Monte Carlo Generators for International Linear Collider Physics

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Outline

- Motivations
- Monte Carlo tools
  - ⋆ general purpose Monte Carlo's
  - ⋆ *ad-hoc*, dedicated Monte Carlo's
- Physics results (and issues)
- Conclusions

Six (and more) fermions at LC

- LEP1 was the factory for two-body processes

$$\sqrt{s} = M_Z \quad \longrightarrow \quad Z \to f\bar{f}\ (f = q, \ell)$$

- LEP2 was the factory for four-body processes

$$\sqrt{s} \geq 2M_V \quad \longrightarrow \quad VV \to f\bar{f}f'\bar{f}'\ (V = W, Z)$$

- at LC ($\sqrt{s} =$ 0.35-1 TeV) higher multiplicities available (6f)

$$\begin{aligned}
e^+e^- &\to t\bar{t} \to (bW^+)(bW^-) && \text{(top physics)}\\
&\to ZH \to (f\bar{f})(VV) && \text{(Higgs-stralhung)}\\
&\to \nu_e\bar{\nu}_e[e^+e^-]H \to \nu_e\bar{\nu}_e[e^+e^-](VV) && \text{(VBF)}\\
&\to W^+W^-Z[ZZZ] \to (f\bar{f})(f'\bar{f}')(f''\bar{f}'') && \text{(QGCs)}\\
&\to ZHH \to (f\bar{f})(b\bar{b})(b\bar{b}) && (H \text{ self couplings})\\
&\to \nu_e\bar{\nu}_e[e^+e^-]HH \to \nu_e\bar{\nu}_e[e^+e^-](b\bar{b})(b\bar{b}) && (idem)
\end{aligned}$$

Six (and more) fermions at LC (II)

- ... and more !

$$e^+e^- \quad \to \quad t\bar{t}H \to \text{8f} \quad (\text{top} - \text{Yukawa})$$

- Add 2HDM:

$$e^+e^- \to AH \to (b\bar{b})(VV) \to \text{6f} \quad (\text{Pseudoscalar} - \text{Higgs})$$

$$\begin{aligned} e^+e^- \to H^+H^- \quad &\to \quad (t\bar{b})(\tau^-\bar{\nu}_\tau) \to \text{6f} \quad (\text{Charged} - \text{Higgs}) \\ &\to \quad (t\bar{b})(\bar{t}b) \to \text{8f} \quad (\text{ditto}) \end{aligned}$$

- Add SUSY:

$$e^+e^- \to \text{Sparticles} \to \ \text{a jungle of fermions !}$$

$$(e.g.,\ e^+e^- \to \tilde{t}\tilde{t}^* \to \text{6f} \ + \ \text{2 LSPs})$$

General purpose MC tools

Computational tools are highly needed to investigate the sensitivity of experiments and the feasibility of physics studies.
Many multi-purpose MC's are available

- general MC `Pythia`, `Herwig`, `Isajet`: via resonant ("signal") subprocesses (e.g. $t\bar{t}$,ZH,...), *production* $\otimes$ *decay*
  - \+ QCD (QED) Parton Shower (PS), hadronisation, etc.
  - \+ MC@NLO started
  - \- no irreducible background, no complete matrix elements, factorisation in NWA
- multi-purpose (for generic final states, not tuned for 6f, 8f, etc.) parton level generators/integrators
  - complete ME (at tree-level): irreducible background and interferences included
  - \+ (semi-)automated, given a model all processes implemented
  - \- not tuned, not efficient, in general not high-precision tools
  - ⋆ QCD PS & hadronisation can be easily included by means of the Les Houches Standard Accord

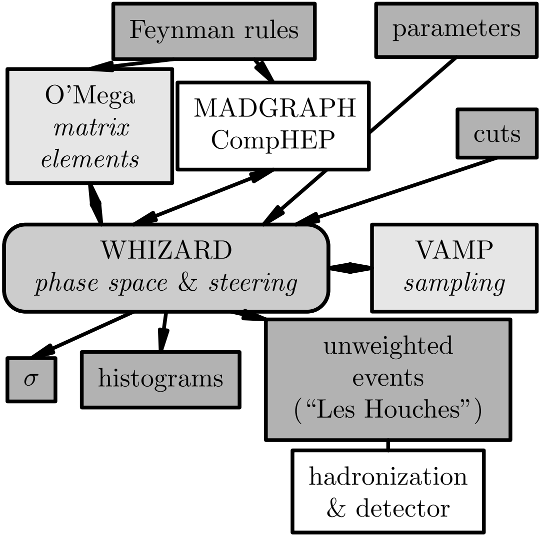
General purpose MC tools (II)

Some examples

- ⋆ `CompHEP/CalcHEP` (Boos et al.; Pukhov et al.)
- ⋆ `Grace` + `Bases/Spring` (Minami Tateya group)
- ⋆ `Helas/MadGraph/MadEvent` (Hagiwara, Murayama, Watanabe; Stelzer, Long; Maltoni, Stelzer): see Maltoni's talk
- ⋆ `Whizard`+ `O'Mega/MadGraph/CompHEP` (Kilian; M. Moretti, Ohl, Reuter; Boos et al.)
- ⋆ `AmegiC++` (Krauss, Kuhn, Schumann, Soff) also `ApaciC++` (PS) $\rightarrow$ `Sherpa` MC
- ⋆ `Helac/Phegas` (Papadopoulos; Kanaki, Papadopoulos; Papadopoulos, Worek)

- SM implemented by all, plus MSSM, NMSSM, etc. in some cases: SUSY Les Houches Accord also defined

Flow chart example (Whizard)



Dedicated tools

Developed specifically for 6f physics → ideal for precision studies

- eett6f (Kolodziej)
  - ⋆ for $e^+e^- \to t\bar{t} \to b\bar{b} + 4f$, including QCD
- Lusifer (Dittmaier, Roth)
  - ⋆ all 6f final states (massless fermions), ISR, QCD but not α_s^2
- Sixfap (Gangemi, Montagna, M. Moretti, Nicrosini, Piccinini)
  - ⋆ in principle all 6f (massive fermions), based on ALPHA, no QCD
- Sixphact (Accomando, Ballestrero, Pizzio), same family as LHC programs Phase (Accomando, Maina, Ballestrero) & Phantom (Ballestrero, Belhouari, Bevilacqua, Kashkahn, Maina)
  - ⋆ all CC 6f (massive, not top), based on Phact (Ballestrero, Maina): now superseeded by Phantom for ILC (see talk by Bevilacqua)
- Sixrad (S. Moretti)
  - ⋆ for QCD final states ($f = q$) at $\mathcal{O}(\alpha_s^4)$).
    Only jets can be observed, need to add also gluonic final states (e.g. $q\bar{q}q'\bar{q}'q''\bar{q}''$ requires also $q\bar{q}q'\bar{q}'gg$ and $q\bar{q}gggg$). Interface to showering mandatory for phenomenological studies

- lot of work in the italian community

Tuned comparisons

In the context of the "Extended Joint Ecfa/Desy Study on Physics and Detector for a Linear e^+e^- Collider" (started April 2003), a round of tuned comparison among some of the generators was performed.

Some results on $e^+e^- \to t\bar{t} \to$ 6f

- Full set of diagrams vs. signal diagrams vs. narrow-width approximation (NWA) for $e^+e^- \to \mu^+\nu_\mu\mu^-\bar{\nu}_\mu b\bar{b}$ (from `eett6f`):

$\sqrt{s}$[GeV]	σ_{full}[fb]	σ_{signal}[fb]	σ_{NWA}[fb]
360	4.416(6)	4.262(1)	4.624(2)
500	6.705(6)	6.354(2)	6.400(7)
800	3.538(29)	3.058(2)	2.973(4)

$\hookrightarrow$ Full calculation necessary for proper signal definition (see later on)

Tuned comparisons (II)

Various full calculations ($\sqrt{s}$=500 GeV, agreed cuts, m_{f}=0):

σ_{full} [fb]	AMEGIC++	eett6f	Lusifer	PHEGAS	SIXFAP	Whizard
$\nu_e e^+ e^- \bar{\nu}_e b\bar{b}$	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)	5.820(3)	5.800(4)	5.798(4)	5.798(2)	5.796(3)
$\nu_\mu \mu^+ d\bar{u} b\bar{b}$	17.209(9)	17.275(28)	17.171(24)	17.204(18)		
last no QCD:	17.097(8)	17.106(15)	17.095(11)	17.107(18)	17.096(4)	17.103(8)

Very good agreement among the codes!

Tuned comparisons (III)

More top-quark channels

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$b\bar{b}u\bar{d}d\bar{u}$	yes	32.90(15)	33.05(14)
	yes	49.74(21)	50.20(13)
	no	32.22(34)	32.12(19)
	no	49.42(44)	50.55(26)
$b\bar{b}u\bar{u}gg$	–	11.23(10)	11.136(41)
	–	9.11(13)	8.832(43)
$b\bar{b}gggg$	–	18.82(13)	18.79(11)
	–	24.09(18)	23.80(17)
$b\bar{b}u\bar{d}e^-\bar{\nu}_e$	yes	11.460(36)	11.488(15)
	yes	17.486(66)	17.492(41)
	no	11.312(37)	11.394(18)
	no	17.366(68)	17.353(31)
$b\bar{b}e^+\nu_e e^-\bar{\nu}_e$	–	3.902(31)	3.885(7)
	–	5.954(55)	5.963(11)
$b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$	–	3.847(15)	3.848(7)
	–	5.865(24)	5.868(10)
$b\bar{b}\mu^+\nu_\mu\mu^-\bar{\nu}_\mu$	–	3.808(16)	3.861(19)
	–	5.840(30)	5.839(12)

Tuned comparisons (IV)

Vector fusion with Higgs exchange

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$e^-e^+u\bar{u}d\bar{d}$	yes	0.6842(85)	0.6858(31)
	yes	1.237(15)	1.265(5)
	no	0.6453(62)	0.6527(35)
	no	1.206(14)	1.2394(75)
$e^-e^+u\bar{u}e^-e^+$	–	6.06(36)e-03	6.113(87)e-03
	–	6.58(23)e-03	6.614(80)e-03
$e^-e^+u\bar{u}\mu^-\mu^+$	–	9.24(12)e-03	9.04(11)e-03
	–	9.25(17)e-03	9.145(74)e-03
$\nu_e\bar{\nu}_eu\bar{d}d\bar{u}$	yes	1.15(3)	1.176(6)
	yes	2.36(7)	2.432(12)
	no	1.14(3)	1.134(5)
	no	2.35(7)	2.429(13)
$\nu_e\bar{\nu}_eu\bar{d}e^-\bar{\nu}_e$	–	0.426(11)	0.4309(48)
	–	0.916(30)	0.9121(48)
$\nu_e\bar{\nu}_eu\bar{d}\mu^-\bar{\nu}_\mu$	–	0.425(12)	0.4221(30)
	–	0.878(27)	0.8888(47)

Tuned comparisons (V)

Vector fusion without Higgs exchange

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$e^-e^+u\bar{u}d\bar{d}$	yes	0.4838(50)	0.4842(25)
	yes	1.0514(97)	1.0445(51)
	no	0.4502(31)	0.4524(23)
	no	1.0239(79)	1.0227(43)
$e^-e^+u\bar{u}e^-e^+$	–	3.757(98)e-03	3.577(43)e-03
	–	4.082(56)e-03	4.214(46)e-03
$e^-e^+u\bar{u}\mu^-\mu^+$	–	5.201(61)e-03	5.119(70)e-03
	–	5.805(67)e-03	5.828(49)e-03
$\nu_e\bar{\nu}_e u\bar{d}d\bar{u}$	yes	0.15007(53)	0.15070(64)
	yes	0.4755(21)	0.4711(24)
	no	0.12828(42)	0.12793(55)
	no	0.4417(19)	0.4398(21)
$\nu_e\bar{\nu}_e u\bar{d}e^-\bar{\nu}_e$	–	0.04546(13)	0.04564(19)
	–	0.16033(63)	0.16011(78)
$\nu_e\bar{\nu}_e u\bar{d}\mu^-\bar{\nu}_\mu$	–	0.04230(12)	0.04180(16)
	–	0.14383(53)	0.14439(65)

Tuned comparisons (VI)

Higgs production through Higgs-strahlung

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$\mu^-\mu^+\mu^-\bar{\nu}_\mu e^-\bar{\nu}_e$	–	0.03244(27)	0.03210(15)
	–	0.03747(29)	0.03749(32)
$\mu^-\mu^+u\bar{d}e^-\bar{\nu}_e$	–	0.0924(8)	0.09306(46)
	–	0.1106(22)	0.10901(66)
$\mu^-\mu^+\mu^-\mu^+e^-e^+$	–	2.828(67)e-03	2.923(52)e-03
	–	2.731(65)e-03	2.691(42)e-03
$\mu^-\mu^+u\bar{u}d\bar{d}$	yes	0.2534(24)	0.2540(16)
	yes	0.2634(22)	0.2642(15)
	no	0.2441(23)	0.2471(15)
	no	0.2593(22)	0.2589(14)
$\mu^-\mu^+u\bar{u}u\bar{u}$	yes	1.125(8)e-02	1.135(22)e-02
	yes	8.767(65)e-03	8.978(58)e-03
	no	7.929(57)e-03	8.078(92)e-03
	no	6.098(35)e-03	6.013(26)e-03

Tuned comparisons (VII)

Backgrounds to Higgs-strahlung

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$\mu^-\mu^+\mu^-\bar{\nu}_\mu e^-\bar{\nu}_e$	–	0.01845(14)	0.01843(13)
	–	0.03054(23)	0.03092(19)
$\mu^-\mu^+u\bar{d}e^-\bar{\nu}_e$	–	0.05284(57)	0.05209(33)
	–	0.08911(53)	0.08925(48)
$\mu^-\mu^+\mu^-\mu^+e^-e^+$	–	2.204(52)e-03	2.346(49)e-03
	–	2.280(66)e-03	2.277(62)e-03
$\mu^-\mu^+u\bar{u}d\bar{d}$	yes	0.1412(10)	0.1404(11)
	yes	0.2092(12)	0.2075(13)
	no	0.1358(20)	0.1341(12)
	no	0.2040(12)	0.2015(11)
$\mu^-\mu^+u\bar{u}u\bar{u}$	yes	5.937(24)e-03	5.937(25)e-03
	yes	6.134(29)e-03	6.108(27)e-03
	no	2.722(10)e-03	2.710(11)e-03
	no	3.290(12)e-03	3.303(12)e-03

Tuned comparisons (VIII)

Triple Higgs coupling

Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$\mu^-\mu^+b\bar{b}b\bar{b}$	yes	2.560(26)e-02	2.583(26)e-02
	yes	3.096(60)e-02	3.019(43)e-02
	no	1.711(55)e-02	1.666(28)e-02
	no	2.34(12)e-02	2.36(10)e-02

Backgrounds to triple Higgs coupling

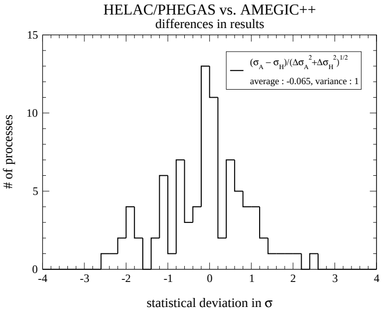
Final state	QCD	AMEGIC++ [fb]	HELAC [fb]
$\mu^-\mu^+b\bar{b}b\bar{b}$	yes	7.002(32)e-03	7.044(22)e-03
	yes	6.308(24)e-03	6.364(21)e-03
	no	2.955(11)e-03	2.972(12)e-03
	no	3.704(15)e-03	3.695(13)e-03

Tuned comparisons (IX)

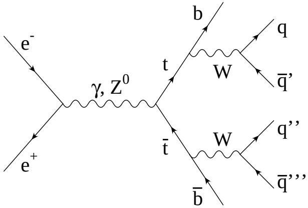
Gleisberg, Krauss, Papadopoulos, Schaelicke, Schumann ’03

- Results are statistically consistent: for each process $i = 1, ...88$ the deviation $s^{(i)}$ of two resulting cross sections $\sigma_{\mathrm{H}}^{(i)}$ and $\sigma_{\mathrm{A}}^{(i)}$ is

$$s^{(i)} = \frac{\sigma_{\mathrm{A}}^{(i)} - \sigma_{\mathrm{H}}^{(i)}}{\sqrt{\left(\Delta\sigma_{\mathrm{A}}^{(i)}\right)^2 + \left(\Delta\sigma_{\mathrm{H}}^{(i)}\right)^2}} .$$



Signal definition, top physics example



Top signal:

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

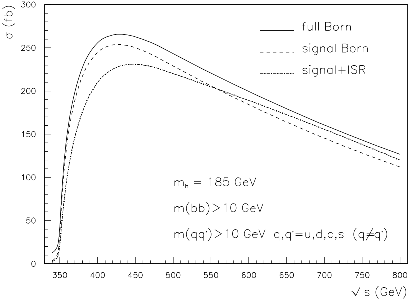
Signatures with one $b\bar{b}$ pair:

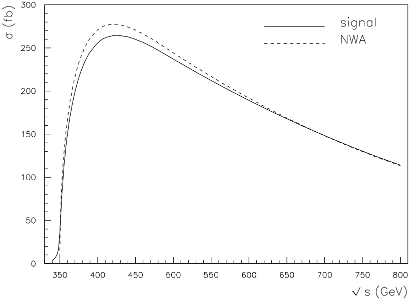
CC only	CC and NC	NC only
$b\bar{b}u\bar{d}\bar{c}s$ $b\bar{b}\bar{u}dc\bar{s}$	$b\bar{b}ud\bar{u}\bar{d}$ $b\bar{b}cs\bar{s}\bar{c}s$	$b\bar{b}u\bar{u}s\bar{s}$, $b\bar{b}c\bar{c}d\bar{d}$ $b\bar{b}u\bar{u}u\bar{u}$, $b\bar{b}c\bar{c}c\bar{c}$ $b\bar{b}d\bar{d}d\bar{d}$, $b\bar{b}s\bar{s}s\bar{s}$ $b\bar{b}u\bar{u}c\bar{c}$,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

- Top "signal" diagram is present only in the first two columns. Other diagrams (e.g. with Higgs) are defined as "background"

Signal definition, top physics example (II)

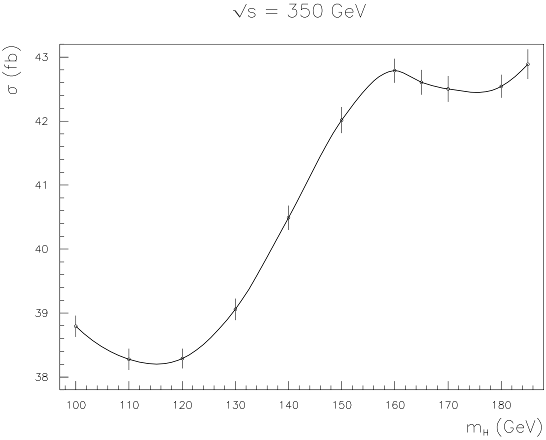
- integrated cross section ($m_t = 175$ GeV, $m_H = 185$ GeV)





- ISR (with QED SF) and beam-strahlung distort considerably the shape
- Background: 30% at threshold and 10% above it
- off-shellness: from 15% to 1%

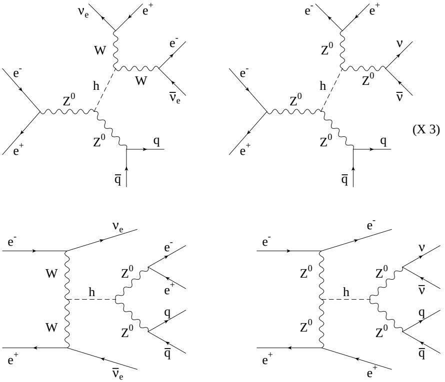
Signal definition, top physics example



- cross section at threshold (strongly) depends on the value of the Higgs mass

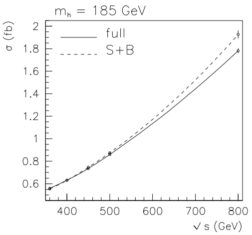
Signal definition, Higgs physics example

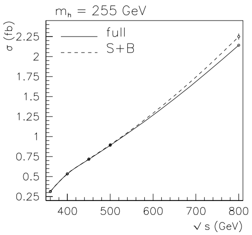
- Signal $e^+e^- \to q\bar{q}\ell^+\ell^-\nu\bar{\nu}$ (resonant and not resonant H)



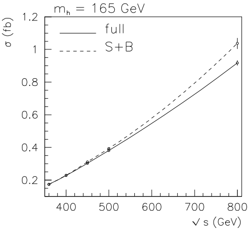
- Background: all the rest, e.g. $e^+e^- \to ZZZ$
- Separation in signal and background can be meaningless

Signal definition, Higgs physics example (II)



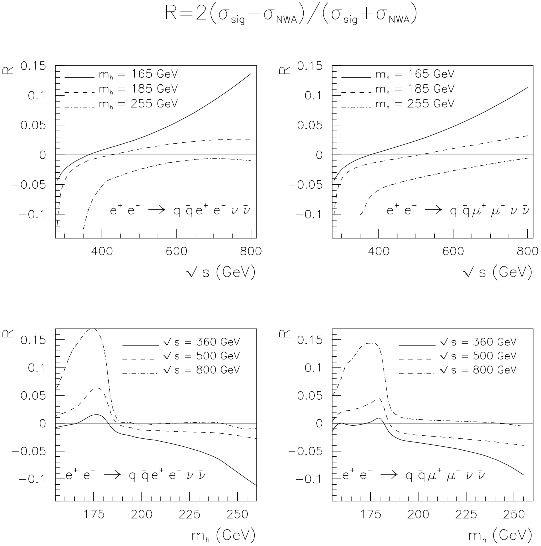


- Signal: diagrams with resonant H
- Background: all diagrams without H as internal line
- $M_{e^+e^-}, M_{q\bar{q}} > 70$ GeV, $5^\circ < \vartheta_\pm < 175^\circ$



Full vs S+B: differences up to 10%

Higgs physics: again on NWA



- off-shellness can reach the 15% effect
- full calculation is mandatory for 1% accuracy

Conclusions

- LC will be a multi-particle factory
- with six and eight fermion final states, a detailed study of top and Higgs particles is possible
- many Monte Carlo tools are available
  - ⋆ general purpose MC event generators
  - ⋆ general purpose MC parton calculators/integrators
  - ⋆ *ad-hoc* generators for 6f physics, needed for precision studies
- due to code complexity, comparison among independent results is really important
- full implementation and optimisation always preferable to approximation
- when detector emulation software for the 4 concepts will be available, full physics studies will be possible