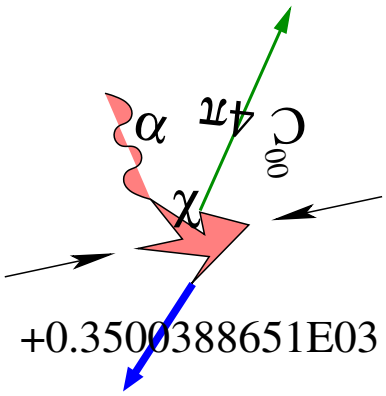

*a*n ÅIntegrated Tool for Automated Loop Calculations

*a*ÅITALC

Version 1.2: *The 2 to 2 fermion release*

January 17, 2005

Alejandro Lorca – Tord Riemann

Cover art by Alejandro Lorca

Nature of the problem

*a*ITALC is designed as a tool to perform automated perturbative calculations of cross sections in high energy physics.

The main goal is to create numerical programs directly from Feynman rules. It is actually developed for few known models like the electroweak standard model and QED, and the limit of application is, for the moment, the $2 \to 2$ particles reactions involving only external fermions.

The user will be expected to cook his or her own process within a set of basic and/or advanced ingredients. As a reward to such effort comes the output of *a*ITALC: Fast and reliable FORTRAN code with differential and integrated cross sections, analytical expressions for the transition amplitude and nice drawings of the individual Feynman graphs. It was never so easy to get all of it at once!

The tool was intended to integrate only free-of-charge packages existing on the market. As the calculation proceeds, in a modular fashion, we will profit from the DIANA package [TF00] (based itself on the QGRAF [Nog] code) for the generation and analysis of Feynman graphs, the FORM [Ver] language when dealing analytically with the large expressions in the amplitudes and, finally, the LOOPTOOLS [HPV99] library (also integrating the FF package [vO91]) for the numerical calculation of the loop integrals.

Last but not least, this tool owns its birth to the evolution of the static FORTRAN code TOPFIT [FLRW03], intended for the calculation of top-pair production. Some of the features then available such as the hard-photon bremsstrahlung or separate weak-QED contributions were discarded in pro of a full automation, higher technical precision and flexibility for many other processes.

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Chapter 1

Installation

Often the installation of scientific software products is a nightmare. This chapter will help you to dribble such initial difficulties and hopefully run your code. Please pay attention to next sections, be a bit patient and cross fingers!

1.1 Technical requirements

We present a list of the necessary conditions to install and run $a\mathring{\text{I}}\text{T}$ALC on your computer.

System compulsory requirements:

- A computer under LINUX[1] operating system with standard[2]
  - GNU MAKE utility
  - C compiler
  - FORTRAN77 compiler (with preprocessing ability)

Suggested optional features:

- CPU speed $\geq$ 333 MHz
- RAM Memory $\geq$ 128 MB
- At least from 1.5 to 10 MB[3] free space on disk for installation

☛ Further limitations given by the individual modules

[1] Installation on other UNIX systems might be possible if you already have some modules ready. The package has been succesfully build in SOLARIS for testing purposes.

[2] Tip: If lacking, free packages can be obtained from `http://www.gnu.org` under the names `make` and `gcc`.

[3] The fewer modules you have already installed the larger the size for including them. Another extra 30 MB will be needed if you build the three examples proposed.

1.2 Downloading

Most of the times, one finds this step as a circular reference: the information about where to download a code appears only in the tutorial attached to the code. Once the reader has broken this closed circuit we acknowledge the official site.

```
http://www-zeuthen.desy.de/theory/aitalc
```

Official site of $a\mathring{\text{I}}\text{TALC}$

1.3 Extracting

The file `aitalc-1.2.tar.gz` is a compressed group of files. Wherever the installer decided to save it[4], the next two commands

```
gunzip aitalc-1.2.tar.gz
tar -xvf aitalc-1.2.tar
```

Uncompress and unpack $a\mathring{\text{I}}\text{TALC}$ at your computer

will create a new system directory called `aitalc-1.2`. From now on we will refer to it as the direcory `$AITALCHOME` in which all the necessary files will be placed.

1.4 Where are the paths? Configuration

In order to share the information between the different modules of the package, the installation routine should know where to look for the libraries or execute binaries. A full installation of $a\mathring{\text{I}}\text{TALC}$ creates the default structure given in Tab. 1.1. Of course, if some of the components are already installed, it will be preferrable to find such valuable parts instead of performing a duplicate installation. Run the next command with such an intention.

```
cd ${AITALCHOME:=`pwd`/aitalc-1.2}
./configure
```

Search and establish the path for each module

If the script is not clever enough to find them or they are not installed on your machine, you might be prompted to request the missing modules from the net. Answer 'yes' (`Y`) if your internet conection is fast enough!

[4]Make sure you have write permission in that directory!!!

1.5 Compiling the modules

It should be straightforward, just type

```
make
```
Compiles everything needed

and the tool will be available. Let's do then interesting physics.

Module	→ **Directory**
DIANA	→ `$AITALCHOME/diana/diana-2.35/bin/diana`
QGRAF	→ `$AITALCHOME/diana/bin/qgraf.out`
TEDI	→ `$AITALCHOME/diana/bin/tedi.bin`
FORM	→ `$AITALCHOME/form/bin/form`
KITFORM3	→ `$AITALCHOME/form/kitFORM3/`
FORTRAN	→ `$AITALCHOME/fortran/`
LOOPTOOLS	→ `$AITALCHOME/fortran/LoopTools-2.1/`

Table 1.1: Default path location for the different software components after a full installation.

1.6 Error report

If you feel desperate because something went wrong, probably you will never want to hear about *a*ÅITALC again. Give it a chance and do not hesitate to contact the authors immediately, reporting the installation or other kind of bug. Maybe the problem can be easily solved and anyone benefit from an appropriate patching in the package.

```
mailto:alejandro.lorca@desy.de,tord.riemann@desy.de
```
Bug!

Chapter 2

How to work with $a\mathring{\text{I}}\text{TALC}$?

Are we ready to run $a\mathring{\text{I}}\text{TALC}$? As being mandatory in any prestigious code, we have a `'Hello world'` testing example; it will be a basic tree level process. Furthermore the description of each of the modules is contained in this chapter and provides the user with sufficient material to customize her or his own calculations.

2.1 A preliminary example at tree level: μ-pair production

Let's satisfy the impatient user and see what this weapon is able to do in unexperienced hands.

The directory `examples/` contains three prepared processes you can play with, one of them is inside `muon_production/`.

☞ From now on we assume you have write access on `examples/muon_production/`. If your system administrator installed $a\mathring{\text{I}}\text{TALC}$ for you, probably you won't be able to write in `$AITALCHOME`. In this case copy the directory `examples/` into a suitable location for running.

```
cd examples/muon_production
make
cd tree
gv muon_production.ps &
```

Go inside the examples and type in successively the commands to run the process of μ-pair production and watch the diagrams

The compilation and execution will take a while, depending on your system from few seconds up to one minute or so, please be patient. When no error messages popped out, then your are viewing the Fig. 2.1. It is a graphical representation of the Feynman diagrams that add up into the scattering amplitude for the selected process. In them, the time coordinate is the horizontal axis that, as usual, is not shown. Incoming particles appear at the left of the diagram. Note that both fields e^- and e^+ are represented by the same symbol e. In order to identify the particle

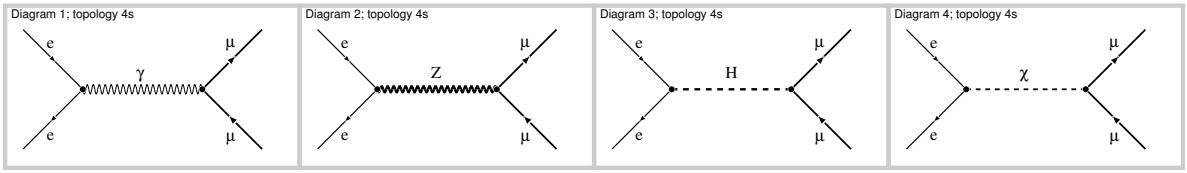

Figure 2.1: Diagrams appearing according to the `EWSM.model` for $e^-e^+ \to \mu^-\mu^+$ at tree–level.

(antiparticle) you have to check whether the fermion arrow points forward (backward) along the time direction; the same applies to all fermions.

If your wish is not so graphical, but instead the numerical achievement of the calculation, consider the following:

```
cd ../fortran
./main.out
cat main.log
```

Enter in this directory to check the numerics of the process

and immediately your screen will be filled with the content of Table 2.1, that you should interpret as the following: *I got in the tree–level approximation for the process* $e^-e^+ \to \mu^-\mu^+$ *the following set of differential cross sections*[1] *(in pb), at different scattering angles for a beam energy of 500 GeV, and maximum soft photon energy of 50 GeV.*

If after such a show you are still interested, read the rest of this chapter which describe extensively the more powerful usage of *aÎTALC*, part by part.

```
#=============================================================================================
# aITALC Version 1.0 (29.10.2004) by A.Lorca -- T.Riemann
#---------------------------------------------------------------------------------------------
#sqrtsman     cost      dcs(Born)    dcs(loop)    dcs(soft)    dcs(B+l+s)   dcs(loop^2)
 0.5000000E+3 -.9000000 0.9458936E-1 0.0000000E+0 0.0000000E+0 0.9458936E-1 0.0000000E+0
 0.5000000E+3 -.5000000 0.8929449E-1 0.0000000E+0 0.0000000E+0 0.8929449E-1 0.0000000E+0
 0.5000000E+3 0.0000000 0.1503198E+0 0.0000000E+0 0.0000000E+0 0.1503198E+0 0.0000000E+0
 0.5000000E+3 0.5000000 0.2865049E+0 0.0000000E+0 0.0000000E+0 0.2865049E+0 0.0000000E+0
 0.5000000E+3 0.9000000 0.4495681E+0 0.0000000E+0 0.0000000E+0 0.4495681E+0 0.0000000E+0
#=============================================================================================
#Energy given in GeV, Cross sections in pb, setfracomega= 0.1000000
```

Table 2.1: File `main.log`, produced by the run of `main.out`.

[1] By default they are given by the value of $\cos\theta$. The scattering angle θ refers to the angle between the 1st incoming and the 1st outgoing particle in a $2 \to 2$ fermion process.

2.2 The environment through Makefile

Automatization requires effective inter–communication and a smart way to organize the tasks. We found that this second concept was by far much easier to implement under a Makefile environment than, let's say, programming everything from the scratch in C++.

The Makefile environment handles with

- Simplification of user interface
- Building the sections `tree`, `loop` and `fortran`
- Running the driver process file
- Writing the intermediate information DIANA → FORM → FORTRAN in a row
- Compiling the numerical program leading to the final results

in a modular fashion. The execution takes place sequentially following the control flow structure depicted in Fig. 2.2

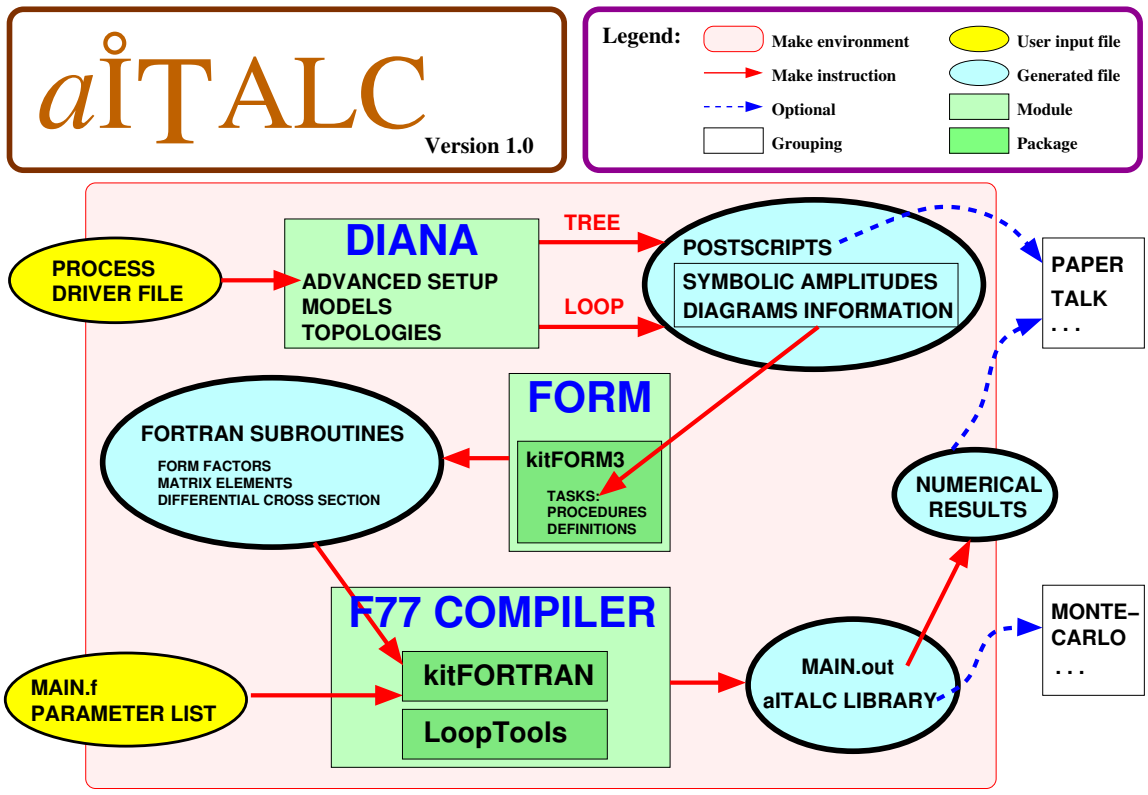

Figure 2.2: Logical flow chart structure for $a\mathring{\text{I}}$TALC.

2.3 DIANA and the driver file

Let us introduce some basic concepts about DIANA. If we are thinking of some process, a very intuitive approach is to draw some Feynman diagrams to get a feeling and support the calculation which comes later.

Such a task is very likely to be implemented with the help of computers since it is basically a combinatorial problem. Once we define a model, the external particles, and the level of loops, the problem can be solved. Indeed, DIANA will do it for us.

2.3.1 Basic driver file: Input

The driver file (e.g. `process.ini`) serves as basic input. It contains primarily:

- incoming and outgoing particles,
- physical model,
- process control flags and options.

These items are crucial for the determination of the DIANA "create" file, in which the `Makefile` also determines the number of loops. Then DIANA is able to offer some of the information to QGRAF and create the possible diagrams appearing at each level. Additionally extra information about the global process and for each individual graph is attached into the output file at each level e.g. `tree/$processname.in`.

Be careful with the momenta definitions. They all should be assigned to be incoming and clockwise indexed (e.g. `p1` addressed to be the first incoming particle, `-p2` to be the first outgoing one and so on). Follow the convention used in the examples, otherwise the results are not guaranteed to be correct.

We suggest the user to have a look to an example driver file, for instance the `process.ini` from the muon production as shown in Fig. 2.3.

As you probably realized, the comment character is * and the `** MODIFY HERE! **` sentences indicate where some modifications are accepted. At this basic level the modifications concern: processname, model name, incoming and outgoing particles and QGRAF options. Regarding the flags for the initial settings, the topology editor (TEDI) can be launched at running time by uncommenting the line: `*SET _TOPOLOGYEDITORNAME="tedi"`. TEDI is designed to allow the user ultimate flexibility on topology naming, shaping and even defining momenta. It requires the X window server in your system, but it's quite intuitive to manage as one may imagine by looking to the Fig. 2.4.

process.ini Page 1/2

```
**********************************************************************
** Driver file for Diana 2.35 <process.ini>                         **
** This file is part of aITALC                                      **
** Copyright (C) 2004 Alejandro Lorca <alejandro.lorca@desy.de>     **
**                                                                  **
** Please, modify the file with your taste, mainly after the        **
** MODIFY HERE! sentence.                                           **
**********************************************************************

* DIANA RUNNING SETTINGS
**====================================================================
** MODIFY HERE! **
SET _processname=muon_production

** To assign direction in loop momenta and naked integration line
*SET _MARK_LOOP="YES"
** Next means remember loop momenta
*SET rlm = "rlm"

** Next (YES/NO) avoid/load
** generic topology tables and internal abstract momenta
SET _NO_TABLES="YES"
*SET _NO_TABLE_MOMENTA="NO"
*--------------------------------------------------------------------
** To be adjusted by autoconf
SET _DIANANAME=diana35
** if you want to edit the topologies:
*SET _TOPOLOGYEDITORNAME=tedi

only interpret
\openlanguage(create.tml)
\MINVERSION(2.35)
*--------------------------------------------------------------------

\Begin(program)

* MODEL TYPE
**====================================================================
** MODIFY HERE! **
*\Begin(model,QED.model)
\Begin(model,EWSM.model)
\End(model)
**--------------------------------------------------------------------

* DESCRIPTION OF OUR PROCESS (INGOING AND OUTGOING PARTICLES)
**====================================================================
\Begin(process)
** MODIFY HERE! **
ingoing le(;p1),Le(;p4);
outgoing lm(;-p2),Lm(;-p3);
** To be adjusted in the Makefile
loops=N;
\End(process)
```

process.ini Page 2/2

```
**--------------------------------------------------------------------
\loopmomenta(q)
\zeromomentum(zero)
* For the topology tables
*\token(bridge,b)
*\token(chord,k)
*\token(loop,q)
**--------------------------------------------------------------------
\include(runningrestrictions.prg)

* LOADING/CREATION OF TOPOLOGIES
**====================================================================
** When creating a topology from the scratch, please save it into
** a file and rerun Diana with that topology file.
**--------------------------------------------------------------------
** To be adjusted with the Makefile
*\tables(4legsNloops.tab)
\Begin(topology,4legsNloops.top)
\End(topology)
**--------------------------------------------------------------------
\Begin(qgrafoptions)
** MODIFY HERE! **
*options=;
options=notadp,onshell;
\End(qgrafoptions)
**--------------------------------------------------------------------

* POSTSCRIPT FLAGS AND OPTIONS
**====================================================================
\Begin(header)
**--------------------------------------------------------------------
** MODIFY HERE! **
SET MakePs = "!"
SET MakeInfo = "!"
SET MakeEps  = "!"
SET MakeInfoEps  = "!"
**--------------------------------------------------------------------
debug off
forced execute
extra call
messages disable
\End(header)
**--------------------------------------------------------------------

* TML LANGUAGE
**====================================================================
\include(thetmlstuff.prg)
**--------------------------------------------------------------------
\indices(mu1,mu2,mu3,mu4,mu5,mu6,mu7,mu8,mu9,mu10,mu11,mu12)
\vectors(p,p1,p2,p3,p4,p5,p6,k,k1,k2,k3,k4,k5,k6,q,q1,q2,zero)
**--------------------------------------------------------------------
\End(program)
```

Figure 2.3: Snapshot for `process.ini` driver file.

2.3.2 Advanced setup

But what about if we want to exclude some couplings or modify the aspect of the diagrams?

After the installation of *a*ÎTALC it is also possible to use DIANA[2] as an independent package (see App. A). For our present purpose, we will show shortly the tested modifications that can be performed at this level.

If you have already been running the example, inside of the `tree` directory (also the `loop` directory in other examples) you can select some files to be considered instead of the default coming from the following directory: `$AITALCHOME/diana/prg`. This is automatically done by placing those files on the `examples/muon_production/` directory.

We do not suggest to copy and modify any other file inside `prg` since they are mostly functions using advanced DIANA declarations, so just consider to play with the following:

- `particleaspect.prg`: Defines how every propagator and particle label looks like in the `.ps` and `.eps` files. Syntax is not described (just a couple of comments), but intuitive. The field label `CT` is assigned to counterterms.

[2]This extends also to FORM and LOOPTOOLS.

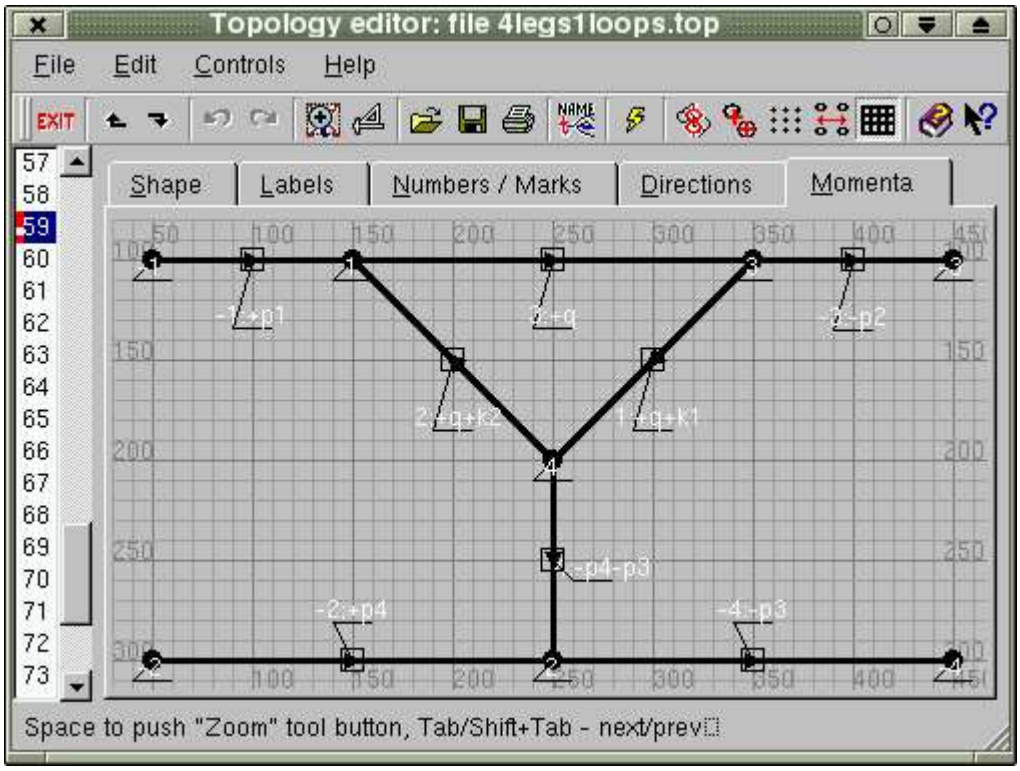

Figure 2.4: Snapshot for the momenta tab in TEDI

- `runningrestrictions.prg`: Exclude some couplings or fields here. As before uncomment or replace as desired.
  Warning: As soon as you may discard some fields or couplings, be aware that the renormalization of parameters and fields is FIXED and complete within each model and does not know about your intentions, so perform always a consistency check of your results!

2.3.3 What can we get?

Let's have a look inside a level directory (e.g. `tree` or `loop`): The organizer file is called `Makefile`. It has the instructions to create, organize and fill the different directories by given commands under the MAKE environment. This means you have to do nothing but wait while monitoring the abundant screen messages. Depending on the process, modifications, hardware and compiler the time for each module varies from seconds till several minutes[3]. You can keep trace about how much it took by looking the time stamps in the `Makefile.log` file at Fig. 2.5.

[3]If large files are to be compiled, occasionally your system might overload. Doubt about everything taking longer than half an hour.

```
alorca@linux:~AITALCHOME/examples/muon_production/tree> ls -XFl
total 183
drwxr-xr-x    2 alorca   users     2048 Oct 14 15:02 EPS/
drwxr-xr-x    2 alorca   users     2048 Oct 14 15:02 FFmuon_production/
drwxr-xr-x    2 alorca   users     2048 Oct 14 15:02 InfoEPS/
-rw-r--r--    1 alorca   users     3291 Oct 14 15:02 Makefile
-rw-r--r--    1 alorca   users     3710 Oct 14 15:02 muon_production.cnf
-rw-r--r--    1 alorca   users       20 Oct 14 15:02 fermioncurrentsnames.in
-rw-r--r--    1 alorca   users     3870 Oct 14 15:02 muon_production.in
-rw-r--r--    1 alorca   users     4531 Oct 14 15:02 Make_kit.log
-rw-r--r--    1 alorca   users      149 Oct 14 15:02 Makefile.log
-rw-r--r--    1 alorca   users     1088 Oct 14 15:02 do_amplitude.log
-rw-r--r--    1 alorca   users      245 Oct 14 15:02 joinff.1.log
-rw-r--r--    1 alorca   users     1059 Oct 14 15:02 joinff.log
-rw-r--r--    1 alorca   users      629 Oct 14 15:02 joinkinematics.log
-rw-r--r--    1 alorca   users   121102 Oct 14 15:02 joinmm.log
-rw-r--r--    1 alorca   users    14779 Oct 14 15:02 muon_production.ps
-rw-r--r--    1 alorca   users    18277 Oct 14 15:02 muon_productionInfo.ps
```

Figure 2.5: Listing for the `tree` directory inside our muon production example.

Diagram info

As it comes out of DIANA, the file `$processname.in` contains the required information about both, global process and individual diagrams. Specially useful for the FORM routines are the preprocessed variables defined for each diagram.

Graphical information

The global files `$processname.ps` and `$processnameInfo.ps` summarize all the Feynman graphs appearing at the process. Inside the `EPS/` (and `EPSInfo/`) directories one may find .eps files with all individual diagrams (and momenta-label definition).

Analytical expressions (FORM processed)

In the files `do_amplitude.log` and `joinmm.log`, information will be found about the individual evaluation of each diagram and the kinematical factor corresponding to the cross product of matrix elements, respectively. Also, extra kinematical information can be found in `joinkinematics.log`. As an intermediate step, individual amplitudes are stored in the `FF$processaname/` directory.

2.4 Using the FORM libraries

As soon as DIANA has finished one of the levels, a complete description of the process falls into our hands, but still in an encoded language. Different FORM programs will prepare the amplitudes in order to render numerically evaluable expressions. Tracing, commuting γ matrices, applying the Dirac equation to external fermions or introducing the Mandelstam variables is part of the physical achievement at this module.

There are basically two kind of programs: The main routines and the procedures. We describe the four routines:

- `do_amplitude.frm`: Takes care of chewing the individual amplitude for each diagram, extracting out the form factors in a given basis of matrix elements.
- `joinkinematics.frm`: Defines how the differential cross section should be composed in terms of fermion currents (`S`, `T` or `U`), the normalization of the incoming flux in the cross section formula, soft photon emission and the definition of the Mandelstam variables.
- `joinmm.frm`: The standard set of matrix elements is considered by this program, giving, as output, the multiplication of any two elements appearing in the amplitude decomposition.
- `joinff.frm`: Once all the diagrams were considered, this part pastes together the form factor contributions sorted by topologies. The final translation into FORTRAN code is also done at this step.

2.4.1 `#procedures` without end

One of the most important principle in any calculation is the correctness of the expression after every step. By using procedures with a clear physical or mathematical intention, we ensure a systematic processing for the Feynman amplitudes and an easy way to eliminate potential bugs.

The listing of the procedures is long, and the description of each of them is shortly presented in App. C.

At least we would like to draw the attention to one option. If you want to neglect the masses of particles (e.g. light fermion masses), you can easily discard any term proportional to them including your costumized `Neglectedmasses.inc` file.

```
cd ..
cp $AITALCHOME/diana/prg/runningrestrictions.prg .
cp $AITALCHOME/form/kitFORM3/Neglectedmasses.inc .
(edit the copied files)
make clean
make
```

Activate your own settings (e.g. neglecting particle's mass terms)

2.5 Getting numbers: the FORTRAN code

Considering the `fortran` module, its structure can be outlined as follows:

- `main.f, parameterlist.hf`: they both give the user access to modify the output structure of the program and the explicit values of the model respectively. In the `main.f` file we find many settings as logical flags, input of kinematics and output control.

- KITFORTRAN: consists of the full set of FORTRAN subroutines and functions needed to compile the `main.f` program. We can divide them into two categories, according to the role they play during running time.

  - **Global** are those that were fixed at installation time and considered to be process independent. They are stored at `$AITALCHOME/fortran/src`
  - **Local** are written at running time by the `tree` and `loop` modules and depend explicitely on the application. They get placed at `$processname/fortran/src`.

- LOOPTOOLS: with the purpose of calculating the loop integrals this library is called.

2.5.1 Understanding and controlling the output

If after all, the desired scattering reaction was calculated, it will not be a waste of time to give a bit of explanation on the results and how to adapt them to your needs.

In the table of differential cross sections (given always in pb), the first column corresponds to the beam energy ($\sqrt{s}$ = `setsqrtsman`) given in GeV, the second one to the $\cos\theta$ (`setcost`), θ being the angle between the three-momenta $\mathbf{p_1}$ and $-\mathbf{p_2}$. Later on we have successively the columns of the Born approximation (`Born`), the interference terms of the tree and loop levels (`loop`) and the soft photonic corrections (`soft`). These three columns (third ,fourth and fifth) are summed into the sixth column (`B+corr`) resulting into the finally corrected cross section. The last column `loop^2` returns back the amplitude concerning the one-loop squared terms in the perturbative approach. The maximum energy fraction that the soft photon may gain out of $\sqrt{s}$ is limited by the variable `setfracomega`.

If the calculation is correct, all the columns should be constant[4] under variation of the ultraviolet (UV) parameter (you can check this by turning on the flag `luvcheck`). The same check for the infrared (IR) behaviour (`lricheck`) will change the explicit values in columns `loop` and `soft`, but the sum should still be invariant! The last column may also suffer against IR variation since it is not compensated by double soft photon emission. Those `loop^2` numbers are crucial when they become the leading order in e.g. flavour changing neutral current processes (FCNC), or just as an estimator of the order of magnitude for the error in the next level of perturbation theory. When integrated cross sections are under study, the integration region is limited by the

[4]Warning: as a result of numerical variation, the round off of intermediate results will modify the last digits in your results. Such variation increases at the collinear cases due to cancellations.

`setlimcost` variable, the `ics` and `fba` being defined as

$$\texttt{ics} = \sigma_{\rm tot} = \int_{-\texttt{setlimcost}}^{\texttt{setlimcost}} \mathrm{d}\cos\theta\ \texttt{dcs} \tag{2.1}$$

$$\texttt{fba} = \frac{\sigma_{\rm fw}-\sigma_{\rm bw}}{\sigma_{\rm tot}} = \int_{0}^{\texttt{setlimcost}} \mathrm{d}\cos\theta\ \frac{\texttt{dcs}}{\texttt{ics}} - \int_{-\texttt{setlimcost}}^{0} \mathrm{d}\cos\theta\ \frac{\texttt{dcs}}{\texttt{ics}}. \tag{2.2}$$

$$\tag{2.3}$$

The integration algorithm is based on a Richardson extrapolation to the Romberg integration [PFTV92] with four steps. The estimated error is supplied in short forms in extra columns. If it does not suffice or for cross checking, the same subroutine with eight steps (`ICS8`) can be called instead of the faster `ICS`. A complete survey of variables is presented in App. D.

2.5.2 A greedy possibility: quadruple precision

Not every compiler[5] allows for extended or quadruple precision. This is a feature outside of the ANSI FORTRAN77. Even if $a\mathring{\imath}\mathrm{T}\mathrm{ALC}$ contains some code's implementations outside the ANSI syntax, they are quite common (e.g. using underscore, or double complex), so decent compilers won't complain.

But on high level computation, or simply as comparison, switching on the quadruple precision could stabilize numerical results or render amazing agreement with other calculations. Next is the roadmap for an activation of this possibility:

1. Have a look in your working process. Open the file called `Fortran.mk` and look to the first lines, where `#QUADRUPLE` is firstly mentioned. If the right hand side is set to `"yes"`, then you can try to uncomment it and see what happens.

2. Check whether your system has access to the quadruple precision LOOPTOOLS libraries (`libooptoolsQ.a`). In case they are not in your path, try to compile them by looking to the `qprec/` directory in the LOOPTOOLS distribution and following the instructions there.

3. Allow for longer printouts inside of the last formats statments in `main.f`. With this you can access to the sector of digits between 16 and 33, where the quadruple precision play a role.

4. Keep calm since this feature is outside of the automation chain, and therefore some minor changes are required in `Makefile`s and so... Be aware of the screen and file logs!

2.6 Examples including loop level

To finish this descriptive chapter of how to work, we would like to present the other examples available with the distribution. They can be tested in a similar way as μ-pair production. Just

[5] Until now, the use of quadruple precision has been only positively tested under INTEL FORTRAN compiler (see `http://www.intel.com/software/products/compilers/flin/noncom.htm`).

for reference, the default numerical result can be viewed in Tabs. 2.3−2.4. A bit of the physics behind of the examples here given might be found on [LR04] and the references therein.

With the purpose of giving flavour of timings, expected to take during the execution, all the examples were studied on two different machines, representing the today's typically available computers. The results are shown on Tab. 2.2. There we can see that when the size of the produced FORTRAN code begin to be large (i.e. more than ∼200kB for a single subroutine to be compiled), then the compiling time for the GNU compiler gets extremely long, in comparison with the magnitude of the other processes.

	muon_production		leLe.bS		bhabha_QED	
Module	Desktop	Laptop	Desktop	Laptop	Desktop	Laptop
tree	9”	3”	4”	1”	30”	9”
loop	–	–	2’20”	52”	37”	12”
fortran	15”	4”	4:35’56”	33”	26”	8”
Total	24”	7”	4:38’20”	1’26”	1’33”	29”

Table 2.2: Typical timings for the different modules. The technical specifications for system Laptop are: Intel Centrino 1.5GHz cpu, 512MB RAM, Intel `icc` and `ifort` version 8.1 compilers. For Desktop: Intel Pentium III 853MHz cpu, 256MB RAM, GNU `gcc` and `g77` version 3.3.3 compilers.

✎ Exercise: Repeat in another directory the example of `leLe.bS`, in which you recreate the process $e^-e^+ \to b\bar{s}$, but this time neglecting analytically the terms proportional to the electron mass.
a) How many diagrams can you avoid to be generated?
b) How large is the numerical difference for the default differential cross sections?
c) How much time did you save on the compilation of the `fortran` module?
d) Which from both codes is more stable against UV-parameter check?

☆ Hint: Make use of the overriding possibilities with the files
`$AITALCHOME/diana/prg/runningrestriction.prg`,
`$AITALCHOME/form/kitFORM3/Neglectedmasses.inc`
and the `llongoutput` variable in `main.f`.

```
#=============================================================================================================================================
# aITALC Version 1.0 (29.10.2004) by A.Lorca -- T.Riemann
#---------------------------------------------------------------------------------------------------------------------------------------------
#sqrtsman      cost      dcs(Born)             dcs(loop)             dcs(soft)             dcs(Born+loop+soft)   dcs(loop^2)
 0.5000000E+03 -.9000000 0.523873625293772E+00 0.104514245255543E+00 -.219313307956275E+00 0.409074562593040E+00 0.923544633715657E-02
 0.5000000E+03 -.5000000 0.611600720838859E+00 0.176786637556097E+00 -.292280085880001E+00 0.496107269806955E+00 0.172748338575392E-01
 0.5000000E+03 0.0000000 0.117253629320705E+01 0.397406280604550E+00 -.606584657480458E+00 0.963357916331143E+00 0.420671139611335E-01
 0.5000000E+03 0.5000000 0.550440648756388E+01 0.212664263210930E+01 -.306463515349883E+01 0.456641396617436E+01 0.240547593782348E+00
 0.5000000E+03 0.9000000 0.189118378731798E+03 0.870334082480635E+02 -.116499974637966E+03 0.159651812341895E+03 0.108965601218541E+02
#=============================================================================================================================================
#Energy given in GeV, Cross sections in pb, setfracomega= 0.1000000
```

Table 2.3: File `main.log`, for the `bhabha_QED` example and `llongoutput=.true.`

```
#=============================================================================================================================================
# aITALC Version 1.0 (29.10.2004) by A.Lorca -- T.Riemann
#---------------------------------------------------------------------------------------------------------------------------------------------
#sqrtsman      cost      dcs(Born)             dcs(loop)             dcs(soft)             dcs(Born+loop+soft)   dcs(loop^2)
 0.5000000E+03 -.9000000 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.653411795813974E-08
 0.5000000E+03 -.5000000 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.709542147963438E-08
 0.5000000E+03 0.0000000 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.104868950766147E-07
 0.5000000E+03 0.5000000 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.208494230993482E-07
 0.5000000E+03 0.9000000 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.000000000000000E+00 0.464395594522522E-06
#=============================================================================================================================================
#Energy given in GeV, Cross sections in pb, setfracomega= 0.1000000
```

Table 2.4: File `main.log`, for the `leLe.bS` example and `llongoutput=.true.`

Chapter 3

Hot potatoes in the scope

At the end of the day one expects the results to be correct, but how to proceed when we have done some intuitive manipulations not very well (or not at all) described before?

The following pretends to clarify some hot points, historically considered without no difficulties, and the way that were implemented in *a*ÎTALC.

1. **Renormalization**: Since the renormalization of the parameters and fields is model dependent, it was our solution to implement a fixed FORTRAN subroutine with the required elements in any $2 \to 2$ process with only external fermions. Therefore, whenever one makes modifications on the process settings on the DIANA or FORM modules, possible violations can arise. A typical example of this is to neglect any photon field to generate a gauge independent subset of pure weak diagrams. In such a case, be sure you also comment out any photon contribution inside of the `renormalization.f` or `renormalization_QED.f` files (indeed that is a tough job!).

2. **Running with a finite gauge boson width**: This feature is strictly going beyond a classical one-loop calculation, but still needed if one requests an accuracy of $\mathcal{O}(\alpha)$ of the corrections to the tree-level results with dressed propagators. The algorithm followed here is quite straightforward, based on the fix-width scheme

   - Self-energies of the finite width gauge boson are discarded to avoid double-counting
   - Complex masses are taken into account where needed in propagators and loop integrals to avoid singularities or discontinuities.

3. **Stability at the kinematical edges**: Experience taught us that in the limits, $\cos\theta \to \pm 1$, large numerical cancellations between different topologies and their loop integral values will occur. Thus, it is strongly advised to perform ultraviolet checks in your region of study, that will inform you how strong or weak is the stability of the numbers. Moreover, when computing integrated cross sections in that limits, the error of the calculation will never be better than the limit of precision shown by the differential cross section itself.

4. **Treatment of CKM-type couplings**: We adopt the solution of not implementing counterterms for the CKM elements. This has some limitation on charge current processes but, for neutral current ones, correct expressions can be retrieved by considering actively the loops on the external legs (usually discarded with the `onshell` option of QGRAF). You can have a look to the `leLe.bS` in the `examples/` directory to see how this is done.

5. **Extensions beyond 2 → 2 fermion processes**: They should be dealt carefully. There is plenty of code that can still be useful in a treatment of processes with more external legs or computation of simple self-energies (as it was done for the counterterms). Nevertheless, it requires a deep monitoring and understanding of the physics and technicalities behind. Then you would better forget about the FORTRAN module and run individually the MAKE commands in an analytical level by adding your own FORM programs or DIANA functions. But this is only a hint, the world of possibilities is then in your hands.

Acknowledgements

A.L. would like to thank Nils Christian for his endless lessons on `CVS`, `autoconf`, and many other UNIX tools. Without his support this project would have never become a reality.

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Appendix A

References for the package DIANA

For the sake of completeness, we would like to extend the referencing of any potential user further interested in DIANA.

Tutorials

The perhaps slightly outdated web site of DIANA still contains most of the available information:

- `http://www.physik.uni-bielefeld.de/~tentukov/diana.html`.

Alternative access to the documents is found at our mirror under

- `http://www-zeuthen.desy.de/theory/aitalc/downloads/doc/diana.ps`
- `http://www-zeuthen.desy.de/theory/aitalc/downloads/doc/diana2.ps`

for the first and second versions respectively. Additionally there is a draft describing extra features like the automatization of momenta distributions at
`http://www.physik.uni-bielefeld.de/~tentukov/topoltables.ps.gz`.

Articles

Besides the tutorial and log files, the user may find interesting the following collection of articles and contributions [TF99], [FT00], [TF03], [FTT03], [TF04], [GLR04] and [FLR04]. They compile somehow a long heritage of the code's evolution.

Contact

In case you want to use DIANA independently of $a\mathring{\text{I}}$TALC, it might be sometimes useful to contact its authors. They provided us with useful comments and wise guidance in our adventure.
`mailto:tentukov@physik.uni-bielefeld.de,fl@physik.uni-bielefeld.de`.

Appendix B

Implemented models

Code	Arguments	Particle	Name	Lorentz type
Lepton				
`le`, `Le`	`(;`p_i`)`	e^-, e^+	electron, positron	fermion
Gauge boson				
`A`	`(`μ_i`;`p_i`)`	γ	photon	boson

Table B.1: Particle content for the QED model (`QED.model`)

Code	Arguments	Particle	Name	Lorentz type
Leptons				
`ne , Ne`		ν_e, $\bar{\nu}_e$	neutrino-e, antineut-e	
`nm , Nm`	`(;`p_i`)`	ν_μ, $\bar{\nu}_\mu$	neutrino-μ, antineut-μ	fermion
`nt , Nt`		ν_τ, $\bar{\nu}_\tau$	neutrino-τ, antineut-τ	
`le , Le`		e^-, e^+	electron, positron	
`lm , Lt`	`(;`p_i`)`	μ^-, μ^+	muon, antimuon	fermion
`lt , Lt`		τ^-, τ^+	tau, antitau	
Quarks				
`u , U`		u, $\bar{u}$	up, antiup	
`c , C`	`(;`p_i`)`	c, $\bar{c}$	charm, anticharm	fermion
`t , T`		t, $\bar{t}$	top, antitop	
`d , D`		d, $\bar{d}$	down, antidown	
`s , S`	`(;`p_i`)`	s, $\bar{s}$	strange, antistrange	fermion
`b , B`		b, $\bar{b}$	bottom, antibottom	
Gauge bosons				
`A`		γ	photon	
`Z`	`(`μ_i`;`p_i`)`	Z	Z-boson	vector
`Wm , Wp`		W^-, W^+	W-boson	
Higgs sector				
`H`		H	Higgs	
`G0`	`(;`p_i`)`	χ	"the would-be	scalar
`Gm , Gp`		ϕ^-, ϕ^+	Goldstone bosons"	
Faddeev-Popov ghosts				
`ghA, GhA`		η_γ, $\bar{\eta}_\gamma$	photon ghosts	
`ghZ, GhZ`	`(;`p_i`)`	η_Z, $\bar{\eta}_Z$	Z-ghosts	scalar
`ghm, Ghm`		η_{W^-},$\bar{\eta}_{W^-}$	W^--ghosts	(with fermion statistics)
`ghp, Ghp`		η_{W^+}, $\bar{\eta}_{W^+}$	W^+-ghosts	

Table B.2: Particle content for the electroweak sector in the Standard Model (`EWSM.model`)

Appendix C

List of FORM procedures in KITFORM3

Name	Args.	Description
`LTtoPV`		Translates the indexing of loop integrals from [Den93] into [tHV79] convention.
`aitalcnotation`	N	Translates the FORM code into FORTRAN readable. The argument $N = 1$ allows for complex masses while $N = 0$ does not
`analyzeterms`		Part of `simplifygrams`
`argsymmetries`		Applies symmetry properties on arguments for loop functions and Gram determinants
`canceldens`		To cancel composition of `den(a,b)*(a-b)=1`
`chisholm`		Applies Chisholm identities by converting all chains of γ matrices that are contracted by their dimensional value
`contgammas`		Simplifies contractions in products of gamma matrices
`contractepsilon`		It contracts the product of two ϵ tensors
`ctfeynmanrules`		Insertion of Feynman rules with counterterms
`definegrams`		Defines a FORM global variable with the explicit expression of a Gram determinant
`derivateself`		Derivates self energies functions
`dimensionfour`		To reach the limit $D \rightarrow 4$ taking care of the UV-behaviour of scalar integrals
`diracequation`		Applies Dirac equation to available spinors
`dummytovar`	N	Part of `simplifygrams`. N stands for the amount of arguments in `dummyN` function
`equalindex`		Gives the same index to potentially different contractions keeping them ordered by number

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Name	Args.	Description
`externalmomenta`		To substitute the internal momenta in loops with external ones
`gamma3to1`		Introduces an ϵ tensor and γ_5 to remove the product of three γ's
`gammaalgebra`		Prepares γ chain structures for `diracequation`
`gammamunu`		Introduces indices in the vector structures
`gramback`	N	Part of `simplifygrams`. Returns the Gram determinant of order N if no simplification was found
`gramsubstitution`	N, w	It substitutes the w-element to match posssible order N Gram determinants
`identifyintegrals`		Picks up the different loop integrals and provides a set of FORM `$`-variables with the right substitutions, inserting the function `LoopIntegral=LI(n)`
`integrationde93`		Procedure to integrate 4,3,2,1-point functions with internal momenta decomposition like in [Den93]
`invgammamunu`		Undoes the `gammamunu` effects
`keepUVloops`		Keeps only integrals actually UV divergent
`loopsymmetries`		Minimize loop integrals in boxes by symmetrizing arguments
`lorentzinvariants`		Adapts scalar product of vectors to Lorentz invariant squared masses
`massconvention`		To use single variables with M instead of MM outside arguments
`massivefofa`	j, c, N	Calculates and saves the formfactors as [Lor05]. `j` stands for topology, `c` for left-right or $\mathbb{1}$-γ_5 and `N=1(0)` do (not) print the formfactors
`movepslash`		Places the desired $\not{p}_i$ to the side of fermion chain to apply `diracequation`
`neglectmass`	`zero`	Neglects positive powers of terms as indicated in the file `Neglectedmasses.inc`. `zero` is the substituted value
`nosymboliccouplings`		To put explicit values of charges and weak couplings
`onshell`		Substitutes external momenta for external particle masses and Mandelstam variables
`pslashaway`		Reorder away the non desired position of $\not{p}_i$
`pushgamma5`		Pushes γ_5 to the right in fermion chains
`pushomegas`		Orders and pushes Left or Right projectors ($\omega_{L,R}$) to the right in fermion chains

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Name	Args.	Description
`recoverargumentsde93`		Catchs back the arguments of loop integrals in combination with `integrationde93`
`reductionDD02`	N	Reduction algorithm from scalar tensor integrals to master integrals given in [DD03]. $N = 1$ sorts after each integral type, $N = 0$ does not sort at all
`reductionLT`		`reductionDD02(1)` with LOOPTOOLS notation
`simplifygrams`		Tries to remove inverse Gram determinants by looking to the numerator (time and memory consuming!)
`simplihelp`	N, r	It helps `simplifygrams` to run sequentially r times from the highest power of one variable for N order Gram determinants
`storeself`	j, c, N	Stores self energies, `j` stands for topology, `c` for left-right or $\mathbb{1}$-γ_5 and `N=1(0)` do (not) print the form factors
`threegammastoepsilon`		Introduces and removes the ϵ tensor simplifying chains of 3 γ matrices that naturally don't dissappear after `diracequation`
`tracefermiloops`		Traces possible fermion loops in self-energies
`transvorlongit`	x	Sets the longitudinal and transverse part of self energies, keeping off-shell but with mass^2 argument x
`unityCKM`		Makes $\mathrm{CKM}_{ij} = \delta_{ij}$
`usegamma5`		Uses γ_5, instead of $\omega_{L,R}$ projectors
`useomegas`		The opposite to `usegamma5`
`vartodummy`		Part of `gramback`, opposite as `dummytovar`

Appendix D

Settings for `main.f`

Variable	Type	Default Value	Meaning
Kinematical			
`icostloop`	integer	`5`	Dimension of `setcostarray`
`isqrtsloop`	integer	`5`	Dimension of `setsqrtsmanarray`
`setcostarray`	double prec.	`data //`	Set of default values for the `setcost` ($\cos\theta$) do loop in the `dcs` evaluation
`setsqrtsmanarray`	double prec.	`data //`	Set of default values for the `setsqrtsman` ($\sqrt{s}$) do loop in the `ICS` evaluation
`setfracomega`	double prec.	`0.1d0`	Limit for the maximum soft photon energy
`setlimcost`	double prec.	`0.9999d0`	Limit of integration for `ics` and `fba`
Process flags			
`lrenorm`	logical	`.true.`	Call the renormalization subroutine to calculate the counterterms parameters
`lwidth`	logical	`.false.`	Call the loop integrals with complex values for boson masses. For the four-point integral, only the case with one massless boson (photon) is considered.
`lidentCKM`	logical	`.false.`	Brings the CKM mixing matrix in a diagonal form, so no mixing occurs
Checking flags			
`luvcheck`	logical	`.false.`	Perform a shift in the `mudim` and `delta` parameters in LoopTools
`lircheck`	logical	`.false.`	Perform a shift in the `lambda` parameter in LoopTools

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Variable	Type	Default Value	Meaning
Output flags			
lcostloop	logical	.true.	Performs a do-loop over setcost
lprintics	logical	.false.	Performs a do-loop over setsqrtsman and prints the results of ics
lprintfba	logical	.false.	Performs a do-loop over setsqrtsman and prints the results of fba
llongoutput	logical	.false.	Prints the cross sections in double precision format

Appendix E

Log of changes to previous version

E.1 Changes in 1.2 to version 1.1

14.12.04 `form/kitFORM3/joinkinematics.frm`: Closing quote mark (") was absent in a comment line when creating the subroutine `dcs.f` for the case of identical particles in final state. Fixed

13.12.04 `diana/prg/particleaspect.prg`: Nicer postscript fonts with Times-Italic instead of Times-Roman[1].

13.12.04 `examples/Default/parameterlist.hf`: Width for the Higgs boson adequated to theoretical expectation.

08.12.04 `fortran/src/d0wdd0.f`: `d0wdd0` function improved for the case of two equal complex numbers giving quotient unity.

E.2 Changes in 1.1 to version 1.0

07.12.04 `fortran/src/cden.f` Function improved to correctly cancel infrarred divergencies with the given `D0w` and `C0w` fixed-width implementation.

07.12.04 `form/kitFORM3/aitalcnotation.prc`: The translation of real mass variables (`MM`s) into complex ones (`cMM`s) did not replace more than once the same variable, leading to inconsistent calls for the `D0w` and `C0w` loop functions for complex masses. This is fixed and tested.

07.12.04 `configure.in`: The command '`which gmake`' does not always return the GNU-MAKE location. This is fixed.

[1] See for instance the standard postscript fonts under `http://www.tac.dk/cgi-bin/info2www?(fontname.info)Standard%20PostScript%20fonts`.

23.11.04 `Makefile.in`: Automatic installation of LoopTools fails when the FORTRAN compiler requires no optimization (`-O0` option) to properly run the FF routine `ffinit`. Now `-O0` is default.

Appendix F

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