Interner Bericht
DESY-Zeuthen 96–05
LMU–03/96
Freiburg–THEP 96/5
März 1996
hep-ph/9603438

GENTLE/4fan

A package of Fortran programs for the description of e^+e^- annihilation into four fermions†

D. Bardin[1,21] , D. Lehner[3], A. Leike[4], T. Riemann[1]

[1] *DESY – Zeuthen, Platanenallee 6, D-15738 Zeuthen, Germany*

[2] *Bogoliubov Laboratory for Theoretical Physics, JINR, ul. Joliot-Curie 6, RU-141980 Dubna, Russia*

[3] *Fakultät für Physik, Albert-Ludwigs-Universität, Hermann-Herder-Str. 3, D-79104 Freiburg, Germany*

[4] *Sektion Physik, Ludwig-Maximilians-Universität, Theresienstr. 37, D-80333 München, Germany*

Abstract

We describe the program package `gentle/4fan`, which consists of the Fortran codes `gentle_4fan.f`, `4fan.f`, and `gentle_nc_qed.f` and is devoted to the description of e^+e^- annihilation into four fermions. The codes are based on the semi-analytical approach. Initial state QED corrections are taken into account. The program versions, which are described here were used in the 1995 workshop 'Physics at LEP 2'.

† *Contributions to the working groups on 'Event Generators for WW Physics' and 'Event Generators for Discovery Physics' of the 1995 Workshop on Physics at LEP 2, to appear in the proceedings (G. Altarelli, T. Sjöstrand and F. Zwirner (eds.), CERN 96–01)*

---

[1] Supported by European Union with grant INTAS–93–744.

1 Introduction

This note collects two slightly updated contributions to the working groups on 'Event Generators for WW Physics' [1] and on 'Event Generators for Discovery Physics' [2] of the Workshop on 'Physics at LEP 2' held at CERN in 1995. The underlying formulae may be found in references [3]–[9]. In this series of papers we advocate a semi-analytical approach to the reaction

$$e^+e^- \to f_1\bar{f}_1 f_2\bar{f}_2(n\gamma). \tag{1}$$

The approach is characterized by the attempt to perform at least part of the eight-dimensional phase space integration analytically. As a result, the numerical integrations are smoothened and often faster than in a completely numerical approach. Further, the numerical accuracy is well under control. The analytical integrations are performed over (part of) the angular variables, while the boson invariant masses are left for numerical integration.

Four-fermion production processes may be very complex and proceed via a large variety of intermediate states. Doubly resonant processes are usually calles 'basic processes'. The others are called background contributions. We repeat the classification of reference [5], with the number of Feynman diagrams in the charged current (CC) classes are shown in table 1 and for the final states corresponding to the neutral current (NC) classes in table 2.

	$\bar{d}u$	$\bar{s}c$	$\bar{e}\nu_e$	$\bar{\mu}\nu_\mu$	$\bar{\tau}\nu_\tau$
$d\bar{u}$	*43*	**11**	20	**10**	**10**
$e\bar{\nu}_e$	20	20	*56*	18	18
$\mu\bar{\nu}_\mu$	**10**	**10**	18	*19*	**9**

Table 1: *Number of Feynman diagrams for class CC final states.*

	$\bar{d}d$	$\bar{u}u$	$\bar{e}e$	$\bar{\mu}\mu$	$\bar{\nu}_e\nu_e$	$\bar{\nu}_\mu\nu_\mu$
$\bar{d}d$	4·16	*43*	48	**24**	21	**10**
$\bar{s}s, \bar{b}b$	**32**	*43*	48	**24**	21	**10**
$\bar{u}u$	*43*	4·16	48	**24**	21	**10**
$\bar{e}e$	48	48	4·36	48	*56*	20
$\bar{\mu}\mu$	**24**	**24**	48	4·12	19	*19*
$\bar{\tau}\tau$	**24**	**24**	48	**24**	19	**10**
$\bar{\nu}_e\nu_e$	21	21	*56*	19	4·9	12
$\bar{\nu}_\mu\nu_\mu$	**10**	**10**	20	*19*	12	4·3
$\bar{\nu}_\tau\nu_\tau$	**10**	**10**	20	**10**	12	**6**

Table 2: *Number of Feynman diagrams for class NC final states.*

2 GENTLE/4fan

Authors:

D. Bardin[a] `bardin@ifh.de`
M. Bilenky[a] `bilenky@ifh.de`
D. Lehner[b] `lehner@phyv4.physik.uni-freiburg.de`
A. Leike[a] `leike@graviton.hep.physik.uni-muenchen.de`
A. Olchevski[a] `OLSHEVSK@VXCERN.CERN.CH`
T. Riemann[a] `riemann@ifh.de`

[a] FORTRAN code `gentle_4fan.f`
[b] FORTRAN code `gentle_nc_qed.f`

Description of the package

The **GENTLE/4fan** package is designed to compute selected total four-fermion production cross-sections and final-state fermion pair invariant mass distributions for charged current (*CC*) and neutral current (*NC*) mediated processes within the Standard Model (SM). For the *CC03* subprocess, the *W* production angular distribution is also accessible. In the *NC* case, SM Higgs Production is included. The phase space integration is carried out by a semi-analytical technique, which is described below. The **GENTLE/4fan** package is written in **Fortran**. It consists of two branches. The basic branch **gentle_4fan.f** contains all features of the package but complete initial-state radiation (ISR) to *NC* processes. The subroutine **FOURFAN**, which is called by **gentle_4fan.f** performs the computation of *NC* cross-sections and is described in the next section.The independent branch **gentle_nc_qed.f** includes complete ISR to *NC02* and *NC08* and will be merged into **gentle_4fan.f**.

Program features:

1. **Method of integration:**
   The package is a *semi-analytical* one. Without (with) ISR, the phase space is parametrized by five (seven) angular variables and the final-state fermion pair invariant masses (plus the reduced center of mass energy squared). All angular phase space variables are integrated analytically. The resulting formulae are input to the package. Invariant masses are subsequently integrated numerically with a self-adaptive Simpson algorithm. Optionally, for the *CC03* subprocess, the W production angle may also be numerically integrated. The method is numerically stable and, in most cases, very fast.

2. **Possible final states:**
   The package may treat all four-fermion final states which do not contain identical particles, electrons, or electron neutrinos. This means that the package accesses all final states that are described by *annihilation* and *conversion* type Feynman diagrams:

(1) *CC03* (with complete ISR) [3]

(2) *NC02*, *NC08* (with complete ISR) [9]

(3) *CC9*, *CC10*, *CC11* [8]

(4) *NC06*, *NC10*, *NC24*, *NC32* [6]

(5) *NC* + Higgs [7]

Via flags, cross-sections for subsets of Feynman diagrams may be extracted.

3. **Cuts**
Cuts may be imposed on invariant masses of fermion pairs and on the invariant mass of the final-state four-fermion system. Using the structure function approach in **`gentle_4fan.f`**, cuts on the electron/positron momentum fraction can be imposed. For the *CC03* subprocess, cuts on the W production angle are enabled.

4. **Initial state radiation**
ISR is implemented into the package. *Universal* ISR is present for all processes [8]. In addition, the package includes complete, i.e. *universal* and *non-universal* ISR for the *CC03*, *NC02*, and *NC08* processes [3, 9]. *Non-universal* ISR does not contribute to *annihilation* diagrams. It may be argued that *non-universal* ISR is very small, $\mathcal{O}(10^{-3})$, for *conversion-annihilation* interferences. The speed of the package is reduced, if *non-universal* ISR is included, due to its complex analytical structure.

5. **Final state radiation**
Final state radiation is not implemented.

6. **Treatment of final state decays**
Final state decays are not accounted for.

7. **Treatment of the Coulomb Singularity**
The Coulomb singularity is included according to reference [4].

8. **Treatment of the Anomalous Couplings**
Anomalous couplings are not included.

9. **Treatment of masses**
In general, final-state masses are neglected in the matrix elements. Where needed, however, masses are retained in the phase space. In addition, masses of heavy particles coupling to the Higgs boson are taken into account where appropriate; see section 3.

10. **Hadronization**
No interface to hadronization is foreseen.

Input parameters

All input parameters are set inside the `Fortran` code. `gentle_4fan.f` uses the following flags, set in the subroutine `WWINOO`:

`IBCKGR`:	*CC03* case (`IBCKGR`=0) or *CC11* case (`IBCKGR`=1)
`IBORNF`:	Tree level (`IBORNF`=0) or ISR corrected (`IBORNF`=1) quantities
`ICHNNL`:	*CC03* (`ICHNNL`=0), *CC11* with specific final state [$l_1\nu_1 l_2\nu_2$(`ICHNNL` = 1), $l\nu q\bar{q}$ (`ICHNNL` = 2, 3), $q_1\bar{q}_1 q_2\bar{q}_2$ (`ICHNNL` = 4)], and inclusive *CC11* (`ICHNNL`=5)
`ICOLMB`:	Inclusion of Coulomb singularity (`ICOLMB`=1,...,5) or not (`ICOLMB`=0) Recommended value: `ICOLMB`=2
`ICONVL`:	Flux function (`ICONVL`=0) or structure function approach (`ICONVL`=1) for ISR. Recommended value: `ICONVL`=0
`IGAMZS`:	Constant Z width (`IGAMZS`=0) or s-dependent Z width (`IGAMZS`=1)
`IINPT`:	Input for tuned comparison [10] (`IINPT`=0) or preferred input (`IINPT`=1)
`IIQCD`:	Naive inclusive QCD corrections are included (`IIQCD`=1) or not (`IIQCD`=0)
`IMMIM`:	Minimum number of a moment requested by `IREGIM`
`IMMAX`:	Maximum number of a moment requested by `IREGIM`
`IONSHL`:	On-shell (`IONSHL`=0) or off-shell heavy bosons (`IONSHL`=1)
`IPROC` :	*CC* case (`IPROC`=1) or *NC* case (`IPROC`=2, call to `FOURFAN` is initialized)
`IQEDHS`:	Determination of the *universal* ISR radiator: $\mathcal{O}(\alpha)$ exponentiated (`IQEDHS`=–1,0); $\mathcal{O}(\alpha)$ exponentiated plus different $\mathcal{O}(\alpha^2)$ contributions (`IQEDHS`=1,...,4) Recommended value: `IQEDHS`=3
`IREGIM`:	Calculation of the total cross-section (`IREGIM`=0), the moments of the radiative loss of final-state four-fermion invariant mass (`IREGIM`=1), the moments of the radiative energy loss (`IREGIM`=2), the moments of the W mass shift $\left(\sqrt{s_+}+\sqrt{s_-}-2M_W\right)$ (`IREGIM`=3), and the first moments of $\cos(n\theta_W)$, $n = 1, ..., 4$ (`IREGIM`=4)
`IRMAX` :	Maximum value of `IREGIM`
`IRSTP` :	Step in a DO loop over `IREGIM`
`ITVIRT`:	*Non-universal* virtual ISR included (`ITVIRT`=1) or not (`ITVIRT`=0)
`ITBREM`:	*Non-universal* bremsstrahlung included (`ITBREM`=1) or not (`ITBREM`=0)
`IZERO` :	See equation (4.5) of [8]. Recommended value: `IZERO`=1
`IZETTA`:	See equation (4.21) of [8]. Recommended value: `IZETTA`=1

In the `gentle_nc_qed.f` branch, only the flags `IBORNF, IONSHL, ITVIRT, ITBREM` are used. The additional flag `IBOSON` in `gentle_nc_qed.f` distinguishes between the *NC02* and the *NC08* processes.

The center of mass energy squared is chosen by setting the variable `IREG` and the parameters `ISMAXA` or `ISMAXB` in the main program. The following input may be changed by the user:

$$
\begin{aligned}
\texttt{GFER} &= G_\mu &&= 1.16639 \times 10^{-5}\ \mathrm{GeV}^{-2}, \text{ the Fermi coupling constant} \\
\texttt{ALPW} &= \alpha(2M_W) &&= 1/128.07, \text{ the running fine structure constant at } 2\,M_W \\
\texttt{AME} &= m_e &&= 0.51099906 \times 10^{-3}\ \mathrm{GeV}, \text{ the electron mass} \\
\texttt{AMZ} &= M_Z &&= 91.1888\ \mathrm{GeV}, \text{ the } Z \text{ mass,} \\
\texttt{AMW} &= M_W &&= 80.230\ \mathrm{GeV}, \text{ the } W \text{ mass} \\
\texttt{GAMZ} &= \Gamma_Z &&= 2.4974\ \mathrm{GeV}, \text{ the } Z \text{ width} \\
\texttt{ALPHS} &= \alpha_s(2M_W) &&= 0.12
\end{aligned}
$$

Output

The following derived quantities are computed in **gentle_4fan.f** and printed in the output:

$$
\begin{aligned}
\texttt{GAMW} &= \Gamma_W \;=\; \frac{9}{6\sqrt{2}\pi}\, G_\mu M_W^3 \left(1 + \frac{2\alpha_s(2M_W)}{3\pi}\right) \\
\texttt{SIN2W} &= \sin^2\theta_W \;=\; 1 - M_W^2/M_Z^2 \\
\texttt{GAE} &= -\frac{e}{4 s_W c_W} \;=\; -\frac{\sqrt{4\pi\alpha(2M_W)}}{4 s_W c_W} \\
\texttt{GVE} &= \texttt{GAE} \cdot (1 - 4 s_W^2) \\
\texttt{GWF} &= \frac{g}{2\sqrt{2}} = -\texttt{GAE} \cdot \sqrt{2} c_W \\
|\texttt{GWWG}| &= \sqrt{4\pi\alpha(2M_W)} \\
|\texttt{GWWZ}| &= |\texttt{GWWZ}| \cdot \frac{c_W}{s_W}
\end{aligned}
$$

GVE and GAE are the electron vector and axial vector couplings, GWF is the fermion-W coupling, and |GWWG| and |GWWZ| are the trilinear gauge boson couplings for the photon and the Z respectively. Further the output repeats the flag settings. After the cross-section calculation, the following output is printed:

$$
\begin{aligned}
\texttt{SQS} &= \sqrt{s} \\
\texttt{XSECO} &= \sigma_{\mathrm{tot}}(s) \quad \text{in nanobarns}
\end{aligned}
\tag{2}
$$

In addition, the calculated MOMENTS are printed. In the first column IREGIM is printed. The second column is arranged in blocks of three lines each. The first line contains the integer n. The second line contains the n^{th} moment of the physical quantity indicated by IREGIM. The third line contains the dimensionless n^{th} moment obtained through division of the n^{th} moment by the proper power of $\sqrt{s}/2$.

Although variable names are slightly different, **gentle_nc_qed.f** uses the same derived quantities as **gentle_4fan.f**. For one run, **gentle_nc_qed.f** outputs the used flag values together with the fermion code numbers IFERM1/IFERM2, the color factors RNCOU1/RNCOU2, the masses AM1/AM2, and the invariant pair mass cuts CUTM12,CUTM34 for the final-state fermion pairs. In addition, the lower cut CUTXPR on the ratio of the four-fermion invariant mass squared over the center of mass energy squared, s'/s is output. The main output, however, is an array of center of mass energies and the corresponding total cross-sections.

Availability

The codes and this description are available from the authors upon E-Mail request or via WWW

`gentle_4fan.f`	from	`http://www.ifh.de/~bardin/gentle_4fan.uu`
`gentle_nc_qed.f`	from	`http://www.ifh.de/~lehner/gentle_nc_qed.uu`
DESY-Zeuthen 96–05	from	`http://www.ifh.de/theory/publist.html`

3 4fan version 1.3

Authors:

D. Bardin	`bardin@ifh.de`
A. Leike	`leike@graviton.hep.physik.uni-muenchen.de`
T. Riemann	`riemann@ifh.de`

Description of the package

`4fan` is a semi-analytical program which calculates the process

$$e^+e^- \to f_1\bar{f}_1f_2\bar{f}_2, \tag{3}$$

where the three involved fermions e, f_1 and f_2 must be in different electroweak multiplets (the *NC32* class) [6]; see table 2. Optionally, Standard Model Higgs production can be included [7]. For calculations at the Born level, `4fan` can be used as a stand-alone program. For the calculation of cross-sections including initial state radiation, the initial state radiation environment of the code `gentle_4fan.f` must be used which calls `FOURFAN` as a subroutine. For the description of `gentle_4fan.f` we refer to section 2. In the following, we describe the stand-alone program `4fan.f`:

Six of the eight integrations of the four particle phase space were done analytically. The two remaining integrations over $s_1 = [p(f_1) + p(\bar{f}_1)]^2$ and $s_2 = [p(f_2) + p(\bar{f}_2)]^2$ are performed numerically allowing the inclusion of cuts for these variables.

Finite mass effects are taken into account using the following approximations:

- The phase space is treated exactly.
- In the Higgs contributions and the conversion diagrams $e^+e^- \to (\gamma\gamma) \to f_1\bar{f}_1f_2\bar{f}_2$, the masses are treated up to order $O[m^2(f_i)/s_i]$.
- Fermion masses are treated identically in traces and Higgs couplings.
- The Higgs width is calculated including the decays into b-, c- and τ-pairs.

The numbers quoted in the tables of the report [10] are produced for zero fermion masses except in the Higgs couplings. The Higgs propagator is always connected with s_2 by convention.

The initialization routine `BBMMIN` contains the input from the Particle Data Group [11]. In the subroutine `DSDSHSZ`, the interferences between the three main subsets of the diagrams of the *NC32* class are calculated as well as those with the Higgs signal diagram. Their sum yields the double differential cross-section. Single interferences between these subsets are not printed.

The numerical integration is done by a twofold application of a one-dimensional self-adaptive Simpson algorithm with control over the relative and the absolute error. The singularities due to resonant vector boson propagators are eliminated by transformations of the integration variables. To avoid numerical instabilities, the kinematical functions resulting from the six-fold analytical integration are replaced by Taylor expansions near the borders of the phase space. The shortest calculation time is achieved by a choice of the required absolute and relative errors in such a way that they give approximately equal contributions to the error of the output.

The calculation time of a Born cross-section is several seconds on an HP workstation, depending on the required accuracy and the cuts on s_1 and s_2. Ten times higher accuracy needs approximately two times longer calculational time.

Input and output are transferred through the arguments of the subroutine only.

Usage of the program:

```
CALL FOURFAN(EPS,ABSE,IF1,IF2,S,S1MIN,S1MAX,S2MIN,S2MAX,AMH,IOUT,OUT)
```

Input:

`EPS,ABSE:`		The required relative and absolute error. If one of the two criteria is fulfilled, the calculation stops.
`IF1,IF2:`		Integers specifying the two final fermion pairs as in the Monte Carlo particle numbering scheme, see Particle Data Group [11], chapter 32.
`S:`		The c.m. energy squared of the e^+e^- pair.
`S1MIN,S1MAX:`		The integration bounds of s_1.
`S2MIN,S2MAX:`		The integration bounds of s_2.
`AMH:`		The Higgs mass.
`IOUT:`		Integer, selecting the output. Currently `IOUT`=1, 2, 11 and 12 are implemented:
	`IOUT=1:`	Total cross-section σ_t without Higgs.
	`IOUT=2:`	Differential cross-section $d\sigma/ds_2$ without Higgs.
	`IOUT=11, 12:`	The same as `IOUT=1, 2` but *with* Higgs.

The units of the input (if required) are GeV^2 or GeV.

Output: `OUT` Depends on the value of `IOUT`. The output is given in fb or in fb/GeV.

On HP workstations **4fan** must be compiled with the -K option.

Availability

The code and this description are available from the authors upon E-Mail request or via FTP or WWW

`4fanv13.f`	from	`ftp://gluon.hep.physik.uni-muenchen.de`
`4fanv13.f`	from	`http://www.ifh.de/theory/publist.html`
DESY-Zeuthen 96–05	from	`http://www.ifh.de/theory/publist.html`

4 Concluding remarks

Not all of the final-state topologies of tables 1 and 2 have been treated by our approach so far. Those which have been treated belong to the classes *CC11* and *NC32* and are printed in **boldface** in the tables.

Presently we are studying the semi-leptonic and leptonic processes of the classes *CC20, NC48, NC21*, which are printed in the tables in roman [12].

For a complete treatment of the *NC32* class, the four jet production from e^+e^- annihilation into $q\bar{q}gg$ has to be covered in addition to $4f$ production [13].

Besides a verification of the Standard Model predictions for WW and ZZ pair production and in Higgs boson searches via ZH production, one is also interested in searches for anomalous triple gauge boson couplings. A description of *CC03, CC11* cross-sections with anomalous couplings is under development [14].

For a detailed study of the underlying physics, angular distributions are extremely helpful. Although in the semi-analytical approach one has a limited flexibility concerning distributions and cuts, we made several attempts to calculate some of them [8, 14, 15].

References

[1] D. Bardin, D. Lehner, A. Leike and A. Olchevski, contribution to the report of the Working Group *Event Generators for WW Physics*, D. Bardin and R. Kleiss (conveners), in: G. Altarelli, T. Sjöstrand and F. Zwirner (eds.), Proceedings of the Workshop *Physics at LEP 2*, CERN 96–01, to appear.

[2] A. Leike and T. Riemann, contribution to the report of the Working Group *Event Generators for Discovery Physics*, M.L. Mangano and G. Ridolfi (conveners), in: G. Altarelli, T. Sjöstrand and F. Zwirner (eds.), Proceedings of the Workshop *Physics at LEP 2*, CERN 96–01, to appear.

[3] D. Bardin, M. Bilenky, A. Olchevski and T. Riemann, *Off Shell W Pair Production in e^+e^- Annihilation: Initial State Radiation*, *Phys. Lett.* **B308** (1993) 403; E: *Phys. Lett.* **B357** (1995) 725; complete revised version: hep-ph/9507277.

[4] D. Bardin, W. Beenakker and A. Denner, *The Coulomb Singularity in Off Shell W Pair Production*, *Phys. Lett.* **B317** (1993) 213.

[5] D. Bardin, M. Bilenky, D. Lehner, A. Olchevski and T. Riemann, *Semianalytical Approach to Four Fermion Production in e^+e^- Annihilation*, in: T. Riemann and J. Blümlein (eds.), Proc. of the Zeuthen Workshop *Elementary Particle Theory – Physics at LEP200 and*

Beyond, Teupitz, Germany, April 10–15, 1994, *Nucl. Phys.* (Proc. Suppl.) **37B** (1994) p. 148 [hep-ph/9406340].

[6] D. Bardin, A. Leike and T. Riemann, *The Process $e^+e^- \to l\bar{l}Q\bar{Q}$ at LEP and NLC*, *Phys. Lett.* **B344** (1995) 383.

[7] D. Bardin, A. Leike and T. Riemann, *Higgs Production in $e^+e^- \to l\bar{l}Q\bar{Q}$ at LEP and NLC*, *Phys. Lett.* **B353** (1995) 513.

[8] D. Bardin and T. Riemann, *Off Shell W Pair Production in e^+e^- Annihilation: the CC11 Process*, preprint DESY 95–167 (1995), to appear in *Nucl. Phys.* **B** [hep-ph/9509341].

[9] D. Bardin, D. Lehner and T. Riemann, *Complete Initial State QED Corrections to Off Shell Gauge Boson Pair Production in e^+e^- Annihilation*, preprint DESY 96–028 (1996) [hep-ph/9602409];
D. Lehner, *Initial State Radiative Corrections to Z Pair Production in e^+e^- Annihilation - The Semi-Analytical Approach*, Ph.D. thesis, Humboldt-Universität zu Berlin (1995), DESY-Zeuthen 95-07, [hep-ph/9512301], available from `http://www.ifh.de/~lehner`.

[10] D. Bardin and R. Kleiss et al., report of the Working Group *Event Generators for WW Physics*, in: G. Altarelli, T. Sjöstrand and F. Zwirner (eds.), Proceedings of the Workshop *Physics at LEP 2*, CERN 96–01, to appear.

[11] Particle Data Group (L. Montanet et al.) *Review of Particle Properties*, *Phys. Rev.* **D40** (1994) 1173.

[12] D. Bardin, J. Biebel, A. Leike and T. Riemann, under investigation.

[13] M. Jack and A. Leike, in progress.

[14] J. Biebel and T. Riemann, in progress; a preliminary Fortran program exists.

[15] A. Leike, in: B. Kniehl (ed.), Proceedings of the Workshop *Perspectives for electroweak interactions in e^+e^- collisions*, Ringberg, Germany, February 1995 (World Scientific, Singapore, 1995), p. 121 [hep-ph/9504358].