the same set of questions for every process it calculates. Often there is only one acceptable response. If you enter a response outside of the allowed range, or simply hit <RETURN>, the value shown in parenthesis is used. One benefit of this method is that to test the program you can enter a process and hit return for all other requests and the default values will be used.

The information required is the process you want to have calculated, the order of the coupling in QCD and QFD, if the Weak sector is to be included, and a name for the process. The process is specified by entering the initial state particles, then a ‘>’, and then the final state particles. The string is parsed by searching for key characters. Any character entered which does not represent a particle is simply ignored. A one digit number specifies the order of QCD from which the order of QFD is inferred. If the order of QFD is non zero, and there are no external Weak bosons, you will be queried as to whether or not to include the Weak sector. If a ‘y’ is found anywhere in the response the Weak sector is included. Finally, a name to call the function is requested. This name will also be used for the Fortran file and the Postscript file. We include the trivial example of Møller scattering to show the format of the output.

Standard Model particles include:

Quarks: \( d u s c b t d^- u^- s^- c^- b^- t^- \)
Leptons: \( e^- mu^- ta^- e^+ mu^+ ta^+ ve^+ vm^- vt^- ve^- vm^+ vt^+ \)
Bosons: \( g a z w^+ w^- h \)

Enter process you would like calculated in the form \( e^+ e^- \rightarrow a \). (<return> to exit MadGraph.)
e- e- -> e- e-

Attempting Process: e- e- -> e- e-

Enter the number of QCD vertices between 0 and 0 (0):

The number of QFD vertices is 2
Would you like to include the Weak sector (n)?

Enter a name to identify process (emem_emem):

Generating diagrams for 4 external legs
There are 2 graphs.
Writing Feynman graphs in file emem_emem.ps
Reduced color matrix 1 2
Writing function emem_emem in file emem_emem.f.

Standard Model particles include:
  Quarks:  d u s c b t d^- u^- s^- c^- b^- t^-  
  Leptons:  e- mu- ta- e+ mu+ ta+ ve vm vt ve^- vm^- vt^-  
  Bosons:  g a z w+ w- h

Enter process you would like calculated in the form e+ e- -> a.  
(<return> to exit MadGraph.)

Thank you for using MadGraph

You can see the input lines used to specify the process as mentioned above. The final output lines give information about the process, the number of graphs found, and the name of the postscript file and the function file. Both files are included in Appendix A. The postscript file contains the two diagrams for Möller scattering. The important features of the Fortran file are the calling name of the two functions and the common block variables. The functions have the form:

  SEMEM_EMEM(P1,P2,P3,P4)  
  EMEM_EMEM(P1,P2,P3,P4,NHEL)
where \( P_1 \ldots P_4 \) are the four-momentum of particles 1 through 4 respectively. The first function returns the amplitude summed and averaged over helicity states, and the second returns the amplitude for the explicit helicity state specified by \( \text{NHEL} \), an array of dimension four. There are also eight common blocks which contain information on the particle masses and the coupling constants. A subroutine \texttt{INITIALIZE} is included in the package which if called at the beginning will set these to reasonable values. It is beyond the scope of this article to explain the HELAS calls, but the HELAS manual provides a clear description of their function.

5. \( Z + 4 \) Jets

The real benefit in using MadGraph comes in evaluating processes with many diagrams. To illustrate this, we have chosen \( P \ P \to Z + 4 \) jets. There are many subprocesses possible, but the example \( u + g \to u + g + Z + g + g \) will demonstrate how to generate all of the necessary functions.

\textbf{Standard Model particles include:}
\begin{itemize}
  \item Quarks: \( d \ u \ s \ c \ b \ t \ d^- \ u^- \ s^- \ c^- \ b^- \ t^- \)
  \item Leptons: \( e^- \ mu^- \ ta^- \ e^+ \ mu^+ \ ta^+ \ ve^- \ vm^- \ vt^- \)
  \item Bosons: \( g \ a \ z \ w^+ \ w^- \ h \)
\end{itemize}

Enter process you would like calculated in the form \( e^+ e^- \to a \).
(<\text{return}> to exit MadGraph.)
\( u g \to u g Z g g \)

\textbf{Attempting Process:} \( u g \to u g Z g g \)

Enter the number of QCD vertices between 4 and 4 (4):

The number of QFD vertices is 1
QFD required for this process ok?:
\( y \)

Enter a name to identify process (\texttt{ug_ugzgg}): 

Generating diagrams for 7 external legs
There are 516 graphs.
Writing Feynman graphs in file ug_ugzgg.ps
Reduced color matrix 105 516
Writing function ug_ugzgg in file ug_ugzgg.f.

Standard Model particles include:
  Quarks:  d u s c b t d~ u~ s~ c~ b~ t~
  Leptons: e- mu- ta- e+ mu+ ta+ ve vm vt ve~ vm~ vt~
  Bosons:  g a z w+ w- h

Enter process you would like calculated in the form e+ e- --> a.
(<return> to exit MadGraph.)

Thank you for using MadGraph

Generating this process took about three minutes to on an HP720. Most of that time was spent determining the color factors, with only a few seconds to actually draw the graphs and write the code. The resulting functions are

\[
\text{SUG}_\text{UGZGG}(P_1,P_2,P_3,P_4,P_5,P_6,P_7) \\
\text{UG}_\text{UGZGG}(P_1,P_2,P_3,P_4,P_5,P_6,P_7,NHEL)
\]

where the P's are the four-momenta of the particles and NHEL is a seven dimensional array which contains the helicities of the particles. Again there are several common blocks which can be set up by calling the subroutine \text{INITIALIZE}. However since this involves QCD, the strong coupling constant may need to be assigned for each momentum configuration since it depends on your choice of scale \( Q^2 \). This should be done in the subroutine which calls \text{SUG}_\text{UGZGG}. The value returned by \text{SUG}_\text{UGZGG} is the matrix element squared summed and averaged over colors and helicities. Since the helicity technique was used, the addition of 3 lines of HELAS calls allows you to decay the Z boson.

In order to perform a full Z + 4 jets analysis requires determining all of the possible subprocesses listed in Table 1. Table 1 also shows the number of diagrams, the time needed to generate the code, and the time needed to run the code for one set of momentum on an HP 720.

The optimized speed is the speed for summing only over the non zero helicity states. Further speed increases can be obtained by using an optimized color sum routine, and by using intelligent methods for summing the helicity
Table 1: Times on HP 720 in seconds

| Process            | Diagrams | Creation | 1 Event | Optimized |
|--------------------|----------|----------|---------|-----------|
| $u_g \rightarrow u_g Z g g$ | 516      | 180      | 4.0     | 2.0       |
| $u_g \rightarrow u_g Z c c$  | 204      | 12       | 1.5     | 0.5       |
| $u_d \rightarrow u_d Z c c$  | 48       | 1        | 0.5     | 0.1       |

states. In a fully optimized code it is reasonable to expect about 50 events per second for the process $u_g \rightarrow u_g Z g g$.

6. Conclusions

MadGraph allows the user to easily generate cross sections for complex tree level processes along with a postscript file of the corresponding Feynman diagrams. All $2 \rightarrow 4$ processes and many $2 \rightarrow 5$ processes can be calculated in a nominal amount of time. Although the code is not fully optimized, present day workstations are adequately powerful to integrate most processes. Using this program will allow the physicist to concentrate on the physics rather than on coding processes, and hopefully encourage investigating otherwise formidable problems.

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Appendix A - Example Output Files

MadGraph can be configured to generate either FORTRAN 77 or Fortran 90 style output functions. Both versions of the function to compute Möller scattering are listed below. The FORTRAN 77 version uses some common language extensions: IMPLICIT NONE, long variable names, double precision complex, REAL*8 and COMPLEX*16 declarations, and the DO / ENDDO construct. The output file is easily edited to remove these extensions if necessary.
The Fortran 90 version conforms to the ISO Fortran standard in fixed-source form.

demem_emem.f, FORTRAN 77 Version

    REAL*8 FUNCTION SEMEM_EMEM(P1, P2, P3, P4)
    C FUNCTION GENERATED BY MADGRAPH
    C RETURNS AMPLITUDE SQUARED SUMMED/AVG OVER COLORS
    C AND HELICITIES
    C FOR THE POINT IN PHASE SPACE P1,P2,P3,P4,...
    C FOR PROCESS : e- e-  → e- e-
    C
    IMPLICIT NONE
    C CONSTANTS
    C
    INTEGER NEXTERNAL, NCOMB
    PARAMETER (NEXTERNAL=4, NCOMB= 16)
    C ARGUMENTS
    C
    REAL*8 P1(0:3),P2(0:3),P3(0:3),P4(0:3)
    C LOCAL VARIABLES
    C
    INTEGER NHEL(NEXTERNAL,NCOMB),NTRY
    REAL*8 T
    REAL*8 EMEM_EMEM
    INTEGER IHEL
    LOGICAL GOODHEL(NCOMB)
    DATA GOODHEL/NCOMB*.FALSE./
    DATA NTRY/0/
    DATA (NHEL(IHEL, 1),IHEL=1,4) / -1, -1, -1, -1/ 
    DATA (NHEL(IHEL, 2),IHEL=1,4) / -1, -1, -1, 1/
DATA (NHEL(IHEL, 3),IHEL=1,4) / -1, -1, 1, -1/
DATA (NHEL(IHEL, 4),IHEL=1,4) / -1, -1, 1, 1/
DATA (NHEL(IHEL, 5),IHEL=1,4) / -1, 1, -1, -1/
DATA (NHEL(IHEL, 6),IHEL=1,4) / -1, 1, -1, 1/
DATA (NHEL(IHEL, 7),IHEL=1,4) / -1, 1, 1, -1/
DATA (NHEL(IHEL, 8),IHEL=1,4) / -1, 1, 1, 1/
DATA (NHEL(IHEL, 9),IHEL=1,4) / 1, -1, -1, -1/
DATA (NHEL(IHEL, 10),IHEL=1,4) / 1, -1, -1, 1/
DATA (NHEL(IHEL, 11),IHEL=1,4) / 1, -1, 1, -1/
DATA (NHEL(IHEL, 12),IHEL=1,4) / 1, -1, 1, 1/
DATA (NHEL(IHEL, 13),IHEL=1,4) / 1, 1, -1, -1/
DATA (NHEL(IHEL, 14),IHEL=1,4) / 1, 1, -1, 1/
DATA (NHEL(IHEL, 15),IHEL=1,4) / 1, 1, 1, -1/
DATA (NHEL(IHEL, 16),IHEL=1,4) / 1, 1, 1, 1/

C BEGIN CODE

real*8 function emem_emem(p1, p2, p3, p4,nhel)
  c
  c function generated by madgraph
  c returns amplitude squared summed/avg over colors
C FOR THE POINT IN PHASE SPACE P1,P2,P3,P4,...
C AND HELICITY NHEL(1),NHEL(2),....
C
C FOR PROCESS : e- e- -> e- e-
C
IMPLICIT NONE
C
C CONSTANTS
C
INTEGER NGRAPHS, NEIGEN, NEXTERNAL
PARAMETER (NGRAPHS= 2,NEIGEN= 1,NEXTERNAL=4)
REAL*8 ZERO
PARAMETER (ZERO=0D0)
C
C ARGUMENTS
C
REAL*8 P1(0:3),P2(0:3),P3(0:3),P4(0:3)
INTEGER NHEL(NEXTERNAL)
C
C LOCAL VARIABLES
C
INTEGER I,J
COMPLEX*16 ZTEMP
REAL*8 EIGEN_VAL(NEIGEN), EIGEN_VEC(NGRAPHS,NEIGEN)
COMPLEX*16 AMP(NGRAPHS)
COMPLEX*16 W1(6) , W2(6) , W3(6) , W4(6) , W5(6) , W6(6)
C
C GLOBAL VARIABLES
C
REAL*8 GW, GWWA, GWWZ
COMMON /COUP1/ GW, GWWA, GWWZ
REAL*8 GAL(2),GAU(2),GAD(2),GWF(2)
COMMON /COUP2A/GAL, GAU, GAD, GWF
REAL*8 GZN(2),GZL(2),GZU(2),GZD(2),G1(2)
COMMON /COUP2B/GZN, GZL, GZU, GZD, G1
REAL*8 GWWH,GZZH,GHHH,GWWHH,GZZHH,GHHHH
COMMON /COUP3/ GWWH,GZZH,GHHH,GWWHH,GZZHH,GHHHH
COMPLEX*16 GCHF(2,12)
COMMON /COUP4/ GCHF
REAL*8 WMASS,WWIDTH,ZMASS,ZWIDTH
COMMON /VMASS1/WMASS,WWIDTH,ZMASS,ZWIDTH
REAL*8 AMASS,AWIDTH,HMASS,HWIDTH
COMMON /VMASS2/AMASS,AWIDTH,HMASS,HWIDTH
REAL*8 FMASS(12), FWIDTH(12)
COMMON /FERMIONS/ FMASS, FWIDTH

C
C COLOR DATA
C
DATA EIGEN_VAL(1 )/ 1.0000000000000002D+00 /
DATA EIGEN_VEC(1 ,1 )/ 7.0710678118654746D-01 /
DATA EIGEN_VEC(2 ,1 )/ -7.0710678118654746D-01 /
C ----------
C BEGIN CODE
C ----------
CALL IXXXXX(P1 ,FMASS(1 ),NHEL(1 ), 1,W1 )
CALL IXXXXX(P2 ,FMASS(1 ),NHEL(2 ), 1,W2 )
CALL OXXXXX(P3 ,FMASS(1 ),NHEL(3 ), 1,W3 )
CALL OXXXXX(P4 ,FMASS(1 ),NHEL(4 ), 1,W4 )
CALL JIOXXX(W2 ,W3 ,GAL,AMASS,AWIDTH,W5 )
CALL IOVXXX(W1 ,W4 ,W5 ,GAL,AMP(1 ))
CALL JIOXXX(W1 ,W3 ,GAL,AMASS,AWIDTH,W6 )
CALL IOVXXX(W2 ,W4 ,W6 ,GAL,AMP(2 ))
EMEM_EMEM = 0.D0
DO I = 1, NEIGEN
   ZTEMP = (0.D0,0.D0)
   DO J = 1, NGRAPHS
      ZTEMP = ZTEMP + EIGEN_VEC(J,I)*AMP(J)
   ENDDO
   EMEM_EMEM = EMEM_EMEM+ZTEMP*EIGEN_VAL(I)*CONJG(ZTEMP)
ENDDO
C CALL GAUGECHECK(AMP,ZTEMP,EIGEN_VEC,EIGEN_VAL,NGRAPHS,NEIGEN)
END
function semem_emem(p1,p2,p3,p4)
!
! Function generated by MADGRAPH.
! Returns amplitude squared summed/avg over colors
! and helicities
! for the point in phase space p1,p2,p3,p4,...
!
! For process : e- e- -> e- e-
!
  implicit none
!
! Constants
!
  integer,parameter :: D = selected_real_kind(14,100)
  integer,parameter :: nexternal = 4
  integer,parameter :: ncomb = 16
!
! Arguments
!
  real(D) :: semem_emem
  real(D),dimension(0:3),intent(in) :: p1,p2,p3,p4
!
! External Function
!
  interface
    function emem_emem(p1,p2,p3,p4,nhel)
      real(D) :: emem_emem
      real(D),dimension(0:3),intent(in) :: p1,p2,p3,p4
      integer,dimension(nexternal),intent(in) :: nhel
    end function
  end interface
!
! Local Variables
!
  integer :: ihel,ntry
integer, dimension(nexternal,ncomb) :: nhel
real(D) :: t
logical, dimension(ncomb) :: goodhel
!
! Helicity combination tables
!

! Begin Code
!

semem_emem = 0.0_D
ntry=ntry+1
do ihel=1,ncomb
  if (goodhel(ihel) .or. ntry < 10) then
    t=emem_emem(p1,p2,p3,p4,nhel(1:4,ihel))
    semem_emem = semem_emem + t
    if (t > 0.0_D .and. .not. goodhel(ihel)) then
      goodhel(ihel)=.true.
      write(*,*) ihel,t
    endif
  endif
enddo
endif
enddo
semem_emem = semem_emem/ 4.0_D
end

function emem_emem(p1,p2,p3,p4,nhel)
!
! Function generated by MADGRAPH
! Returns amplitude squared summed/avg over colors
! for the point in phase space p1,p2,p3,p4,...
! and helicity nhel(1),nhel(2),....
!
! For process : e- e- --> e- e-
!
    implicit none
!
! Constants
!
    integer,parameter :: D = selected_real_kind(14,100)
    integer,parameter :: ngraphs = 2
    integer,parameter :: neigen = 1
    integer,parameter :: nexternal = 4
    real(D),parameter :: zero = 0.0_D
!
! Arguments
!
    real(D) :: emem_emem
    real(D),dimension(0:3),intent(in) :: p1,p2,p3,p4
    integer,dimension(nexternal),intent(in) :: nhel
!
! Local Variables
!
    integer :: i
    complex(D) :: ztemp
    real(D),dimension(neigen) :: eigen_val
    real(D),dimension(ngraphs,neigen) :: eigen_vec

complex(D),dimension(ngraphs) :: amp
complex(D),dimension(6) :: w1 , w2 , w3 , w4 , w5
complex(D),dimension(6) :: w6

! Global Variables
!
real(D) :: gw, gwwa, gwwz
common /coup1/ gw, gwwa, gwwz
real(D),dimension(2) :: gal,gau,gad,gwf
common /coup2a/ gal,gau,gad,gwf
real(D),dimension(2) :: gzn,gzl,gzu,gzd,g1
common /coup2b/ gzn,gzl,gzu,gzd,g1
real(D) :: gwwh,gzzh,ghhh,gwwhh,gzzhh,ghhhh
common /coup3/ gwwh,gzzh,ghhh,gwwhh,gzzhh,ghhhh
complex(D),dimension(2,12) :: gchf
common /coup4/ gchf
real(D) :: wmass,wwidth,zmass,zwidth
common /vmass1/wmass,wwidth,zmass,zwidth
real(D) :: amass,awidth,hmass,hwidth
common /vmass2/amass,awidth,hmass,hwidth
real(D),dimension(12) :: fmass,fwidth
common /fermions/ fmass,fwidth

! Color Data
!
data eigen_val(1 )/ 1.000000000000000e+00_D/
data eigen_vec(1 ,1 )/ 7.0710678118654757e-01_D/
data eigen_vec(2 ,1 )/ -7.0710678118654757e-01_D/

! Begin Code
!
call ixxxxx(p1 ,fmass(1 ),nhel(1 ), 1,w1 )
call ixxxxx(p2 ,fmass(1 ),nhel(2 ), 1,w2 )
call oxxxxx(p3 ,fmass(1 ),nhel(3 ), 1,w3 )
call oxxxxx(p4 ,fmass(1 ),nhel(4 ), 1,w4 )
call jioxxx(w2 ,w3 ,gal,amass,awidth,w5 )
call iovxxx(w1 ,w4 ,w5 ,gal,amp(1 ))
call jioxxx(w1,w3,gal,amass,awidth,w6)
call iovxxx(w2,w4,w6,gal,amp(2))
emem_emem = 0.0_D
do i = 1, neigen
    ztemp = sum(eigen_vec(:,i)*amp(:))
    emem_emem = emem_emem + ztemp*eigen_val(i)*conjg(ztemp)
enddo
! call gaugecheck(amp,ztemp,eigen_vec,eigen_val,ngraphs,neigen)
end

In addition to the Fortran source code, MadGraph produces a postscript file containing the corresponding diagrams. For the Møller example, the file emem_emem.ps prints as:

Appendix B - Implementation Notes

f77 Notes

MadGraph is written in Fortran and uses several common extensions to the old FORTRAN 77 standard, including:

- IMPLICIT NONE
- variable names longer than 6 characters
- lower case letters for variable names and keywords
• **DO/ENDDO and DO WHILE/ENDDO** constructs

• **IAND and IOR** bit intrinsics

• comments starting with “!”

In addition, f77 mode output uses the non-standard declarations:

• **REAL*8, COMPLEX*16**

If your f77 compiler does not support **IAND** and **IOR** bit intrinsic functions (included in MIL-STD-1753) a C version of these functions is supplied in the file bits.c which is replicated below:

```c
/* bits.c */
long iand_(long *a, long *b){return (*a & *b);}
long ior_(long *a, long *b){return (*a | *b);}
```

**f90 Notes**

MadGraph conforms to standard[7] Fortran 90 in fixed-source form. A user may convert to free-source form by adding trailing “&” continuation characters where appropriate.

MadGraph creates a Fortran function as part of its output. By default, this function is written for f77 compilers using the non-standard extensions noted in Appendix A. If you prefer an f90 standard-conforming function, edit the beginning of the main program (in driver.f, or at the beginning of madgraph.f) to change the initialization of the variable `fortran` to 90.

**VMS Notes**

The custom version of MadGraph for DEC VMS systems has modified I/O statements to compensate for differences between VMS and Unix formatted output. This version uses some VMS-specific nonstandard extensions to Fortran.
Eigensystem Notes

MadGraph requires a routine which computes the eigenvalues and eigenvectors of a real symmetric matrix. The necessary routines from the Lapack[8] package are included with the distribution. If your system already has the Lapack libraries installed, you may remove the Lapack Fortran sources and use your library versions. In the single-file versions of MadGraph, the Lapack routines are at the end of the file. In the tar’ed version, all the required routines are in a single file, lapack.f.

Additional implementation information and a list of tested platforms is included in a README file supplied with MadGraph.

Appendix C - Availability

Madgraph is available in both Unix and VMS versions via anonymous ftp from phenom.physics.wisc.edu in the directory pub/madgraph. The following four files are provided:

madgraph.f  Unix version as a single file.
madgraph.tar.Z  Unix version as a compressed tar file.
madgraph.tar.gz  Unix version as a gzip’ed tar file.
madgraph_vms.for  VMS version as a single file.

The tar files extract into your current directory and expand to create all the source files, a README file, and a makefile. Edit the makefile as appropriate for your system.

The single-file versions are provided for users without the make facility. These files also include commented sequence numbers in columns 73-80. The README file is included at the beginning as a series of comment lines.

HEPNET users may obtain the VMS version of madgraph as a single file by copying phenoa::local:[lib.madgraph]madgraph.for. The executable file for a DEC AXP (Alpha), madgraph.exe, is available in the same directory.

References

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[6] Grace Maunal: Automatic Generation of Tree Amplitudes in Standard Models: Version 1.0, Minami-Tateya Group (T. Ishikawa, et. al., KEK Report 92-19, February 1993.

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[8] E. Anderson, Z. Bai, C. Bischoff, J. Demmel, J. Dongara, J. Du Croz, A. Greenbaum, S. Hammarling, A. McKenney, S. Ostrouchov, and D. Sorensen, Lapack Users’ Guide (SIAM, Philadelphia, 1992).