Paris, LCWS 2004, 20 April 2004

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(presented by S. Dittmaier)

(On behalf of the ‘Generators’ WG of the New ECFA Study)

Six-fermion (and more !) studies

Why six (and more !) fermions at LCs ?

1. LEP1 was the realm of two-body processes:

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

2. LEP2 was the arena for four-body processes:

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

3. LCs will open the era of even higher multi-body processes:

$$\sqrt{s} = 350 \text{ GeV} - 800 \text{ GeV} \qquad \longrightarrow$$

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

4. ... and more !

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

5. Add 2HDM:

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

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

6. Add SUSY:

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

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

Plenty of tools to deal with all this !

- Standard MC event generators, **PYTHIA**, **HERWIG** (both also **C++**), **ISAJET**: only via resonant subprocesses ($e.g.$, $t\bar{t}$, H^+H^-, ...), no irreducible background, factorisation in NWA, include QCD PS, FSR, ISR, hadronisation, etc.
- Old and new parton generators/integrators/etc.: can compute both signal and irreducible background in multi-body processes (including interference effects)

$\boxed{\text{MEs tree-level ! Some NLO: HERWIG MC@NLO and GRACE-Loop}}$

$\boxed{\text{Consider tree-level parton generators/integrators/etc.}}$

- Two categories:
  1. Multi-purpose: compute a generic final state
  2. Dedicated: selected final states only (*e.g.*, 6f)

- 1. & 2. plus standard MCs can be connected via Les Houches Accord (LHA) to produce *events* starting from multi-body parton production (or `HEPEVT`, etc.)

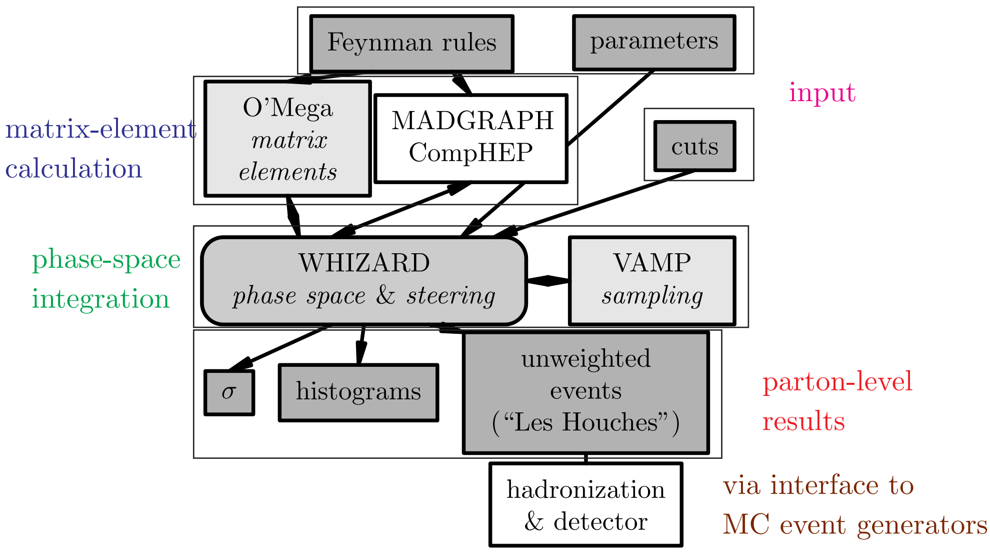
Multi-purpose:

- *GRACE* (MINAMI-TATEYA group '92)
- *HELAS/MadGraph/MadEvent* (Hagiwara, Murayama, Watanabe '91; Stelzer, Long '94; Maltoni, Stelzer '02)
- *Whizard + Omega/MadGraph/CompHEP* (Kilian '01; M. Moretti, Ohl, Reuter '01; Boos et al. '89-'02)
- *SHERPA/AMEGIC++* (Krauss, Kuhn, Schumann, Soff '01, '02)
- *HELAC/PHEGAS* (Papadopoulos '00; Kanaki, Papadopoulos '00)

+ (semi-)automated, many final states, uniform setup for different process classes, ideal for studying the physics potential of colliders

– long codes, improvements by radiative corrections problematic
$\hookrightarrow$ usually not high-precision tools

Whizard A typical flow chart of multi-purpose generator



(See W. Kilian's talk next for more details)

Dedicated (to $e^+e^- \longrightarrow$ 6f, no 8f):

+ Optimised in coding and for generation, higher order effects can be included, ideal for high precision studies

– Number of intermediate/final states limited (*e.g.*, limited QCD)

- *eett6f* (Biernacik, Kołodziej '02)
  for $e^+e^- \longrightarrow t\bar{t} \longrightarrow b\bar{b} + 4$f, includes QCD*
- *Lusifer* (Dittmaier, Roth '02)
  all 6f final states, massless fermions, no $\mathcal{O}(\alpha_s^4)$ QCD*
- *SIXFAP* (Carloni Calame, Gangemi, Montagna, M. Moretti, Nicrosini, Piccinini '97-'03)
  all 6f final states, massive fermions, not public yet, QCD in progress*

* $\boxed{\text{Note on QCD !}}$

- If $f = q$, only jets can be observed !
- Need to include gluon final states: *e.g.*, $q\bar{q}q'\bar{q}'gg$ and $q\bar{q}gggg$ alongside $q\bar{q}q'\bar{q}'q''\bar{q}''$!
- Interface to PS required for phenomenological investigations:

1. Use multi-purpose interfaced via LHA/**HEPEVT**/etc. to PS MCs (*SHERPA* has its own PS, *APACIC++*)
2. Only one dedicated QCD code for all 6 partons through $\mathcal{O}(\alpha_s^4)$: *SIXRAD* (*S. Moretti '98-'99*), not public

Ongoing studies in the 'Generators' WG

Three step procedure:

1. Technical test of Matrix Elements (MEs) and phase space (timescale: preliminary results in Amsterdam, almost completed for LCWS04)
2. Comparisons for physics-oriented observables (timescale: ongoing during current New ECFA Study)
3. Some detector studies in collaboration with experimentalists (timescale: results for proceedings of New ECFA Study)

List of motivations and processes tested

1. Top quark parameters:

$$
\begin{aligned}
e^+e^- &\to b\bar{b}\; u\bar{d}\; d\bar{u} \\
&\to b\bar{b}\; u\bar{u}\; gg
\end{aligned}
$$

[in the two above cases, test total, $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^4)$ contributions]

$$
\begin{aligned}
&\to b\bar{b}\; gg\; gg \\
&\to b\bar{b}\; u\bar{d}\; e^-\bar{\nu}_e \\
&\to b\bar{b}\; \ell^+\nu_\ell\; \ell'^-\bar{\nu}_{\ell'}
\end{aligned}
$$

[in the last process, test all combinations of $\ell^{(\prime)} = e, \mu$ separately, not summed]

2. Higgs production via vector-vector fusion:

$$\begin{aligned}
e^+e^- &\rightarrow e^+e^-\ u\bar{u}\ d\bar{d}\ \text{[also test } \mathcal{O}(\alpha_s^2) \text{ contribution separately]} \\
&\rightarrow e^+e^-\ u\bar{u}\ \ell^+\ell^- \\
e^+e^- &\rightarrow \bar{\nu}_e\nu_e\ u\bar{d}\ d\bar{u}\ \text{[also test } \mathcal{O}(\alpha_s^2) \text{ contribution separately]} \\
&\rightarrow \bar{\nu}_e\nu_e\ u\bar{d}\ \ell^-\bar{\nu}_\ell \\
&\quad\ [\ell^{\,(\prime)} = e, \mu,\ \text{plus test all results also without Higgs]}
\end{aligned}$$

3. Higgs production via Higgstrahlung:

$$\begin{aligned}
e^+e^- &\rightarrow \mu^+\mu^-\ \mu^+\nu_\mu\ e^-\bar{\nu}_e \\
&\rightarrow \mu^+\mu^-\ u\bar{d}\ e^-\bar{\nu}_e \\
e^+e^- &\rightarrow \mu^+\mu^-\ \mu^+\mu^-\ e^-e^+ \\
&\rightarrow \mu^+\mu^-\ u\bar{u}\ e^-e^+ \\
e^+e^- &\rightarrow \mu^+\mu^-\ u\bar{d}\ u\bar{d} \\
e^+e^- &\rightarrow \mu^+\mu^-\ u\bar{u}\ u\bar{u} \\
&\quad\ \text{[in the last two test } \mathcal{O}(\alpha_s^2) \text{ contribution separately, plus} \\
&\quad\ \text{test all results also without Higgs]}
\end{aligned}$$

4. Triple Higgs coupling via Higgstrahlung:

$$e^+e^- \rightarrow \mu^+\mu^-\ b\bar{b}\ b\bar{b}\ \text{[also test } \mathcal{O}(\alpha_s^2) \text{ contribution separately]}$$

5. Top-Higgs Yukawa coupling via $t\bar{t}H$ production (500 GeV only):

$$\begin{aligned}
e^+e^- &\rightarrow \text{all final states as in 1. plus an additional } b\bar{b} \text{ pair} \\
&\quad\ \text{[then add } \mathcal{O}(\alpha_s^6) \text{ contributions separately, where relevant]}
\end{aligned}$$

6. Quartic gauge couplings involving a real photon:

$$e^+e^- \;\to\; e^+\nu_e\, \mu^-\bar{\nu}_\mu\, \gamma$$

[Use *RacoonWW* (Denner, Dittmaier, Roth, Wackeroth '99-'00) too]

7. Supersymmetry (chargino pair production in the MSSM):

$$e^+e^- \;\to\; u\bar{d}\, e^-\bar{\nu}_e\, \widetilde{\chi}_1^0\, \widetilde{\chi}_1^0$$

[SPS1a of Supersymmetry Parameter Analysis in SUSY WG]

$\boxed{\text{SM setup}}$

- SM parameters in G_μ scheme:

$$\begin{aligned}
&m_W = 80.419 \text{ GeV}\,, \quad \Gamma_W = 2.12 \text{ GeV},\\
&m_Z = 91.1882 \text{ GeV}\,, \quad \Gamma_Z = 2.4952 \text{ GeV},\\
&G_\mu = 1.16639 \times 10^{-5} \text{ GeV}^{-2},\\
&\sin^2\theta_W = 1 - m_W^2/m_Z^2,\\
&\alpha_s = 0.0925(0.0891) \;\text{ at } 360(500) \text{ GeV},
\end{aligned} \tag{1}$$

$$\alpha_{\rm em} = \frac{\sqrt{2}\, G_\mu\, M_W^2 \,\sin^2\theta_W}{\pi}.$$

- Higgs parameters:

$$m_H = 130 \text{ GeV}\,, \quad \Gamma_H = 0.00429 \text{ GeV}.$$

- Fermion masses:

$$
\begin{aligned}
&m_\mu = 105.6583 \text{ MeV}, \quad m_\tau = 1.777 \text{ GeV}, \\
&m_u = 5 \text{ MeV}, \quad m_d = 10 \text{ MeV}, \\
&m_s = 200 \text{ MeV}, \quad m_c = 1.3 \text{ GeV}, \\
&m_b = 4.8 \text{ GeV}, \\
&m_t = 174.3 \text{ GeV}, \quad \Gamma_t = 1.6 \text{ GeV}.
\end{aligned} \tag{2}
$$

- Widths of W, Z, H and t are in fixed-width scheme.
- CKM mixing and H couplings to e, u, and d are neglected.
- Cuts:

$$
\begin{aligned}
&\theta(l, \text{beam}) > 5^\circ\ , \quad \theta(l, l') > 5^\circ\ , \quad E_l > 10 \text{ GeV}, \\
&\theta(q, \text{beam}) > 5^\circ\ , \quad \theta(l, q) > 5^\circ\ , \quad E_q > 10 \text{ GeV}, \\
&m(q, q') > 10 \text{ GeV}\ ,
\end{aligned} \tag{3}
$$

  where θ are angles, E energies and m invariant masses.

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

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

- 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)	5.797(5)	5.800(4)	5.798(4)	5.798(2)	5.796(3)
$\nu_\mu \mu^+ d\bar{u} b\bar{b}$	17.209(9)	17.213(23)	17.171(24)	17.204(18)		
last without QCD:	17.097(8)	17.106(15)	17.095(11)	17.107(18)	17.096(4)	17.103(8)

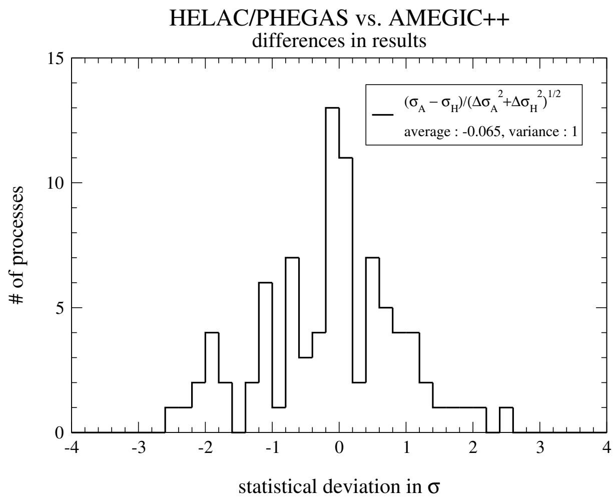
$\hookrightarrow$ Good agreement across all programs !

The all SM 6f lot: *AMEGIC++* vs. *HELAC*

(*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

$$s^{(i)} = \frac{\sigma_{\mathrm{A}}^{(i)} - \sigma_{\mathrm{H}}^{(i)}}{\sqrt{\left(\Delta\sigma_{\mathrm{A}}^{(i)}\right)^2 + \left(\Delta\sigma_{\mathrm{H}}^{(i)}\right)^2}} . \qquad (4)$$



1. Average deviation is $\bar{s} = -0.065$
2. Variance is $\sigma_s \approx 1$
3. Maximal difference is $s^{(\mathrm{max.})} \approx 2.6$
4. Distribution of differences follows roughly a Gaussian distribution.

- Below, $\sqrt{s} = 360$ (first row) and 500 GeV (second row).
- (NB: Most following results are available from other groups too.)

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)

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
$\nu_e\bar{\nu}_e u\bar{d}d\bar{u}$	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)
$\nu_e\bar{\nu}_e u\bar{d}e^-\bar{\nu}_e$	–	0.426(11)	0.4309(48)
	–	0.916(30)	0.9121(48)
$\nu_e\bar{\nu}_e u\bar{d}\mu^-\bar{\nu}_\mu$	–	0.425(12)	0.4221(30)
	–	0.878(27)	0.8888(47)

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)

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

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

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

Summary

- All groups involved except *Madgraph/MadEvent* soon to join in, useful especially for QCD tests !
- Status very good for SM, for 2HDM/MSSM processes needs more groups to participate (*e.g.*, GRACE-MSSM, others ?)
- Several *ad hoc* and LHA/**HEPEVT**/etc. interfaces to MC programs already available
- Plan to use *MC-TESTER* (Golonka, Pierzchała, Was '02) for *automated* comparison of differential distributions at both parton and hadron level (*AMEGIC++ and HELAC* already interfaced)
- For more info, see WG webpage:
  `http://jadach.home.cern.ch/jadach/mc_shop/mcgroup.html`
- Input from experimentalists welcome !
- Stay tuned: more to come ...