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Electroweak Physics in Six-Fermion Processes at Future Colliders

F. Gangemi – *DFNT, Pavia*

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M. Moretti – *Dipartimento di Fisica and INFN, Ferrara*

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Loops and Legs in Quantum Field Theory
Königstein-Weißig, April 09-14, 2000

$e^+e^- \to 6$ fermions: physics motivations

The c.m. energies reached at the future LC allow the production of six-fermion ($6f$) final states, coming mainly from $t\bar{t}$ production and three intermediate vector bosons

- top quark physics
- intermediate mass Higgs study ($m_h \geq 140$ GeV)
- WWZ, ZZZ, ... physics
- anomalous trilinear and quadrilinear gauge couplings

Each item can be signal by itself or a background for another one

Assuming a luminosity of $500 fb^{-1}$ the required theoretical accuracy is in general at the level of 1% or better $\Rightarrow$ "precision" calculations are needed

$e^+e^- \to 6$ fermions: available calculations

- E. Accomando, A. Ballestrero, M. Pizzio (*Nucl. Phys.* B512 (1998) 19, DESY 97-123 p. 31, *Acta Phys. Pol.* B29 (1998) 2811, *Nucl. Phys.* B547 (1999) 81)

  top, WWZ, Higgs in

  $e^+e^- \to l\nu_l + 4q, \quad l\nu_l + ll' + 2q, \quad l\nu_l + l'\nu_{l'} + 2q$

- F. Yuasa,Y. Kurihara and S. Kawabata (*Phys. Lett.* B414 (1997) 178)

  top production in

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

- G. Montagna, M. Moretti, O. Nicrosini and F. Piccinini (*Eur. Phys. J.* C2 (1998) 483)
  F. Gangemi, G. Montagna, M. Moretti, O. Nicrosini and F. Piccinini (hep-ph/9811437, *Eur. Phys. J.* C9 (1999) 31; DESY 97-123 p. 393)

  Higgs production in

  $e^+e^- \to \mu^+\mu^-\tau^-\overline{\nu}_\tau u\overline{d}, \quad \mu^+\mu^-e^-\overline{\nu}_e u\overline{d}, \quad q\bar{q}l^+l^-\nu\bar{\nu}$

  (hep-ph/9905271, *Nucl. Phys.* B559 (1999) 3; hep-ph/0001065, to appear in DESY 97-123F)

  top physics in

  $e^+e^- \to 6q$

- F. Gangemi (hep-ph/0002142)

  anomalous quartic gauge couplings in

  $e^+e^- \to l\nu_l + 4q$

- S. Moretti (*Phys. Lett.* B420 (1998) 367, *Nucl. Phys.* B544 (1999) 289, *Eur. Phys. J.* C9 (1999) 229, hep-ph/9911500, hep-ph/0002103)

  QCD backgrounds in

  $e^+e^- \to$ six jets, $\quad e^+e^- \to qq\ QQ'\ l\nu_l, \quad gg\ QQ'\ l\nu_l$

- D. Miller and S. Moretti (hep-ph/9906395, hep-ph/0001194)

  trilinear Higgs self-coupling in

  $e^+e^- \to HHZ \to b\bar{b}b\bar{b}Z$ (see the talk by D. Miller)

Features of the event generator SIXFAP

developed to study $6f$ final states in e^+e^- collisions

- The matrix element calculation is performed by means of the ALPHA[1] algorithm with the automatic inclusion of finite fermion masses if necessary.

- The phase space generator of weighted and unweighted events is an evolution of the code HIGGSPV/WWGENPV[2] developed for $4f$ physics. In particular a rich structure of multichannel importance sampling has been implemented to take care of CC and NC propagator "singularities".

- The fixed width scheme is adopted for the treatment of the unstable particle propagators. As a check of gauge-invariance of the calculation also the fudge scheme has been used.

- Initial State Radiation is implemented with the Structure Function formalism. Beamstrahlung effects are simulated by means of the circe[3] parametrization.

$$\begin{aligned}\sigma &= \int dz_1 dz_2 D_{BS}(z_1, z_2; s) \int dx_1 dx_2 D(x_1, s) D(x_2, s) \\ &\times \int d\mu_n |\hat{\mathcal{M}}|^2 \vartheta(cuts)(2\pi)^4 \delta(\hat{p}_+ + \hat{p}_- - \sum_{i=1}^{n} \hat{q}_i)\end{aligned}$$

[1] F. Caravaglios and M. Moretti, *Phys. Lett.* B58 (1995) 332

[2] G. Montagna, O. Nicrosini and F. Piccinini, *Comp. Phys. Comm.* 90 (1995) 141

D.G. Charlton, G. Montagna, O. Nicrosini and F. Piccinini, *Comp. Phys. Comm.* 99 (1997) 355

[3] T. Ohl, *Comput. Phys. Comm.* 101 (1997) 269

Top quark physics

Top signal:

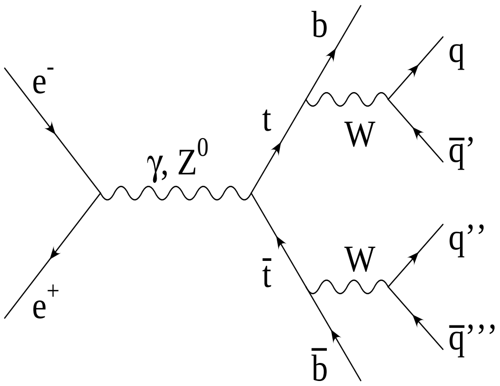
$$b\bar{b}l\nu_l l'\nu_{l'} \sim 10\% \;, \qquad b\bar{b}q\bar{q}'l\nu_l \sim 45\% \;, \qquad b\bar{b}+4q \quad \sim 45\%$$

Signatures with one $b\bar{b}$ pair:

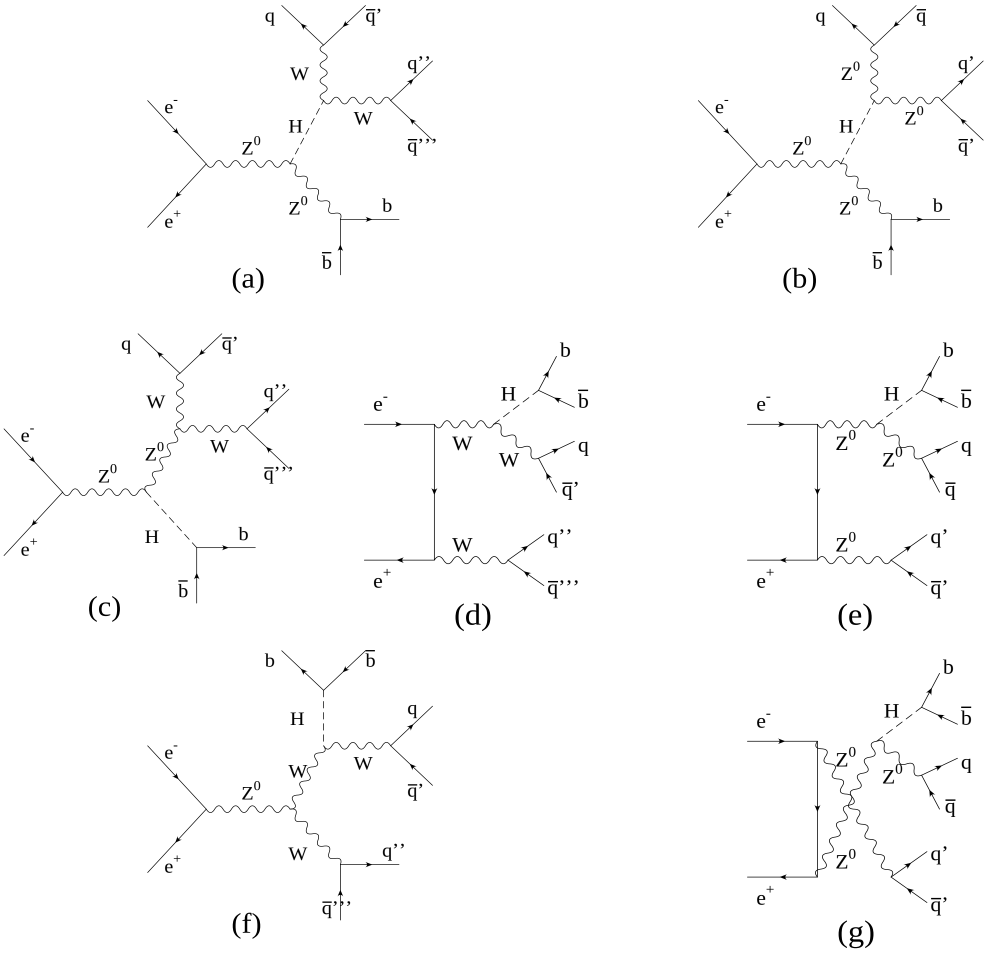
CC only	CC and NC	NC only
$b\bar{b}u\bar{d}\bar{c}s$	$b\bar{b}u\bar{d}\bar{u}d$	$b\bar{b}u\bar{u}s\bar{s}$, $b\bar{b}c\bar{c}d\bar{d}$
$b\bar{b}\bar{u}dc\bar{s}$	$b\bar{b}c\bar{s}\bar{c}s$	$b\bar{b}u\bar{u}u\bar{u}$, $b\bar{b}c\bar{c}c\bar{c}$
		$b\bar{b}d\bar{d}d\bar{d}$, $b\bar{b}s\bar{s}s\bar{s}$
		$b\bar{b}u\bar{u}c\bar{c}$
		$b\bar{b}d\bar{d}s\bar{s}$

- A number of events of the order of 10^5 is expected $\Rightarrow$ experimental statistical precision at the level of few 0.1%
- full electroweak calculation of $e^+e^- \to b\bar{b}+4q$, $q \neq b$ $(m_q = 0)$
- full integrated cross sections and comparison with $t\bar{t}$ $6f$ signal and narrow width approximation
- dependence of the total cross section on the Higgs mass at threshold
- invariant mass distributions: effects of electroweak backgrounds and initial-state radiation on the top mass determination
- study of the topology of the events through analysis of event shape variables

Top signal

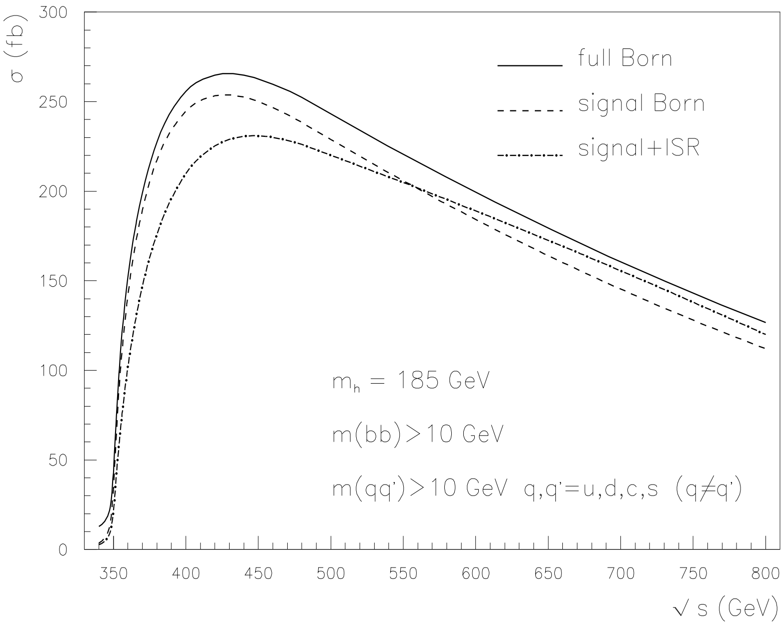


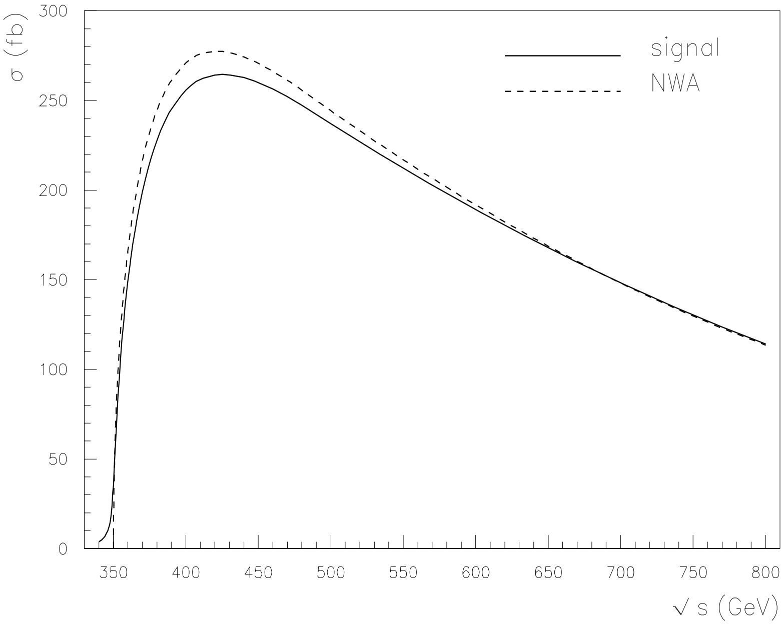
Leading Higgs contributions



Integrated cross sections

Parameters: $m_t = 175$ GeV, $m_h = 185$ GeV

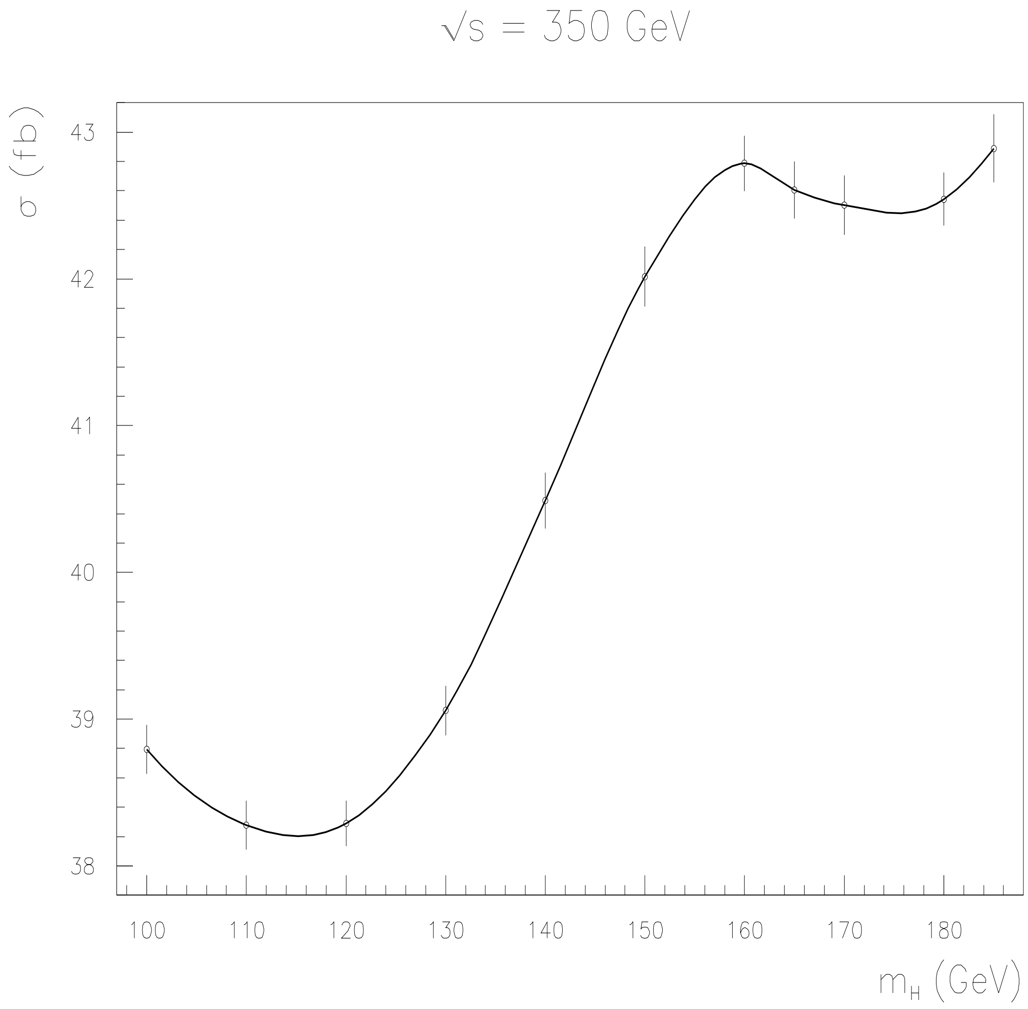




Electroweak background effects: 30% at threshold and 10% above it

Off-shellness: 15% at threshold decreasing to 1% at $\sqrt{s} = 800$ GeV

Dependence on the Higgs mass

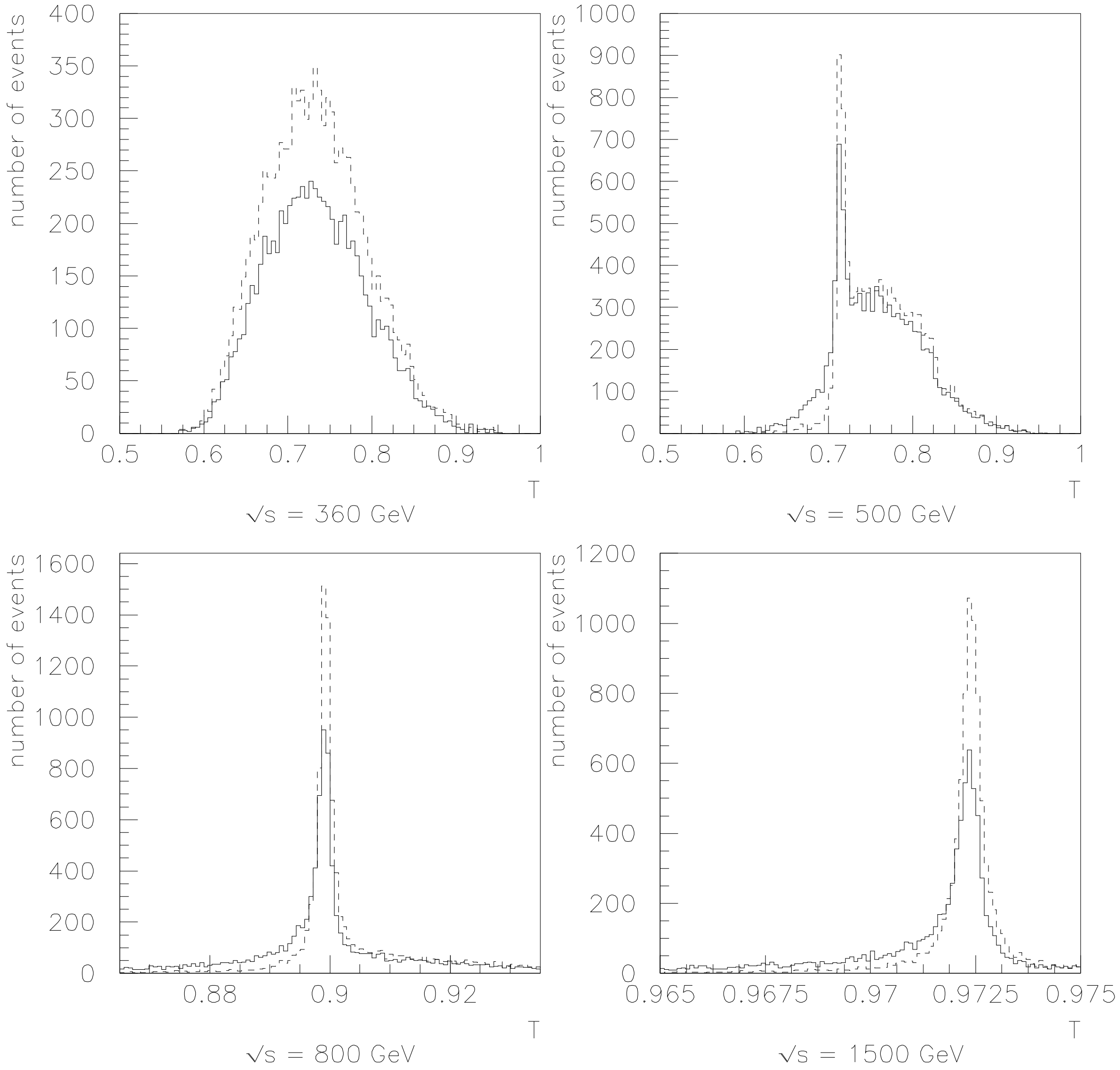


$m_t = 175$ GeV

Variations of the Higgs mass in the range 100–160 GeV induce a variation of about 10% in the $t\bar{t}$ cross section at threshold. Even if the Higgs boson mass is known when running the NLC, its experimental error can induce a theoretical error on the knowledge of the $t\bar{t}$ cross section, especially if the central value lyes in the interval 120–160 GeV

Thrust

(dashed: Born; solid: ISR)



$m_t = 175$ GeV, $m_H = 185$ GeV, 10000 events

The initial state radiation plays a significant role in the event-shape variables, such as the thrust

Physics of intermediate mass Higgs in $e^+e^- \to q\overline{q}l^+l^-\nu\overline{\nu}$

- about 1000–2500 events are expected assuming a luminosity of 500 fb^{-1} $\Rightarrow$ experimental error at the level of few %

- very clean signature (no QCD background)

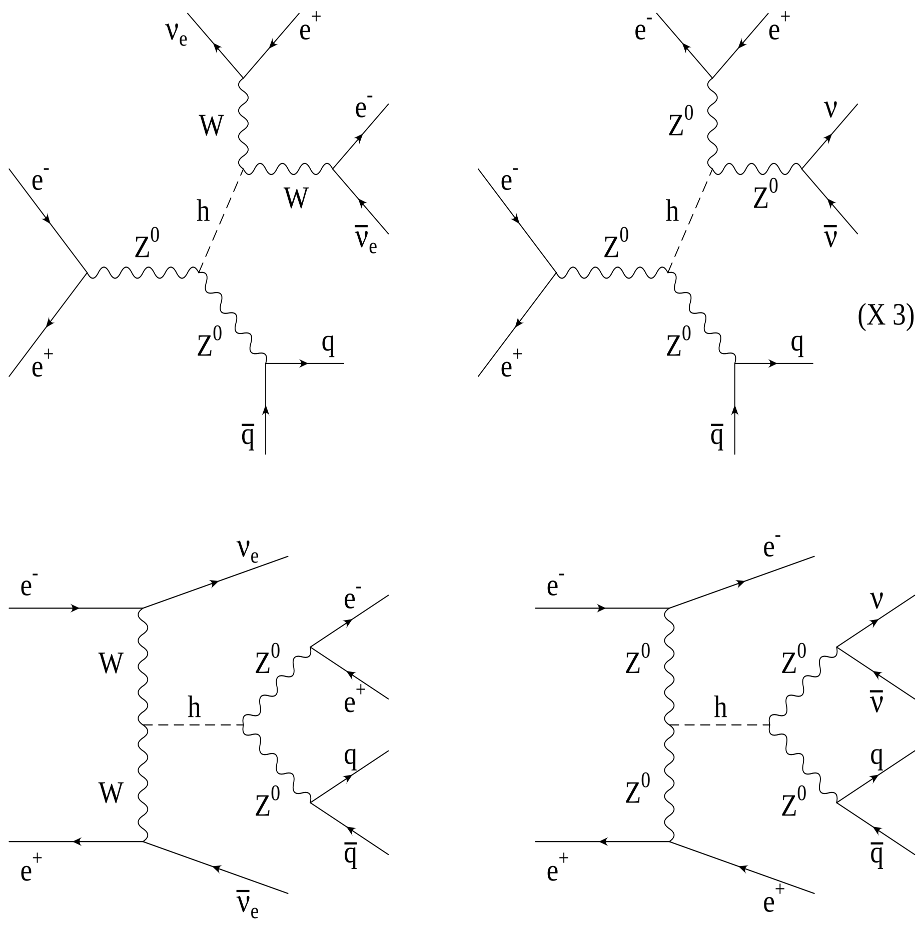
- many important topologies involved, especially t-channel enhancements (e, ν_e) with increasing energy

- CC $(H \to WW)$ and NC $(H \to ZZ)$ production mechanisms

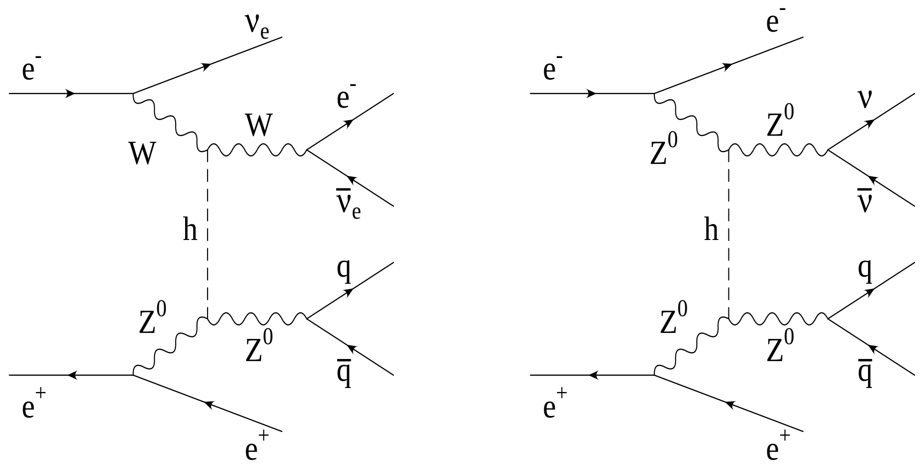
- it is important to quantify the effects of a complete tree-level calculation with respect to an approximate which considers the Higgs boson as a real particle

- question relevant for the Higgs boson search: can be given a signal and a background definition?

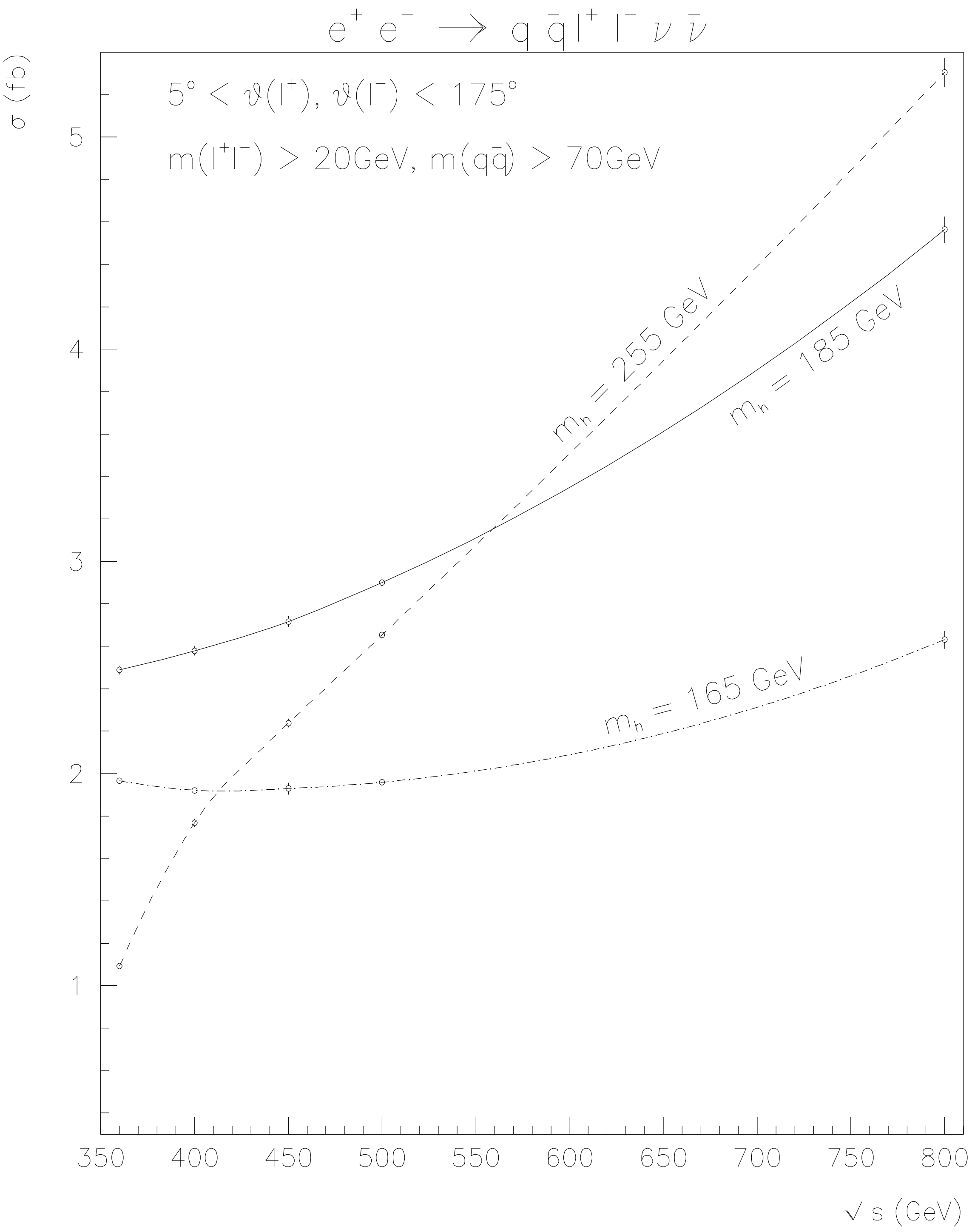
Signal Feynman diagrams (with a resonant Higgs boson)



Non-resonant Feynman diagrams



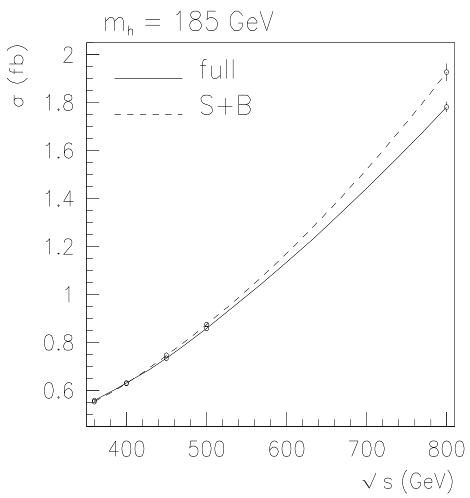
Total cross section (Born approximation)

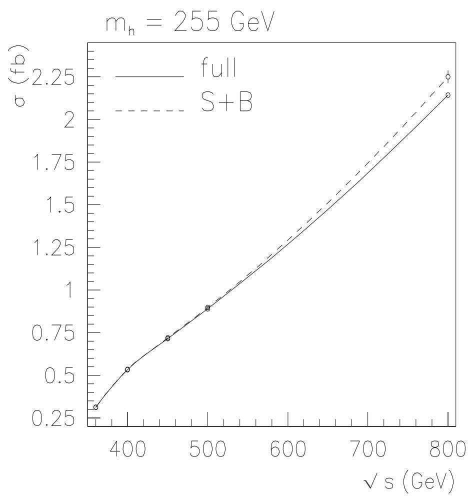


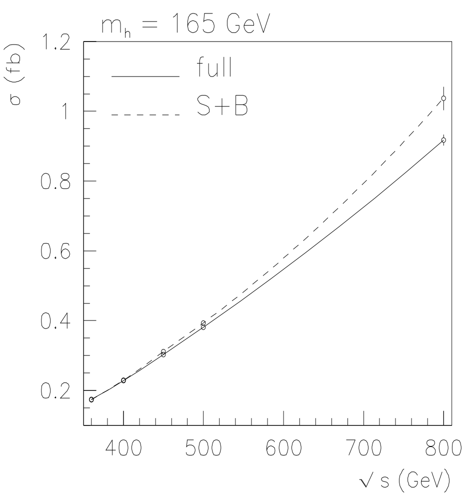
Reliability of a signal definition (Born approximation)

Signal: diagrams with a resonant Higgs boson

Background: all diagrams without Higgs boson as internal lines





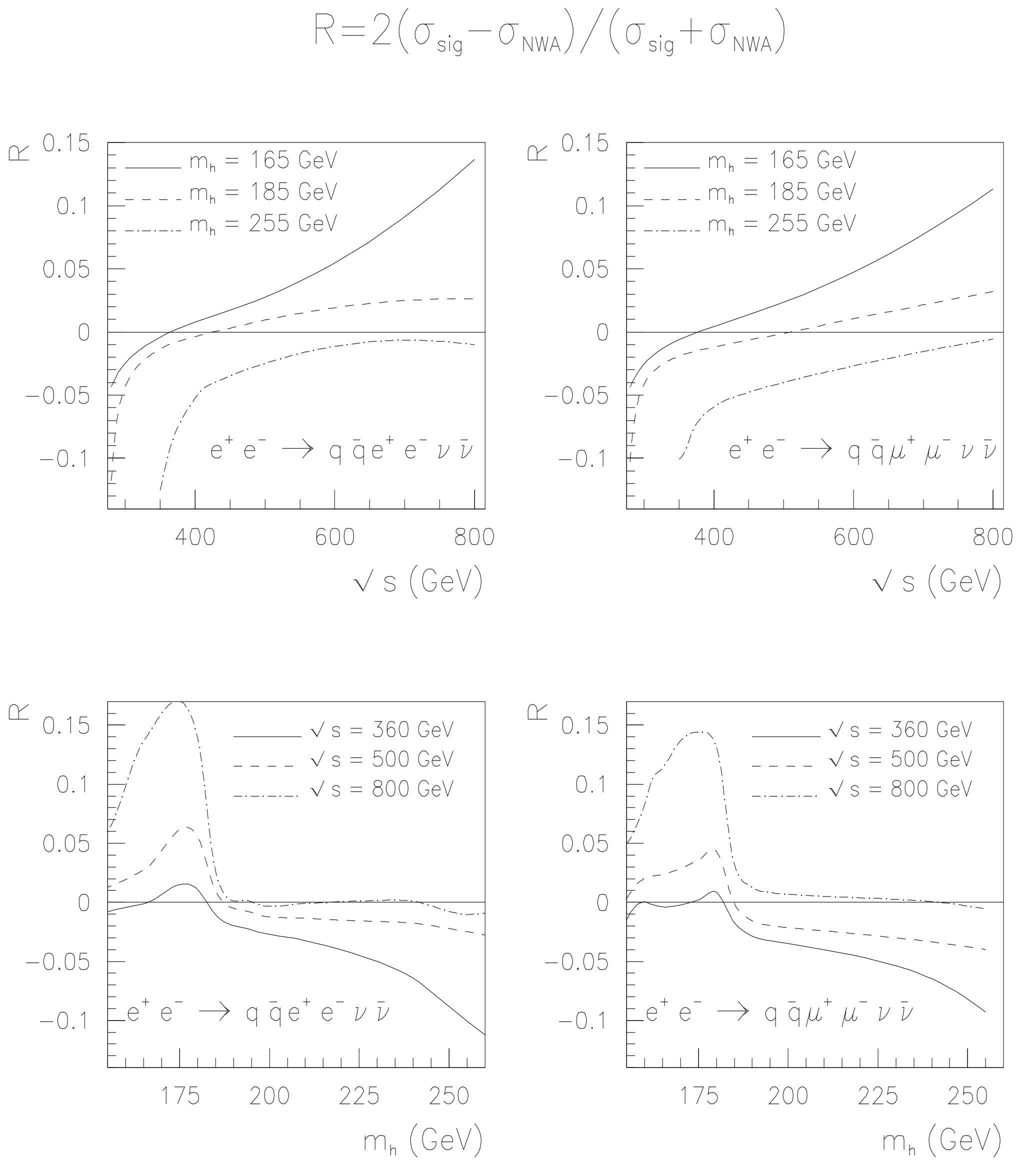


$M(e^+e^-), M(q\bar{q}) \geq 70$ GeV, $\quad 5° \leq \vartheta(e^+), \vartheta(e^-) \leq 175°$

for $\sqrt{s} \leq 500$ GeV signal definition reliable at the 1% level

for $\sqrt{s} = 800$ GeV the deviations between the sum of signal plus background and the full calculation can reach the 10% level, depending on the Higgs mass value and also on the applied cuts

Comparison between $6f$ calculation and narrow width approximation (NWA)



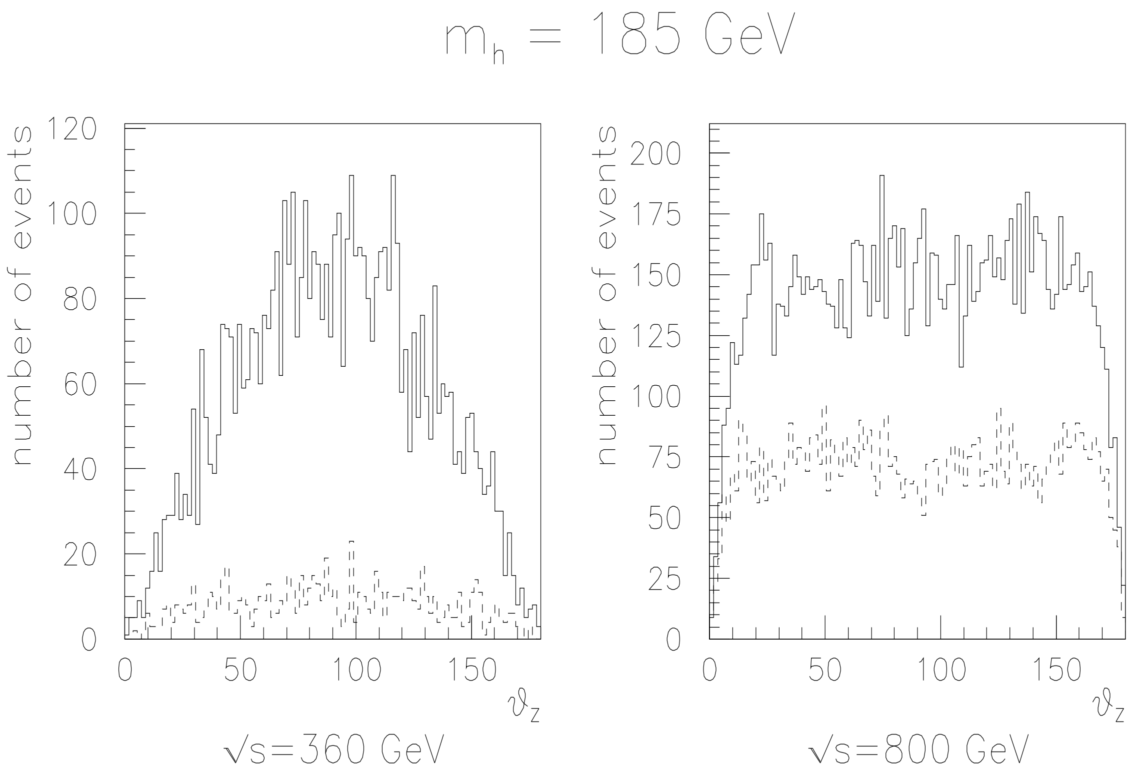
No cuts, Born approximation

The off-shellness effects can reach the 10–15% level

If a theoretical error on the 1% scale is required, a complete $6f$ calculation is unavoidable

Angular distributions $e^+e^- \to q\bar{q}e^+e^-\nu\bar{\nu}$

Angle of the $q\bar{q}$ pair with respect to the beam axis in the laboratory frame



$m(e^+e^-) > 20$ GeV, $m(q\overline{q}) > 70$ GeV, $\quad 5^o < \theta(e^+), \theta(e^-) < 175^o$

Solid histogram: full calculation, dashed histogram: background (no Higgs).

Asymptotic angular distribution for Higgs-strahlung process

$$\frac{d\sigma}{d\cos\theta_Z} \sim \sin^2\theta_Z$$

is a measure of spin-zero nature of the Higgs particle

Quartic anomalous gauge couplings in $e^+e^- \to q\bar{q}q'\bar{q}'\nu_e\bar{\nu}_e$

$(q = u, c; q' = d, s)$

- the genuinely quartic gauge couplings are weakly constrained by present experimental data
- the NLC will provide high sensitivity to such couplings due to the high c.m. energy and the unitarity violations induced by anomalous couplings
- the processes with $4q$ and two ν_e in the final state receive contributions from vertices involving $4W$, $WWZZ$ and $4Z$

$$\mathcal{L} = \mathcal{L}_{YM} + \mathcal{L}_F + \mathcal{L}_S$$

$$\mathcal{L}_S = \mathcal{L}_0 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \mathcal{L}_{10}$$

$$\mathcal{L}_4 = \alpha_4 (Tr(V_\mu V_\nu))^2$$

$$\mathcal{L}_5 = \alpha_5 (Tr(V_\mu V^\mu))^2$$

$$\mathcal{L}_6 = \alpha_6 Tr(V_\mu V_\nu) Tr(T V^\mu) Tr(T V^\nu)$$

$$\mathcal{L}_7 = \alpha_7 Tr(V_\mu V^\mu)(Tr(T V_\nu))^2$$

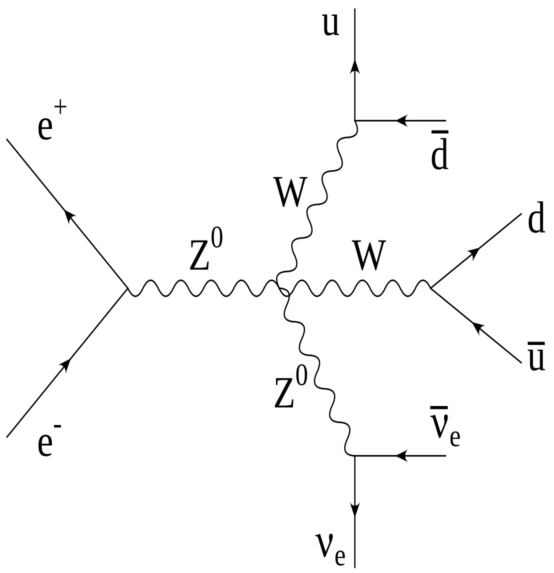
$$\mathcal{L}_{10} = \alpha_{10} \tfrac{1}{2} (Tr(T V^\mu) Tr(T V^\nu))^2$$

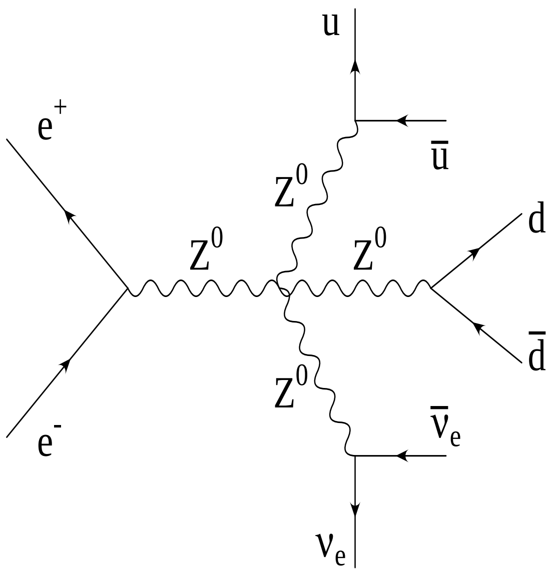
$$T = U\tau_3 U^\dagger,\ V_\mu = (D_\mu U)U^\dagger,\ W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + ig[W_\mu, W_\nu]$$

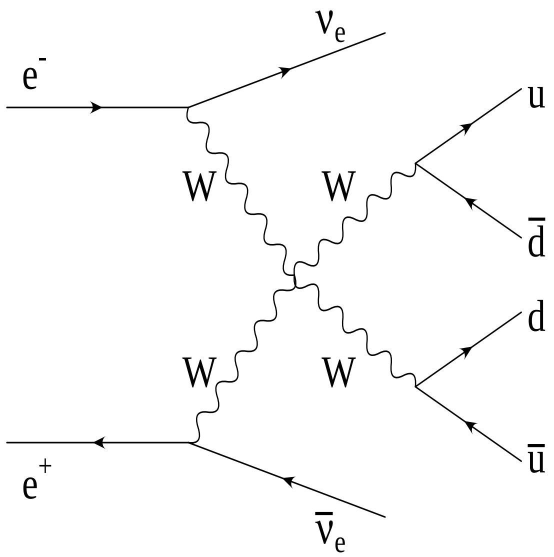
where

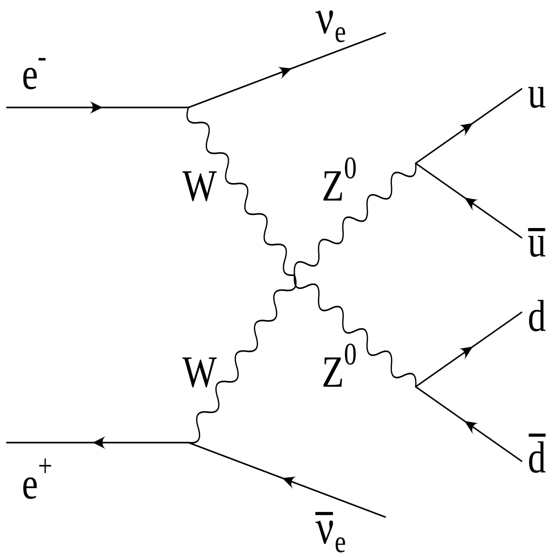
$T = U\tau_3 U^\dagger$, $V_\mu = (D_\mu U)U^\dagger$, $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + ig[W_\mu, W_\nu]$,
$D_\mu U = \partial_\mu U + i\frac{g}{2}\tau_i W^i_\mu - i\frac{g'}{2} B_\mu \tau_3$, $U = \exp\left(i\frac{\tau_i \pi_i}{v}\right)$

Diagrams involving quadrilinear gauge couplings

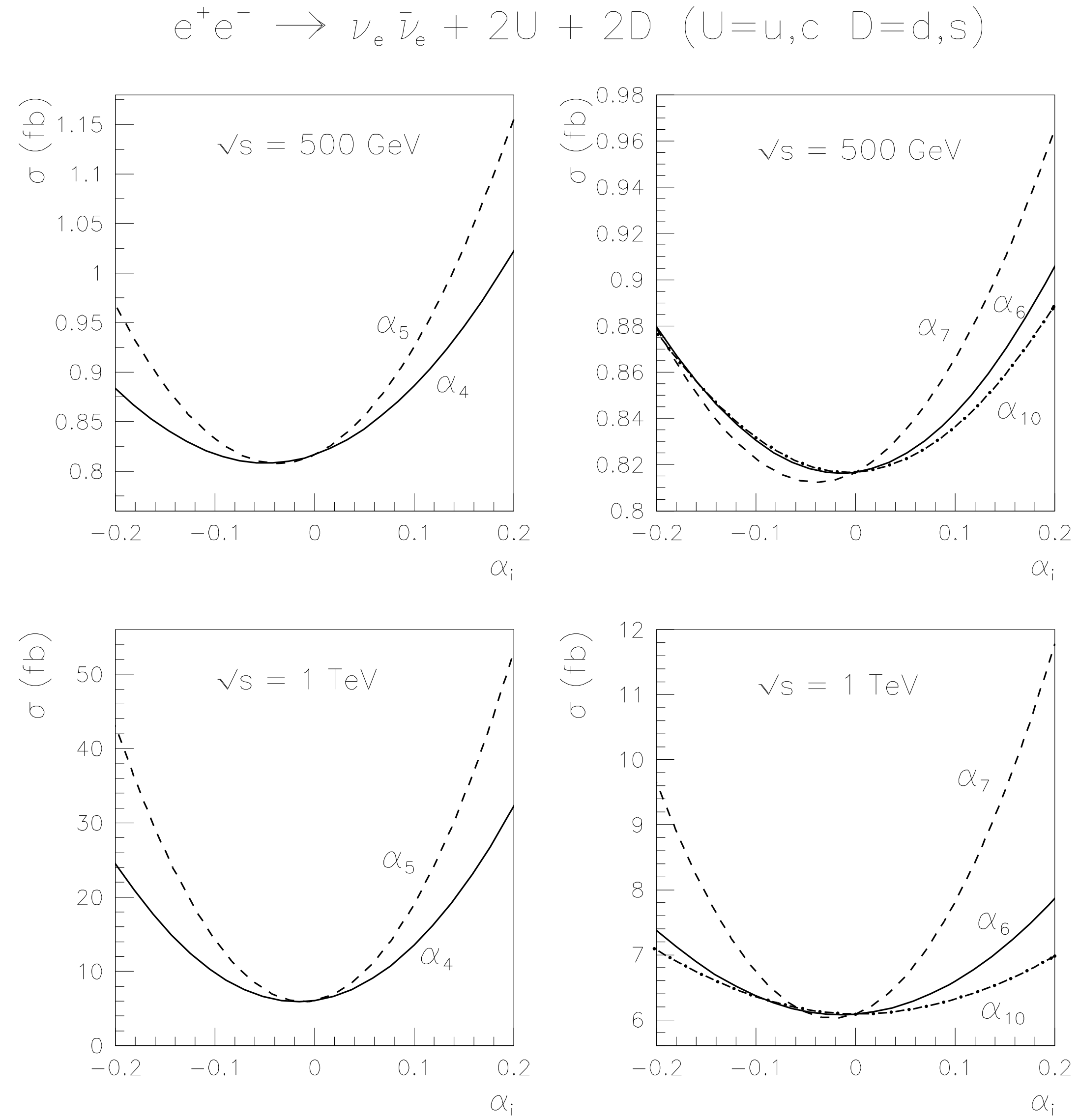








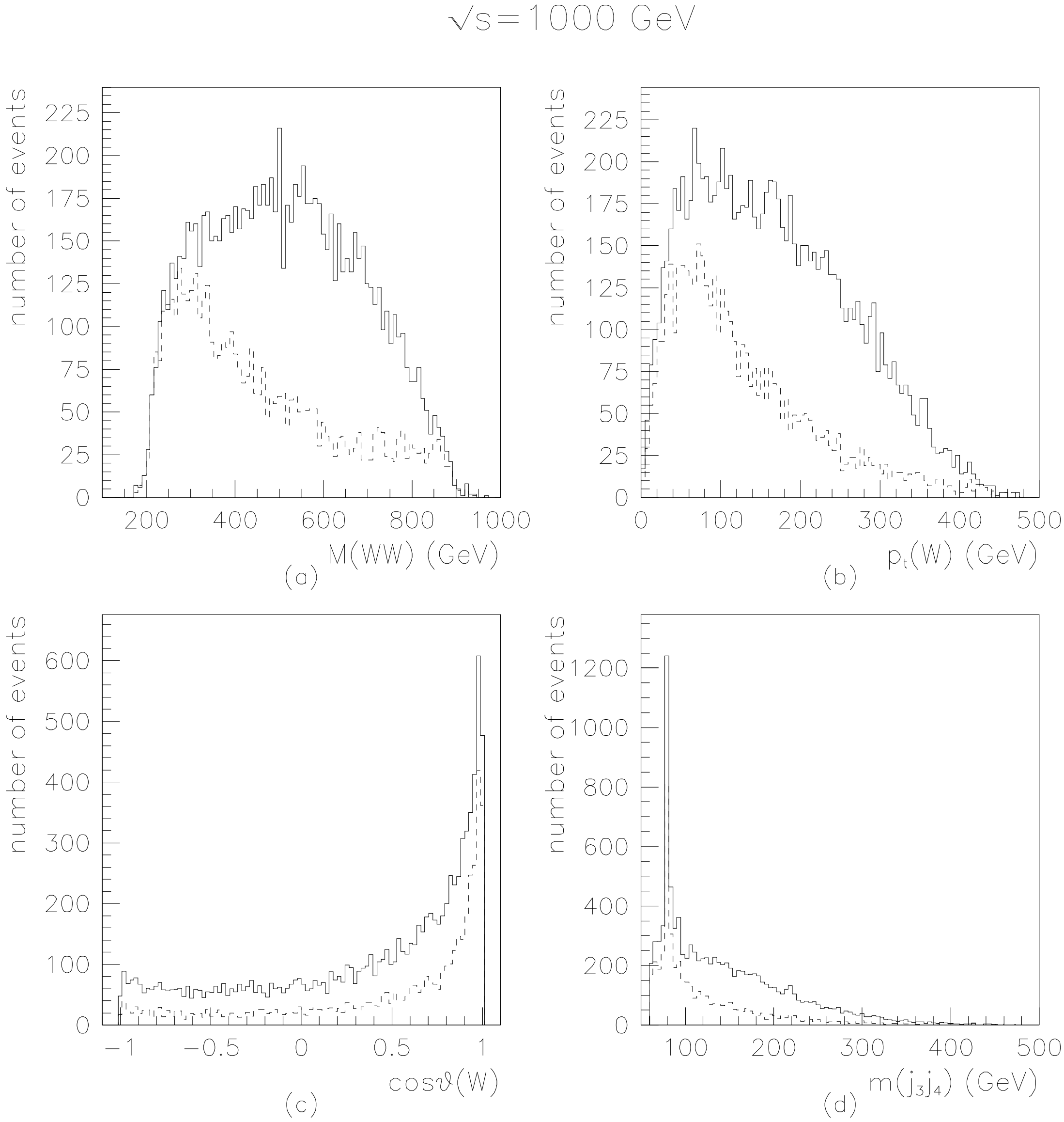
Cross section sensitivity



$M(U\bar{U})$ and $M(D\bar{D}) \geq 70$ GeV

Due to unitarity violations, the cross section enhancements are much more evident at the highest energy. $\mathcal{L}_4$ and $\mathcal{L}_5$ give the greatest effects because they are the only terms contributiong to the $4W$ vertex. On the contrary the smallest effect is given by $\mathcal{L}_{10}$, which contributes only to the $4Z$ vertex

Distribution sensitivity



solid histograms: $\alpha_4 = 0.1$; dashes histograms: $\alpha_i = 0$, in the presence of initial state radiation and beamsstrahlung. (a): invariant mass distribution of the system of four jets; (b): distribution of the transverse momentum of the reconstructed W boson; (c): angular distribution of the reconstructed W boson with respect to the beam axis; (d): invariant mass distribution of the pair of quarks with lowest order transverse momenta

Conclusions

- The relevant new signatures at future e^+e^- linear colliders will be six-fermion final states, coming from $t\bar{t}$, WWZ and intermediate-mass Higgs boson production.

- A Monte Carlo event generator `SIXFAP` has been developed for complete electroweak calculations of such processes at the energies of the NLC.

- In this talk some physics items have been illustrated concerning
  - Higgs production in $e^+e^- \to q\bar{q}l^+l^-\nu\bar{\nu}$ $(q \neq b)$
  - top pair production in $e^+e^- \to b\bar{b} + 4q$ $(q \neq b)$
  - quartic anomalous gauge couplings

- Complete tree-level six-fermion calculations are essential for precision studies at the NLC because they allow to take into account:
  - off-shellness effects, which can reach the 10% level
  - electroweak backgrounds, which are important away from resonances, but also at threshold for some signals (e.g. in $t\bar{t}$ production the effect of EW backgrounds is around 30% at threshold)
  - distributions, angular correlations, event shape variables, useful to disentangle signal effects and to study the observed particle properties