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SIX-FERMIONS (AND MORE) STUDIES

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We review the available event generators suited for multi-fermion final state production in the context of physics studies at a future Linear Collider (LC)

1 Why six (and more !) fermions at LCs ?

While LEP1 ($\sqrt{s} = M_Z$) was the realm of two-fermion processes ($e^+e^- \to Z \to f\bar{f}$, $f = q, \ell$) and LEP2 ($\sqrt{s} \gtrsim 2M_V$, $V = W, Z$) was the arena for four-fermion reactions ($e^+e^- \to VV \to f\bar{f}f'\bar{f}'$), future LCs ($\sqrt{s} = 350 - 800$ GeV) will open the era of multi-fermion channels in both Standard Model (SM),

$$\begin{aligned}
e^+e^- &\to t\bar{t} \to (bW^+)(\bar{b}W^-) \to 6f \ \ (\mathrm{Top-quarks}),\\
&\to Zh \to (f\bar{f})(VV) \to 6f \ \ (\mathrm{Higgs-strahlung}),\\
&\to \nu_e\bar{\nu}_e[e^+e^-]h \to \nu_e\bar{\nu}_e[e^+e^-](VV) \to 6f \ \ (\text{Vector Boson Fusion}),\\
&\to W^+W^-Z[ZZZ] \to\to 6f \ \ (\text{Quartic Gauge Couplings}),\\
&\to Zhh \to (f\bar{f})(b\bar{b})(b\bar{b}) \ \ (\mathrm{Higgs\ self-couplings}),\\
&\to \nu_e\bar{\nu}_e[e^+e^-]hh \to \nu_e\bar{\nu}_e[e^+e^-](b\bar{b})(b\bar{b}) \ \ (ditto),\\
&\to t\bar{t}h \to 8f \ \ (\mathrm{Top-Yukawa-coupling}),
\end{aligned}$$

and general 2-Higgs Doublet Models,

$$\begin{aligned}
e^+e^- \to AH &\to (b\bar{b})(VV) \to 6f \ \ (\mathrm{Pseudoscalar-Higgs}),\\
e^+e^- \to H^+H^- &\to (t\bar{b})(\tau^-\bar{\nu}_\tau)[(t\bar{b})(\bar{t}b)] \to 6f[8f] \ \ (\mathrm{Charged-Higgs}).
\end{aligned}$$

Given the interesting physics accessible through multi-fermion processes, it is of paramount importance to *develop* suitable computational tools as well as *test* these in view of their phenomenological applications.

2 Two categories of computational tools

1. Standard Monte Carlo (MC) *event* generators: e.g., `PYTHIA` [1], `HERWIG` [2] and `ISAJET` [3], wherein the above final states are typically produced via resonant

subprocesses (e.g., $t\bar{t}$, H^+H^-, etc.) and with no irreducible background but have added QCD (and QED) Parton Shower (PS) and hadronisation.

2. So-called *parton* generators: they can compute both signal and irreducible background in multi-fermion processes (including interference effects) but traditionally lack the PS and hadronisation treatment of quarks and gluons. The latter can be further categorised in:

<u>Multi-purpose generators,</u> such as: `GRACE` [4]; `HELAS/MadGraph/MadEvent` [5,6]; `Whizard+Omega/MadGraph/CompHEP` [7,8,9]; `SHERPA/AMEGIC++` [10]; `HELAC/PHEGAS` [11,12]. Their appealing features are that they can provide in a (semi-)automated way a vast choice of final states, with a uniform setup for different process classes, thus being ideally suited for studying the physics potential of future colliders. Their drawbacks are that they are lengthy codes, in which the insertion of radiative corrections becomes problematic, so that they are not normally used as high-precision tools.

<u>Dedicated generators ($e^+e^- \to 6f$, no $8f$ yet)</u>, such as: `eett6f` [13], for $e^+e^- \to t\bar{t} \to b\bar{b} + 4f$ processes, including QCD graphs; `Lusifer` [14], generating all $6f$ final states (with massless fermions), but not via $\mathcal{O}(\alpha_s^4)$; `SIXFAP` [15], wherein all $6f$ final states are available (with massive fermions) but the inclusion of QCD effects is still in progress. (A similar code, currently under development, is `SIXPHACT` [16].) The pluses of these codes is that they are optimised for efficient event generation and that higher order effects can easily be included, thus rendering them ideal tools for high precision studies. The minuses are that the number of final states is necessarily limited.

Finally, it should be noted that for $f = q$, where q represent a quark, only *jets* can be observed, so that gluon final states need to be included too: e.g., $q\bar{q}q'\bar{q}'gg$ and $q\bar{q}gggg$ alongside $q\bar{q}q'\bar{q}'q''\bar{q}''$, through $\mathcal{O}(\alpha_s^4)$. Multi-purpose generators can compute these gluon final states and also dedicated codes (such as `SIXRAD` [17]) exist. Besides, an interface to the PS is required for their phenomenological investigations, e.g., through the Les Houches Accord (LHA) [18]. (`SHERPA` has its own PS, via the `APACIC++` routines [19].)

3 Current studies

The 'Generators' Working Group (WG) of the current ECFA Study of Physics and Detectors for a Linear Collider is engaged in systematic studies of multi-fermion final states following a three-step procedure: 1) test of matrix elements and phase space; 2) comparisons for physics-oriented observables; 3) detector studies. (Comparisons can be automated by using MC-tester [20] and Java interfaces [21].) Stage 1) has now been completed. In Tab. 1 we present a sample of the many results obtained so far: see [22,23] and [24] for setup. The codes display a remarkable agreement thus motivating the WG to moving onto phase 2).

σ [fb]	`AMEGIC++`	`eett6f`	`Lusifer`	`HELAC`	`SIXFAP`	`Whizard`
$\nu_e e^+ e^- \bar{\nu}_e b b$	5.879(8)	5.862(6)	5.853(7)	5.866(9)	5.854(3)	5.875(3)
$\nu_e e^+ \mu^- \bar{\nu}_\mu b\bar{b}$	5.827(4)	5.815(5)	5.819(5)	5.822(7)	5.815(2)	5.827(3)
$\nu_\mu \mu^+ \mu^- \bar{\nu}_\mu b\bar{b}$	5.809(5)	5.807(3)	5.809(5)	5.809(5)	5.804(2)	5.810(3)
$\nu_\mu \mu^+ \tau^- \bar{\nu}_\tau b\bar{b}$	5.800(3)	5.797(5)	5.800(4)	5.798(4)	5.798(2)	5.796(3)

σ [fb]	QCD	`AMEGIC++`	`HELAC`
$\mu^- \mu^+ b\bar{b}b\bar{b}$	yes	3.096(60)e-02	3.019(43)e-02
	no	2.34(12)e-02	2.36(10)e-02

Table 1: Comparison among multi-fermion codes for selected final states.

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