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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:

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

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

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

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

$$\begin{aligned} \sqrt{s} = 350 \text{ GeV} - 800 \text{ GeV} \quad &\longrightarrow \\ e^+e^- \rightarrow t\bar{t} \rightarrow (bW^+)(\bar{b}W^-) \quad &(\text{top - physics}) \\ \rightarrow ZH \rightarrow (f\bar{f})(VV) \quad &(\text{Higgs - strahlung}) \\ \rightarrow \nu_e\bar{\nu}_e[e^+e^-]H \rightarrow \nu_e\bar{\nu}_e[e^+e^-](VV) \quad &(\text{VBF}) \\ \rightarrow W^+W^-Z[ZZZ] \rightarrow (f\bar{f})(f'\bar{f}') \quad &(\text{QGCs}) \\ \rightarrow ZHH \rightarrow (f\bar{f})(b\bar{b})(b\bar{b}) \quad &(\text{Higgs self - couplings}) \\ \rightarrow \nu_e\bar{\nu}_e[e^+e^-]HH \rightarrow \nu_e\bar{\nu}_e[e^+e^-](b\bar{b})(b\bar{b}) \quad &(\text{ditto}) \end{aligned}$$

4. ... and more !

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

5. Add 2HDM:

$$e^+ e^- \rightarrow A H \rightarrow (b\bar{b})(VV) \rightarrow 6f \text{ (Pseudoscalar – Higgs)}$$

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

6. Add SUSY:

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

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

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)

MEs tree-level ! Some NLO: HERWIG MC@NLO and GRACE-Loop

Consider tree-level parton generators/integrators/etc.

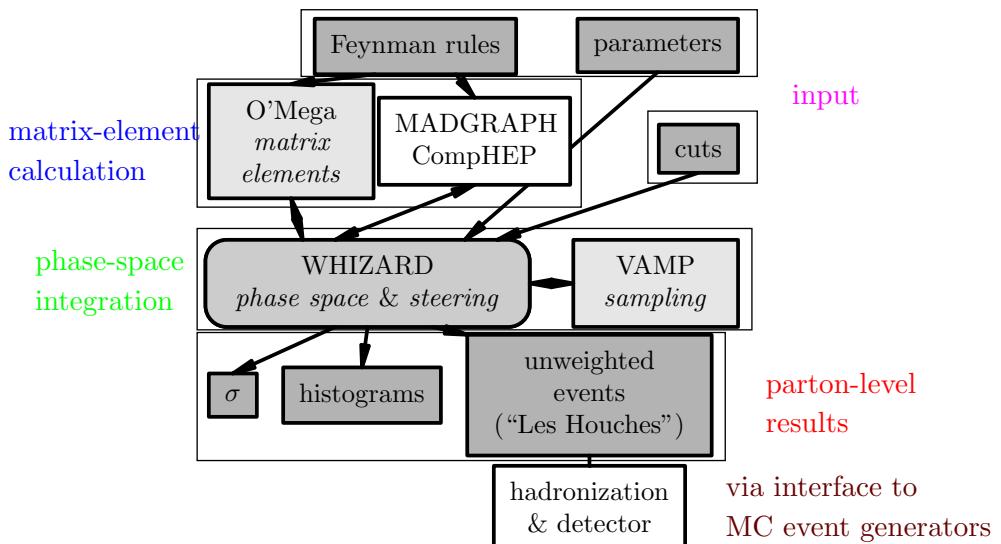
- Two categories:
 1. Multi-purpose: compute a generic final state
 2. Dedicated: selected final states only (*e.g.*, 6f)
- 1. & 2. plus standard MCs can be connected via Les Houches Accord (LHA) to produce events starting from multi-body parton production (or HEPEVT, etc.)

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
→ 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 $e^+e^- \rightarrow 6f$, 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 $e^+e^- \rightarrow t\bar{t} \rightarrow b\bar{b} + 4f$, 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*

* 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:

$$e^+ e^- \rightarrow b\bar{b} u\bar{d} d\bar{u}$$

$$\rightarrow b\bar{b} u\bar{u} gg$$

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

$$\rightarrow b\bar{b} gg gg$$

$$\rightarrow b\bar{b} u\bar{d} e^- \bar{\nu}_e$$

$$\rightarrow b\bar{b} \ell^+ \nu_\ell \ell'^- \bar{\nu}_{\ell'}$$

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

2. Higgs production via vector-vector fusion:

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

3. Higgs production via Higgstrahlung:

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

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):

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

6. Quartic gauge couplings involving a real photon:

$$e^+ e^- \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu \gamma$$

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

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

$$e^+ e^- \rightarrow u \bar{d} e^- \bar{\nu}_e \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

[SPS1a of Supersymmetry Parameter Analysis in SUSY WG]

SM setup

- SM parameters in G_μ scheme:

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

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

- Higgs parameters:

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

- Fermion masses:

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

- 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:

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

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

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

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

→ 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)

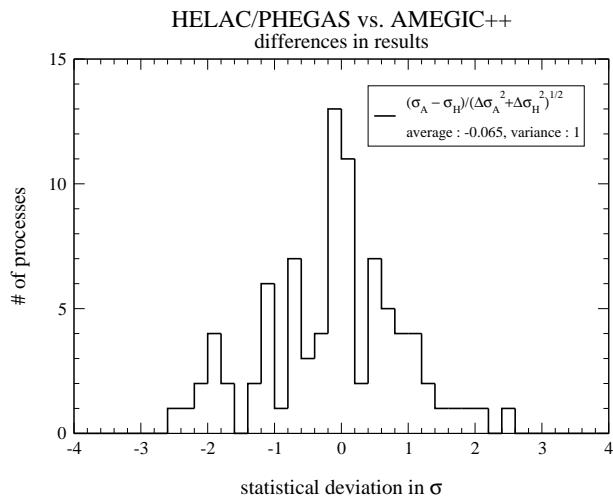
→ Good agreement across all programs !

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

(*Gleisberg, Krauss, Papadopoulos, Schaelicke, Schumann '03*)

- Results are statistically consistent: for each process $i = 1, \dots, 88$ the deviation $s^{(i)}$ of two resulting cross sections $\sigma_H^{(i)}$ and $\sigma_A^{(i)}$ is

$$s^{(i)} = \frac{\sigma_A^{(i)} - \sigma_H^{(i)}}{\sqrt{(\Delta\sigma_A^{(i)})^2 + (\Delta\sigma_H^{(i)})^2}}. \quad (4)$$



1. Average deviation is $\bar{s} = -0.065$
 2. Variance is $\sigma_s \approx 1$
 3. Maximal difference is $s^{(\max.)} \approx 2.6$
 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	<i>AMEGIC++</i> [fb]	<i>HELAC</i> [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	<i>AMEGIC++</i> [fb]	<i>HELAC</i> [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	<i>AMEGIC++</i> [fb]	<i>HELAC</i> [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	<i>AMEGIC++</i> [fb]	<i>HELAC</i> [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	<i>AMEGIC++</i> [fb]	<i>HELAC</i> [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	<i>AMEGIC++</i> [fb]	<i>HELAC</i> [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	<i>AMEGIC++</i> [fb]	<i>HELAC</i> [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 ...