carlomat

a program for automatic computation of multiparticle cross sections

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Motivation

Increasing energy of initial beams at particle colliders such as LHC, or ILC $\Rightarrow$ reactions with a few heavy particles in the final state become possible.

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SM radiative corrections should be included, at least the leading ones.

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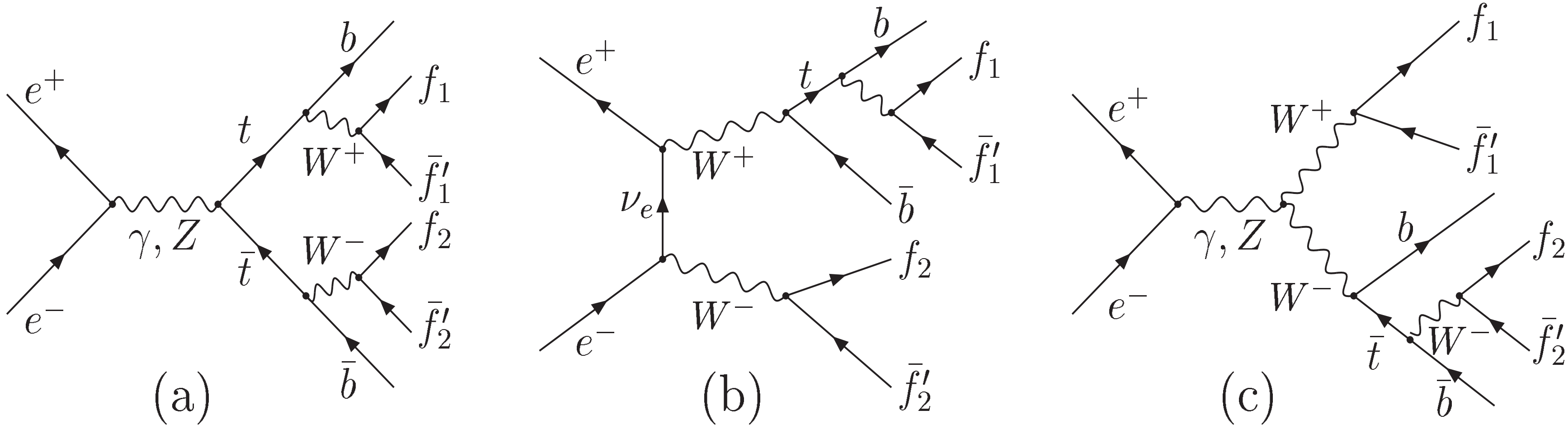
- and W's decay into $f\bar{f}'$-pairs,

$\Rightarrow$ 6 fermion reactions of the form

$$e^+e^- \longrightarrow bf_1\bar{f}_1'\bar{b}f_2\bar{f}_2',$$

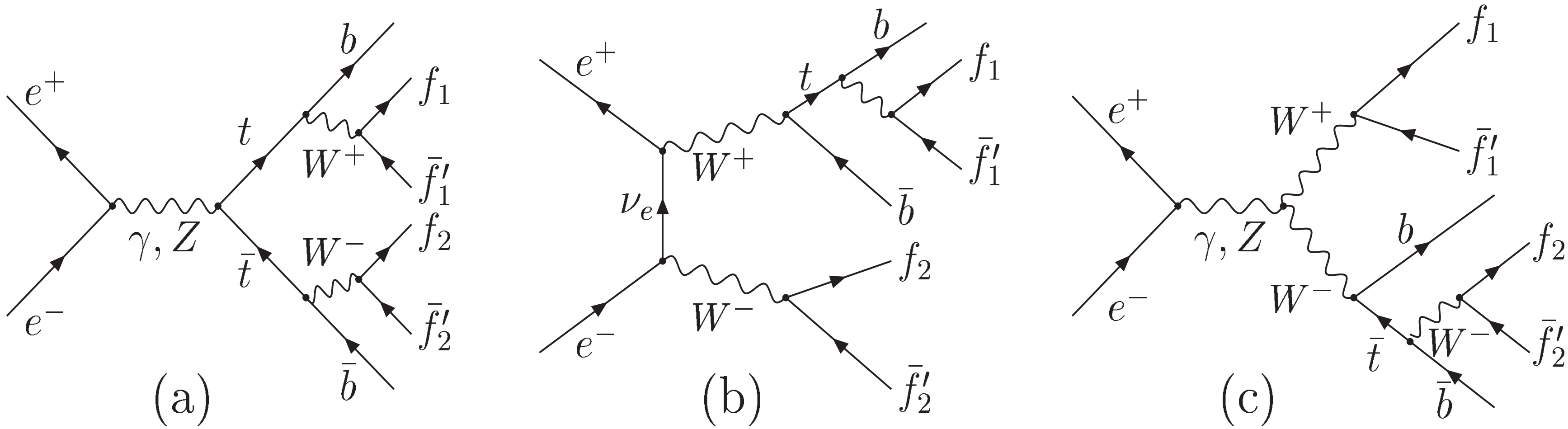
where $f_1, f_2' = \nu_e, \nu_\mu, \nu_\tau, u, c$ and $f_1', f_2 = e^-, \mu^-, \tau^-, d, s$, should be studied with a complete set of the Feynman diagrams, possibly including radiative corrections.

Feynman diagrams of $e^+e^- \to b f_1 \bar{f}_1' \bar{b} f_2 \bar{f}_2'$



(a) ‘signal’, (b) and (c) ‘background’.

Feynman diagrams of $e^+e^- \to b f_1 \bar{f}'_1 \bar{b} f_2 \bar{f}'_2$



(a) 'signal', (b) and (c) 'background'.

- $e^+e^- \to b\nu_\mu\mu^+\bar{b}\mu^-\bar{\nu}_\mu \quad \Rightarrow \quad$ 452 diagrams
- $e^+e^- \to bu\bar{d}\bar{b}d\bar{u} \quad \Rightarrow \quad$ 1484 diagrams

in the unitary gauge of SM, neglecting the Higgs boson couplings to fermions lighter than b.

EW radiative corrections

$$e^+e^- \to t\bar{t} \to bf_1\bar{f}_1'\bar{b}f_2\bar{f}_2'$$

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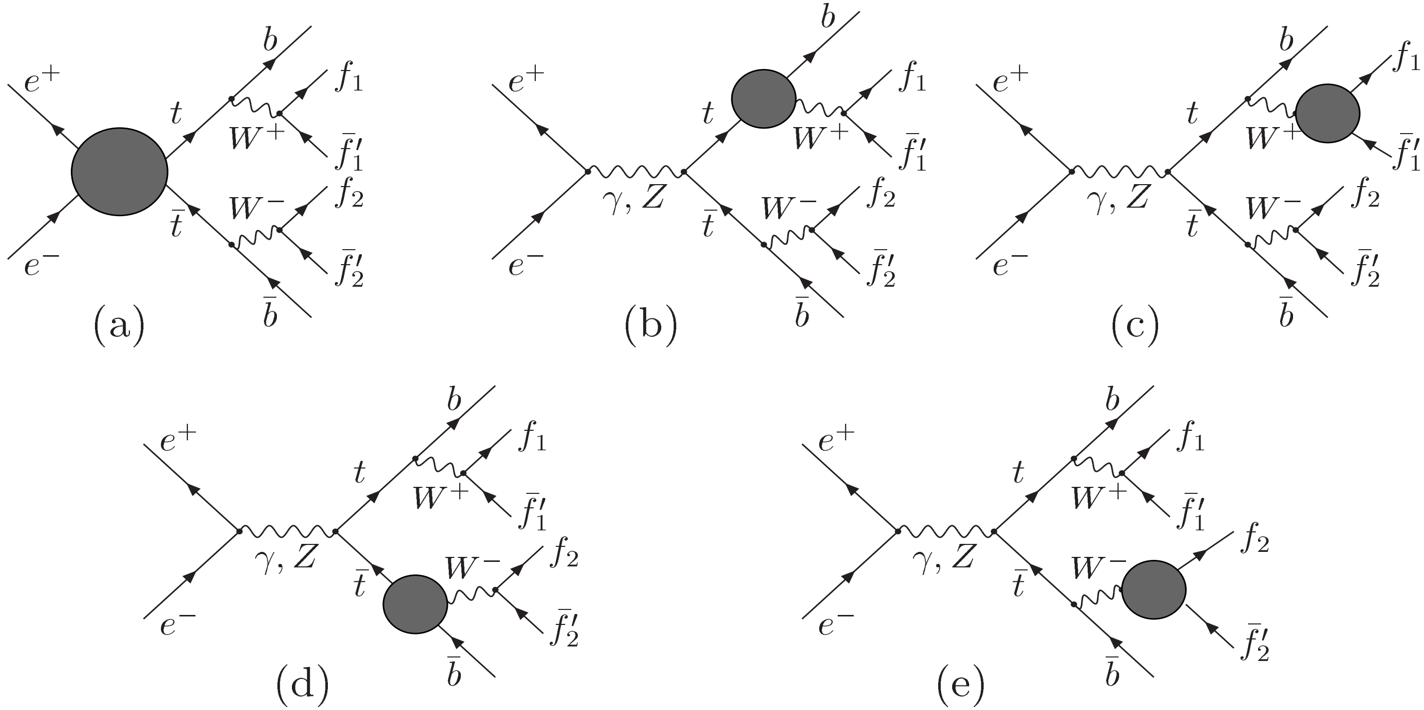

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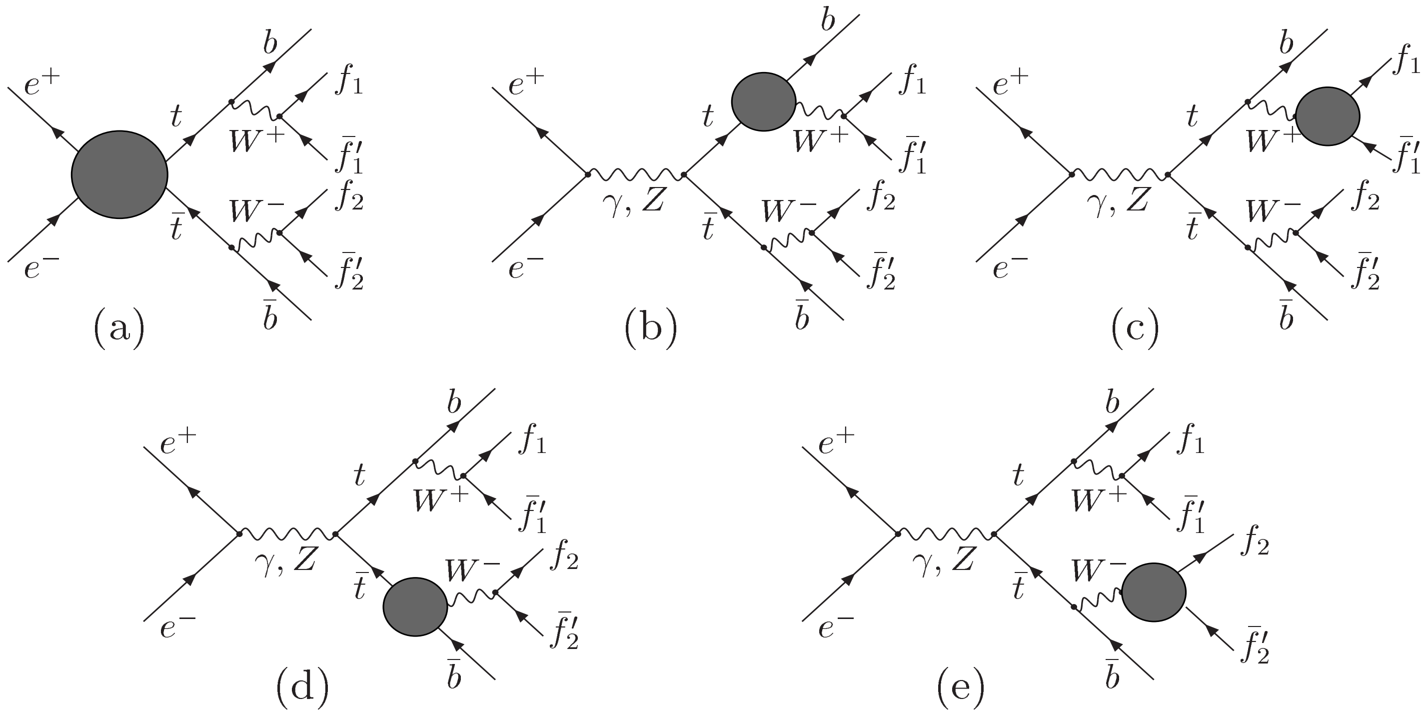

- (a) calculated with a subroutine based on `topfit`, by T. Riemann, *et al.*,
- (b)–(e) with subroutines written by A. Staroń.

$e^+e^- \to t\bar{t}H$

If the Higgs boson has mass below the $t\bar{t}$ threshold, $m_H < 2m_t$, then $t\bar{t}H$ Yukawa coupling can be best determined from this reaction [Djouadi, Kalinowski, Zerwas].

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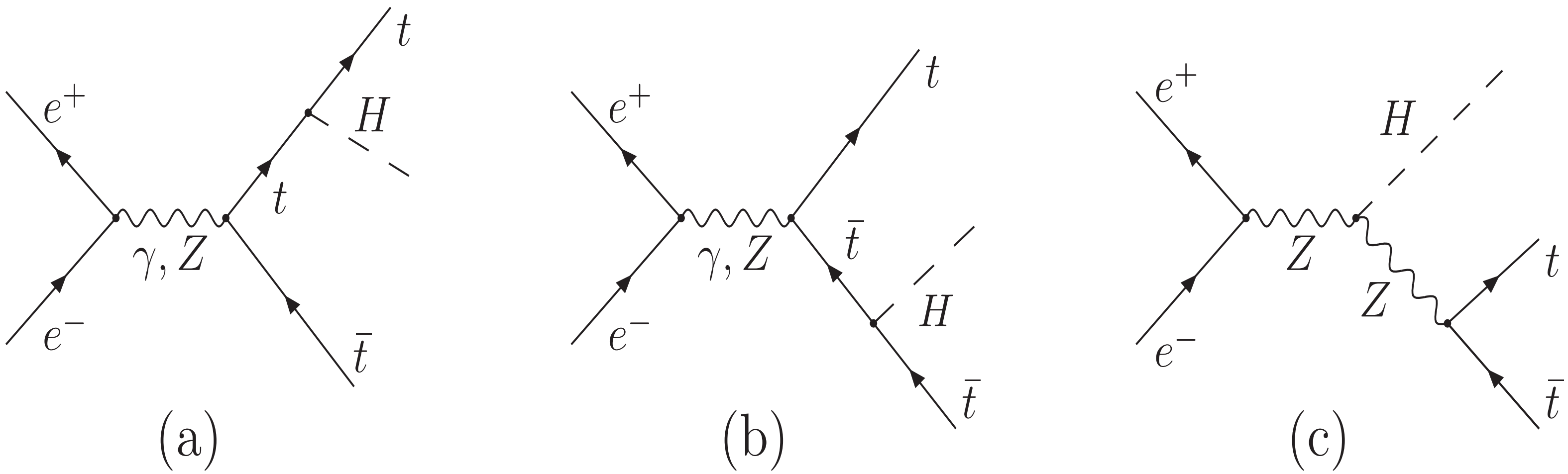

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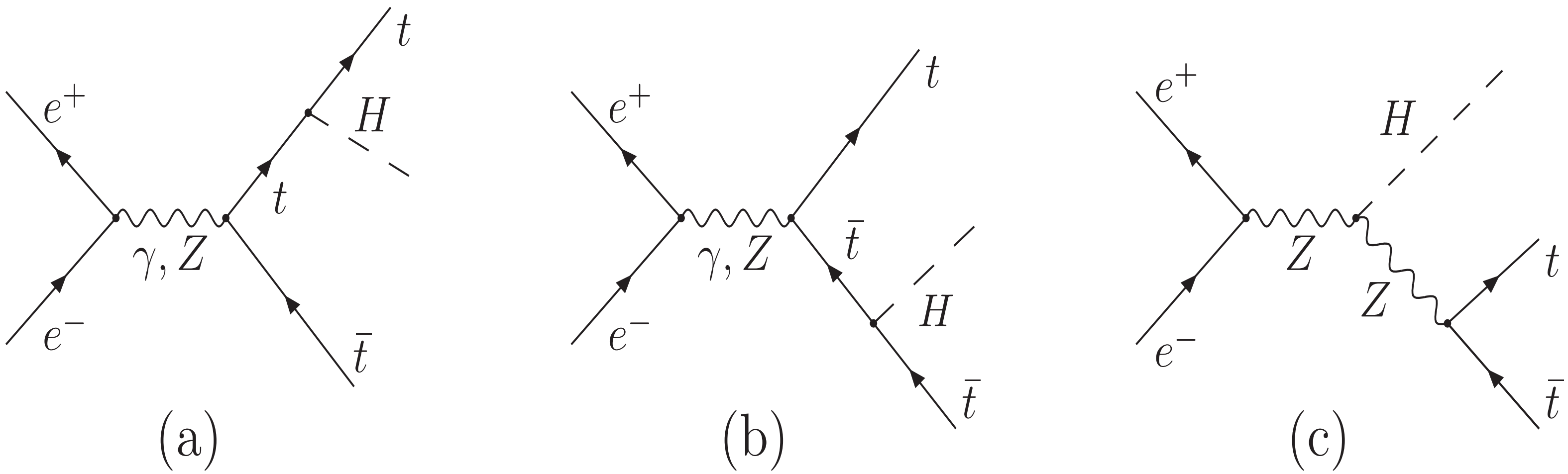

Diagrams (a) i (b) dominate $\Rightarrow$ the cross section $\sim g_{ttH}^2$.

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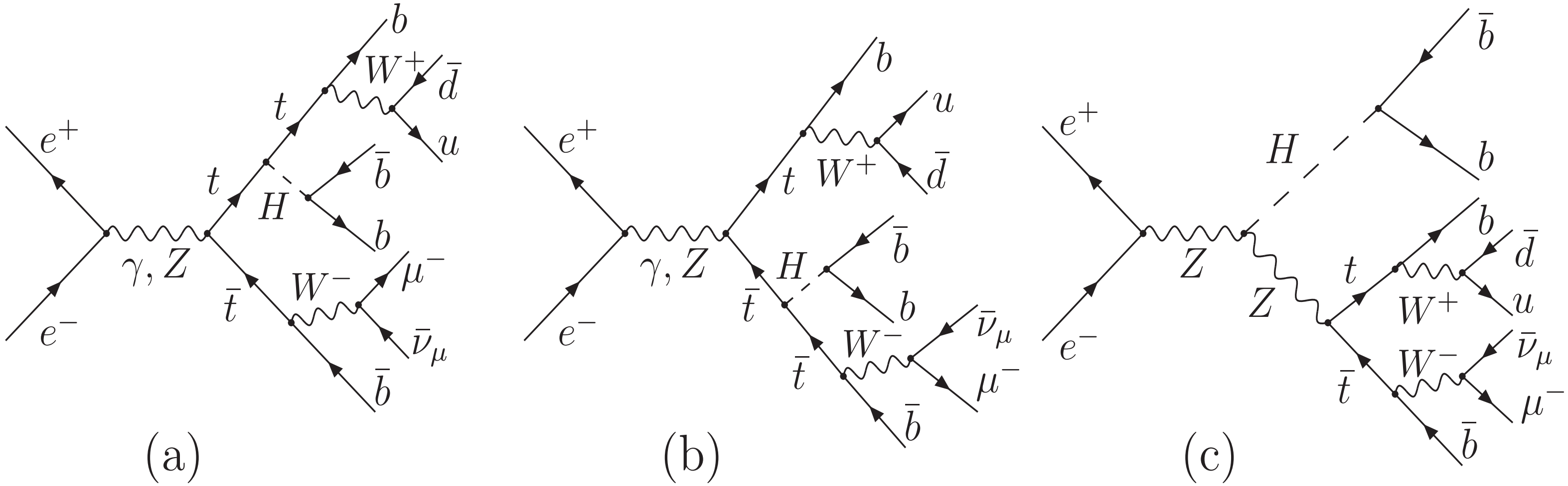

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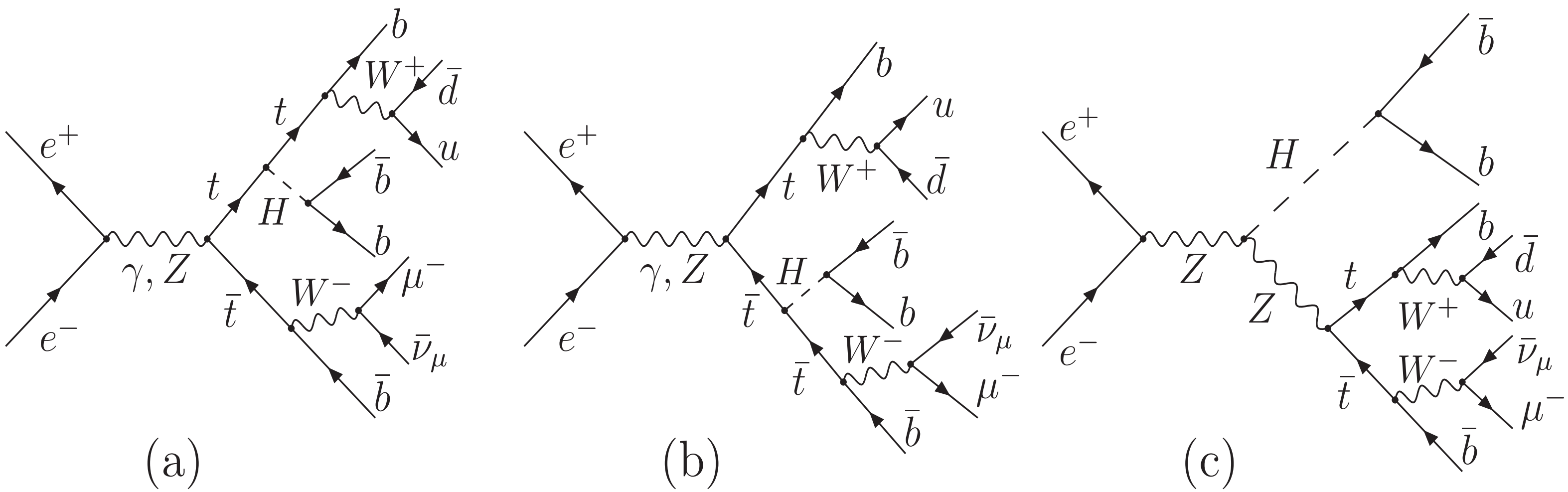

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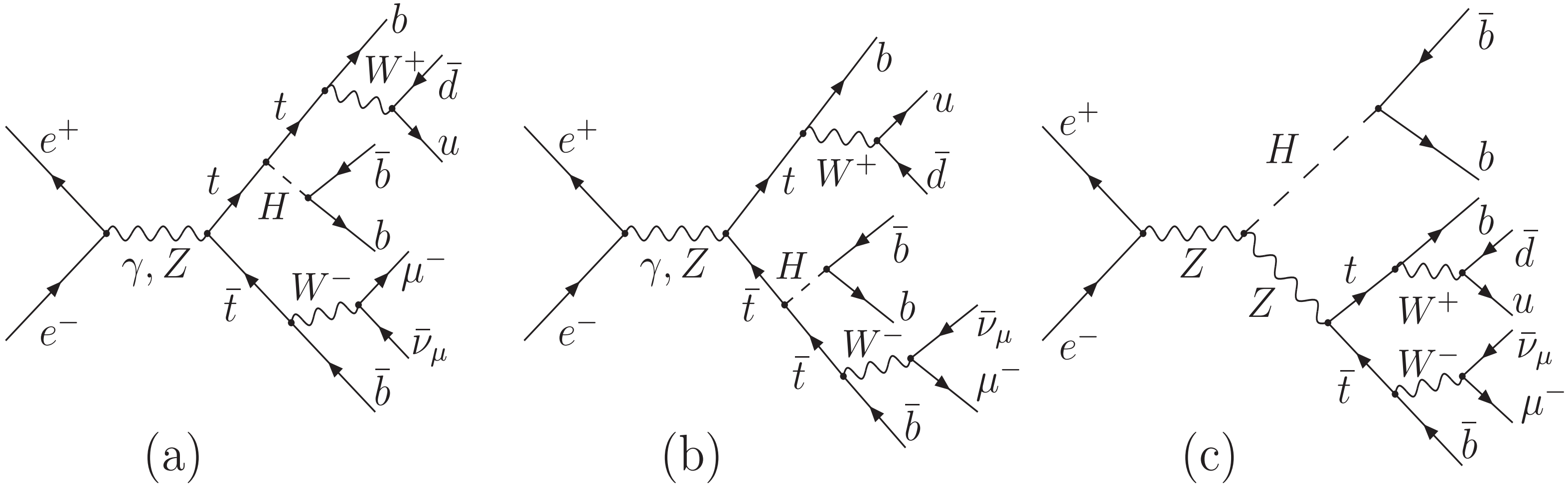

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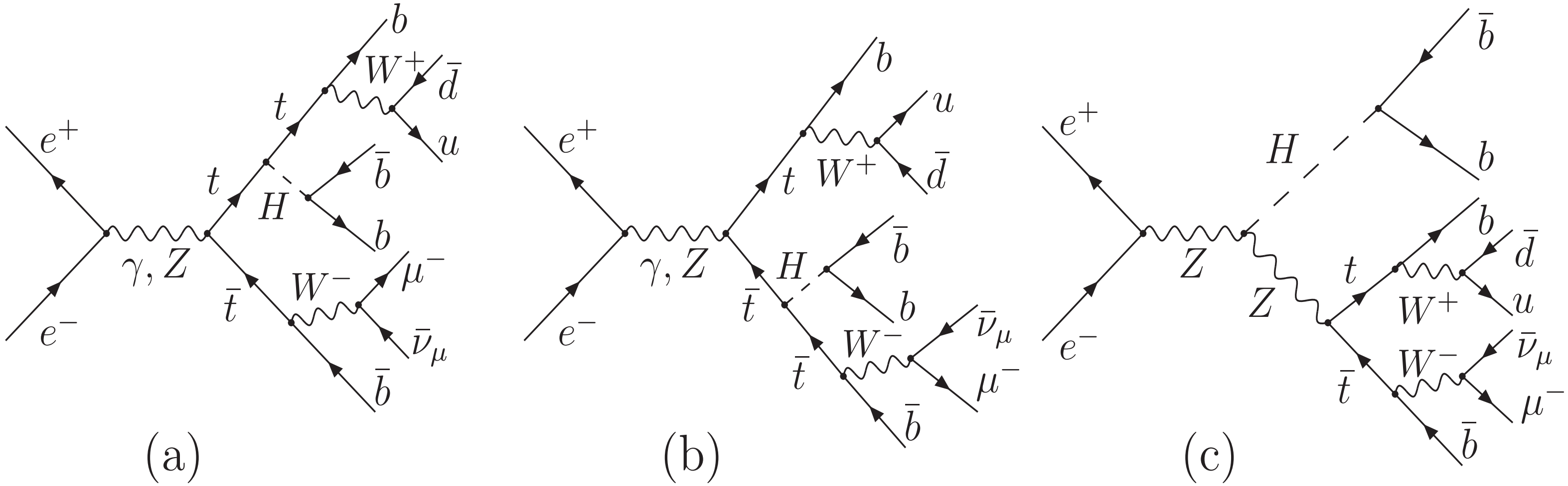

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Do it with `carlomat`!

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- fermion masses are not neglected
- the maximum number of external particles is 12
- only the Standard Model is implemented at the moment

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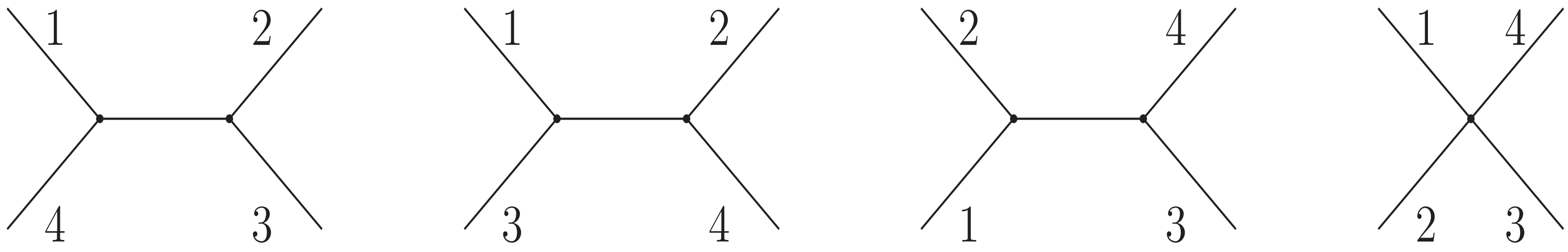
They are copied to another directory where the numerical program is executed.

Generation of topologies

Start with 4 topologies of a 4 particle process.



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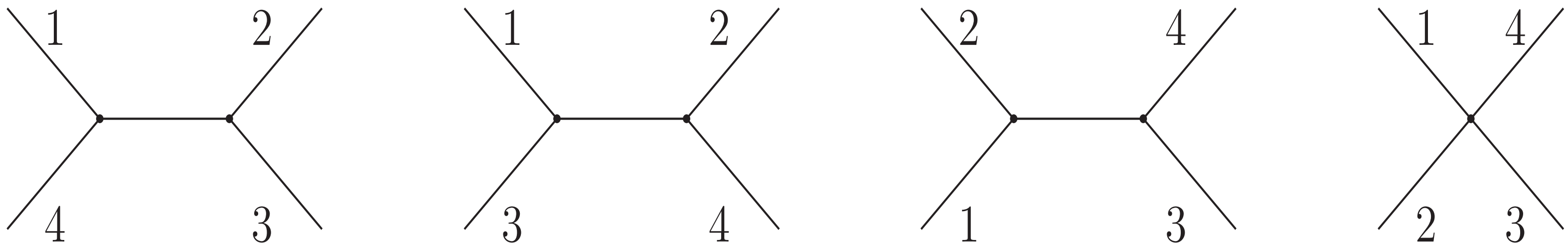

Attach line 5 to each line, including the internal ones, and to each triple vertex $\Rightarrow$ 25 topologies of a 5 particle process.

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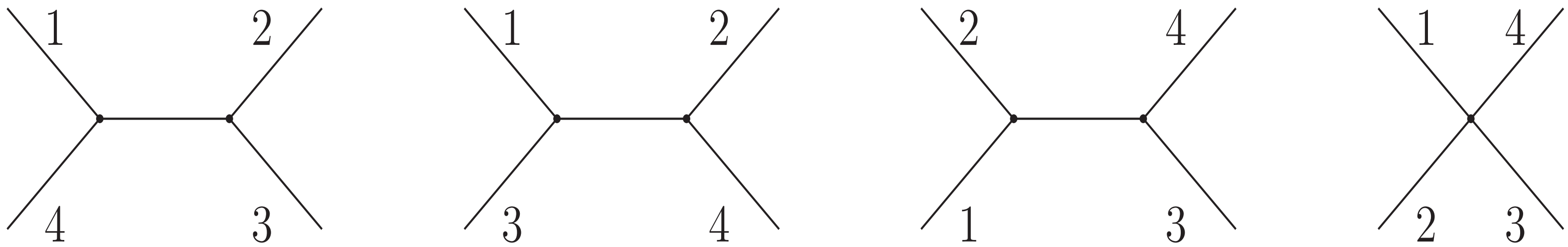

Attach line 5 to each line, including the internal ones, and to each triple vertex $\Rightarrow$ 25 topologies of a 5 particle process.

6 particles	$\Rightarrow$	220 topologies
7 particles	$\Rightarrow$	2485 topologies
8 particles	$\Rightarrow$	34300 topologies
9 particles	$\Rightarrow$	559405 topologies
10 particles	$\Rightarrow$	10525900 topologies
11 particles	$\Rightarrow$	224449225 topologies

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For a process with n external particles, topologies for $n-1$ particles are generated recursively and then, while adding the n-th particle, the program checks whether a topology results in a Feynman diagram or not.

Topologies can be generated and stored on a disk prior to the program execution.

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Each topology is divided into two parts which are separately checked against the Feynman rules. *Actual external particles are assigned to lines* $1, 2, 3, \ldots, n$ *in a strict order.*

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Particles defined for one Feynman diagram are used as building blocks of other Feynman diagrams.

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All the topologies have been checked $\Rightarrow$ subroutines for the matrix element, colour matrix and phase space integration are written.

Helicity amplitudes

Use is made of the routines developed for a Monte Carlo program `eett6f v. 1.0`, for calculating lowest order cross sections of $e^+e^- \to 6$ fermions relevant for a $t\bar{t}$-pair production and decay

K. Kołodziej, Comp. Phys. Commun. **151** (2003) 339, hep-ph/0210199;

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Explicit summing over helicities is also possible. *Spinors or polarization vectors representing particles, both on- and off-shell ones, are computed only once, for all the helicities of the external particles they are made of, and stored in arrays – a novel feature with respect to* e.g. `MadGraph`.

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Total and differential cross sections are computed. `carlomat` can be used as MC generator of unweighted events as well.

Tests

Matrix elements, for randomly selected sets of momenta, of

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in the final state have been checked against `MadGraph`.

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Total cross sections of

- reactions with 4 fermions and a photon in the final state have been checked against `ee4fgamma`
- several reactions with 6 particles in the final state have been checked against `HELAC/PHEGAS` and `AMEGIC++` [T. Gleisberg, et al., hep-ph/0311273, EPJ C34 (2004) 173] and against results of `eett6f`.

Agreement, within one standard deviation.

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Cross sections of $e^+e^- \to b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$ without QCD contributions have been checked against `Whizard`.

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Further thourogh comparisons with other MC generators as `HELAC, MadEvent, Whizard, Sherpa, Alpgen, CompHEP` should be done.

Cross sections of $e^+e^- \to b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$

$\sqrt{s}$ [GeV]	σ_{all} [ab]	$\sigma_{\text{no QCD}}$ [ab]	σ_{signal} [ab]	$\sigma_{\text{signal}}^{\text{no cuts}}$ [ab]	$\sigma_{\text{NWA}}^{\text{no cuts}}$ [ab]
500	26.8(4)	7.80(3)	3.095(3)	3.796(3)	3.920(1)
800	100.2(8)	66.8(1)	46.27(2)	58.36(2)	60.03(2)
1000	93.1(3)	61.4(1)	40.18(2)	51.74(2)	52.42(3)
2000	47.4(2)	28.5(1)	15.14(3)	22.14(4)	20.68(3)

$$5^\circ < \theta(q,\text{beam}),\ \theta(l,\text{beam}) < 175^\circ,\ \ \theta(q,q'),\ \theta(l,q) > 10^\circ,$$

$$E_q,\ E_l,\ \not{E}^T > 15\ \text{GeV}$$

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Large off resonance background! [KK, S. Szczypiński]

Cross sections [ab] at $\sqrt{s} = 500$ GeV of e^+e^- ra

$m_{bb}^{\rm cut}$	$b\bar{b}b\bar{b}u\bar{d}s\bar{c}$		$b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$		$b\bar{b}b\bar{b}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu$	
[GeV]	$\sigma_{\rm all}$	$\sigma_{\rm sig.}$	$\sigma_{\rm all}$	$\sigma_{\rm sig.}$	$\sigma_{\rm all}$	$\sigma_{\rm sig.}$
20	13.88(6)	8.70(2)	3.50(2)	2.38	4.03(9)	0.86
5	10.17(4)	8.66(2)	2.62(1)	2.33	1.89(7)	0.86
1	9.07(4)	8.65(1)	2.37(1)	2.31	1.09(2)	0.86

$$60\ \text{GeV} < m\left(\sim b_1, \sim b_2\right) < 90\ \text{GeV}, \quad m\left(\mu, \not{E}^T\right) < 90\ \text{GeV}$$

$$\left|m\left(b, \sim b_1, \sim b_2\right) - m_t\right| < 30\ \text{GeV},$$

$$m_t - 30\ \text{GeV} < m_T\left(b, \mu, \not{E}^T\right) < m_t + 10\ \text{GeV},$$

$$\left|m\left(b_3, b_4\right) - m_H\right| < m_{bb}^{\rm cut}$$

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$m_{bb}^{\rm cut}$	$b\bar{b}b\bar{b}u\bar{d}s\bar{c}$		$b\bar{b}b\bar{b}u\bar{d}\mu^-\bar{\nu}_\mu$		$b\bar{b}b\bar{b}\tau^+\nu_\tau\mu^-\bar{\nu}_\mu$	
[GeV]	$\sigma_{\rm all}$	$\sigma_{\rm sig.}$	$\sigma_{\rm all}$	$\sigma_{\rm sig.}$	$\sigma_{\rm all}$	$\sigma_{\rm sig.}$
20	13.88(6)	8.70(2)	3.50(2)	2.38	4.03(9)	0.86
5	10.17(4)	8.66(2)	2.62(1)	2.33	1.89(7)	0.86
1	9.07(4)	8.65(1)	2.37(1)	2.31	1.09(2)	0.86

$$60\ \text{GeV} < m\left(\sim b_1, \sim b_2\right) < 90\ \text{GeV}, \quad m\left(\mu, \not{E}^T\right) < 90\ \text{GeV}$$

$$\left|m\left(b, \sim b_1, \sim b_2\right) - m_t\right| < 30\ \text{GeV},$$

$$m_t - 30\ \text{GeV} < m_T\left(b, \mu, \not{E}^T\right) < m_t + 10\ \text{GeV},$$

$$\left|m\left(b_3, b_4\right) - m_H\right| < m_{bb}^{\rm cut}$$

Background substantially reduced! [KK, S. Szczypiński]

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Helicity amplitudes

The constant widths of unstable particles are introduced through the complex mass parameters:

$$M_V^2 = m_V^2 - i m_V \Gamma_V\,, \qquad V = W, Z,$$
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which replace masses in the corresponding propagators, both in the s- and t-channel Feynman diagrams,

$$\Delta_F^{\mu\nu}(q) = \frac{-g^{\mu\nu} + q^\mu q^\nu / M_V^2}{q^2 - M_V^2},$$
$$\Delta_F(q) = \frac{1}{q^2 - M_H^2}, \qquad S_F(q) = \frac{\not{q} + M_t}{q^2 - M_t^2}.$$

Propagators of a photon and a gluon are taken in the Feynman gauge.

Helicity amplitudes

The EW mixing parameter may be defined either real (FWS) or complex (CMS),

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \text{or} \quad \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}.$$

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Colour matrix is calculated only once at the beginning of execution of the numerical program after having reduced its size with the use of the SU(3) algebra properties.