Predictions for multi-particle final states with AMEGIC++

Steffen Schumann

Institute for Theoretical Physics

Dresden University of Technology

in collaboration with Frank Krauss, Andreas Schälicke and Tanju Gleisberg

Outline

- AMEGIC++ a multi-purpose parton level generator

  (F. Krauss, R. Kuhn, G. Soff, JHEP 0202:044,2002)

  - Features of the program
  - Amplitudes and phase space
  - Comparison against LUSIFER and WHIZARD/MADGRAPH
- Numerical results for the linear collider benchmark channels
- Summary

Features of AMEGIC++

- Calculation of arbitrary processes in the SM and the MSSM at the tree level using Helicity amplitudes

  MSSM setup:

  - Feynman rules (unitary gauge) according to J.Rosiek, Phys.Rev.D41:3464,1990
  - Interface to ISASUSY to generate the MSSM spectra
  - Majorana fermion Feynman rules as defined in Denner *et al.*, Nucl.Phys.B387,1992

Features of AMEGIC++

- Calculation of arbitrary processes in the SM and the MSSM at the tree level using Helicity amplitudes
- Full massive matrix elements available
- Unstable particles treated via FWS or CMS
- Explicit external polarizations enabled
- Multi-channel MC integration with adaptive optimization
- Program can be run parallel using the MPI standard
- Completely automatic approach (a generator-generator)

Amplitude Generation

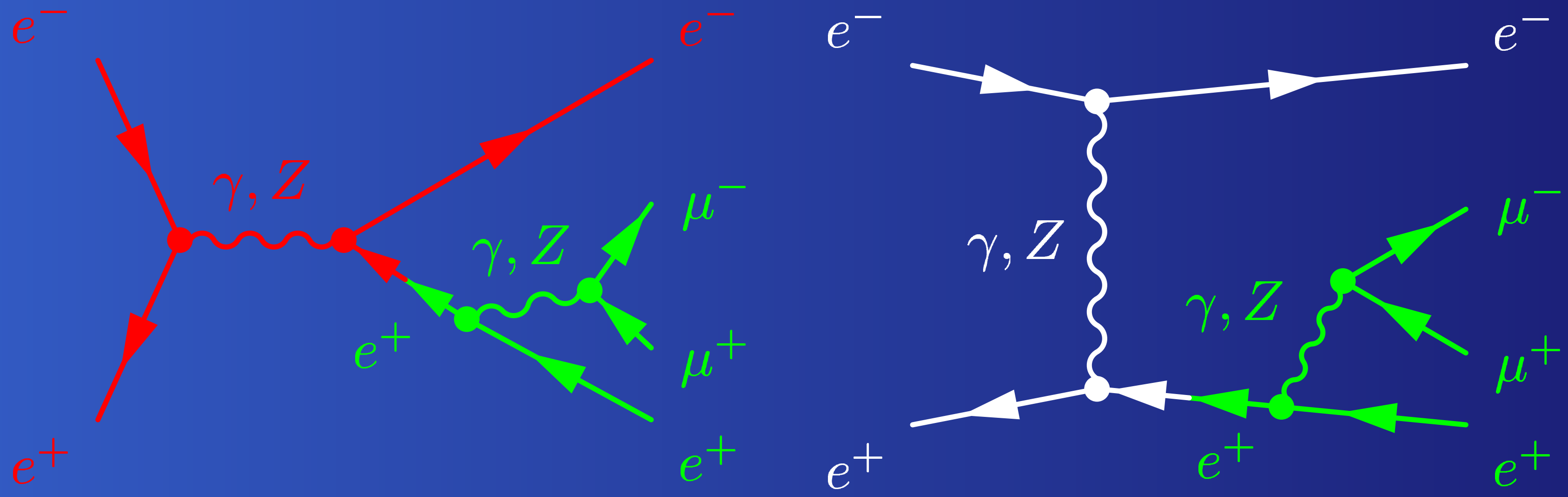
Problem: Factorial growth of Feynman diagrams contributing with increasing number of outgoing particles

$e^+e^- \to$	Feynman diagrams	Superamplitudes
e^+e^-	4	4
$e^+e^-\mu^+\mu^-$	50	10
$e^+e^-e^+e^-$	144	9
$e^+e^-e^+e^-\mu^+\mu^-$	3690	261
$e^+e^-e^+e^-e^+e^-$	13896	323

Idea: Factorize out common Helicity building blocks of different amplitudes

$\Rightarrow$ reduce the number of complex multiplications

Superamplitudes

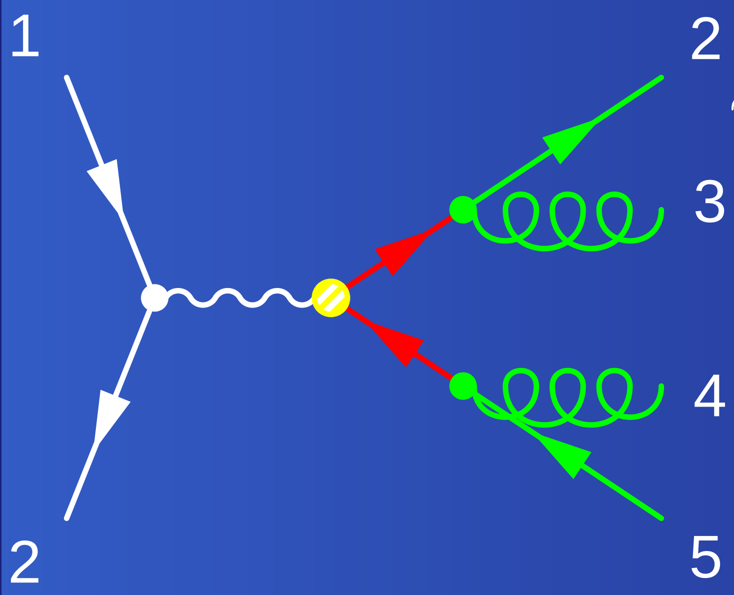


Features of the algorithm:

- Amplitudes that differ only by boson props are combined
- s- and t-channels can be combined as well
- Works only for amplitudes with equal color structure
- Algebraic tools can be improved further to be more efficient

Multi-channel method

- Decompose the phase space into channels
- Channels will be weighted according to their contributions
- Every amplitude is equivalent to one channel
- Each channel will be decomposed into its peak structure



$$\sim P_0(23)\ P_0(45)\ D_S(23,45)\ D_A(2,3)\ D_A(4,5)$$

P_0	massless propagator
D_S	symmetric decay
D_A	asymmetric decay

Multi-channel method

- Decompose the phase space into channels
- Channels will be weighted according to their contributions
- Every amplitude is equivalent to one channel
- Each channel will be decomposed into its peak structure
- Problem: How to get a stable result for $10^5 - 10^6$ channels ?

  $\Rightarrow$ SM 8f final states or SUSY processes
- Solution: Find criteria to reduce this number !

  $\Rightarrow$ Channel selector ?

Checks

AMEGIC++ successfully tested in:

- $t \to Wb + \{\leq 3g, \leq 2\gamma\}$
- $q\bar{q} \to$ 3jets
- $e^+e^- \to 5$ massive or massless jets
- $e^+e^- \to 4f(\gamma)$ (against RacoonWW and ee4fγ)
- $\gamma\gamma \to b\bar{b}(g, gg)$
  (massive fermions, with polarizations)
- $\gamma\gamma \to 4f$ (ALPHA)
- Sparticle pair production and sparticle decays
  presented at the Prague meeting by F. Krauss and S. S.

Checks: 6f production

Comparison with the results of LUSIFER and WHIZARD

the latter using the MEs of MADGRAPH

(S. Dittmaier and M. Roth, Nucl. Phys. B642 (2002))

- $\sqrt{s} = 500$ GeV, phase space cuts, massless fermions, $M_H = 170$ GeV, 10^7 points

Top production channels (incl. QCD): (preliminary)

$e^+ e^- \to$	AMEGIC++ [fb]	LUSIFER [fb]	WHIZARD [fb]
$\mu^- \bar{\nu}_\mu \nu_\mu \mu^+ b \bar{b}$	5.8088(54)	5.8091(49)	5.8102(26)
$\mu^- \bar{\nu}_\mu \nu_\tau \tau^+ b \bar{b}$	5.8002(32)	5.7998(36)	5.7962(26)
$e^- \bar{\nu}_e \nu_\mu \mu^+ b \bar{b}$	5.8268(39)	5.8188(45)	5.8266(27)
$e^- \bar{\nu}_e \nu_e e^+ b \bar{b}$	5.8794(83)	5.8530(68)	5.8751(30)
$\mu^- \bar{\nu}_\mu u \bar{d} b \bar{b}$	17.209(9)	17.171(24)	–
$e^- \bar{\nu}_e u \bar{d} b \bar{b}$	17.329(11)	17.276(45)	–

Checks: 6f production

Four lepton two quark final states: (preliminary)

$e^+ e^- \to$	AMEGIC++ [fb]	LUSIFER [fb]	WHIZARD [fb]
$\mu^- \mu^+ \mu^- \bar{\nu}_\mu u \bar{d}$	0.11847(17)	0.11835(22)	0.11797(26)
$\mu^- \mu^+ \tau^- \bar{\nu}_\tau u \bar{d}$	0.11860(13)	0.11861(42)	0.11791(21)
$e^- \bar{\nu}_e \mu^- \mu^+ u \bar{d}$	0.13854(22)	0.13832(30)	0.13785(36)
$e^- e^+ \mu^- \bar{\nu}_\mu u \bar{d}$	0.53156(81)	0.53352(70)	0.53493(61)
$e^- e^+ e^- \bar{\nu}_e u \bar{d}$	0.5487(14)	0.55089(74)	0.5514(13)
$\mu^- \bar{\nu}_\mu \nu_\mu \bar{\nu}_\mu u \bar{d}$	0.18422(28)	0.18399(11)	0.18396(13)
$\mu^- \bar{\nu}_\mu \nu_\tau \bar{\nu}_\tau u \bar{d}$	0.18423(11)	0.18406(10)	0.18430(13)
$e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu u \bar{d}$	0.20304(14)	0.20272(14)	0.20288(14)
$\nu_e \bar{\nu}_e \mu^- \bar{\nu}_\mu u \bar{d}$	1.6353(29)	1.6326(12)	1.6313(13)
$e^- \bar{\nu}_e \nu_e \bar{\nu}_e u \bar{d}$	1.6492(32)	1.6500(17)	1.6482(15)

- All deviations $\leq 3\sigma$: Programs agree very well.

Linear Collider Benchmark Channels

First step of the comparison:

Technical test of MEs and phase space performance

- Compute predictions for the physics channels of relevance at Future Linear Colliders
  - Top production channels + six-jet backgrounds
  - Higgs production via vector-vector fusion
  - Higgs production via Higgsstrahlung
  - Triple Higgs coupling via Higgsstrahlung
  - Quartic gauge couplings
  - Associated Top-Higgs production
  - Chargino pair production in the MSSM (SPS1a)

Linear Collider Benchmark Channels

First step of the comparison:

Technical test of MEs and phase space performance

- Compute predictions for the physics channels of relevance at Future Linear Colliders
- The conditions:
  - Two energies: 360 and 500 GeV
  - Total cross section with specified phase space cuts
  - Definite SM input parameters including non-zero fermion masses
  - Unstable particles treated according to the fixed-width approach
  - No ISR or FSR
  - In the first step only 10^6 Monte Carlo points

AMEGIC++ calculation setup

Parameters:

G_μ	=	$1.16639\times10^{-5}\mathrm{GeV}^{-2}$	α_s	=	0.0925(0.0891) at 360(500) GeV
M_W	=	80.419 GeV	Γ_W	=	2.12 GeV
M_Z	=	91.1882 GeV	Γ_Z	=	2.4952 GeV
M_H	=	130.0 GeV	Γ_H	=	0.004291 GeV
M_μ	=	105.6583 MeV	M_τ	=	1.777 GeV
M_u	=	5 MeV	M_d	=	10 MeV
M_c	=	1.3 GeV	M_s	=	200 MeV
M_t	=	174.3 GeV	Γ_t	=	1.6 GeV
M_b	=	4.8 GeV			

Phase space cuts:

$$\theta(l(q),\mathrm{beam}) > 5^\circ,\quad \theta(l,l') > 5^\circ,\quad \theta(l,q) > 5^\circ$$

$$E_l > 10\ \mathrm{GeV},\quad E_q > 10\ \mathrm{GeV},\quad m(q,q') > 10\ \mathrm{GeV}$$

AMEGIC++ calculation setup

- Width treatment for unstable particles:

$$
\begin{aligned}
M_V^2 &= m_V^2 - i\, m_V\, \Gamma_V\,, & V &= W, Z \\
M_H^2 &= m_H^2 - i\, m_H\, \Gamma_H\,, & M_t &= m_t - i\Gamma_t/2 \\
D_F^{\mu\nu}(q) &= \frac{-g^{\mu\nu} + q^\mu q^\nu / M_V^2}{q^2 - M_V^2}\,, & D_F(q) &= \frac{1}{q^2 - M_H^2} \\
S_F(q) &= \frac{\not{q} + M_t}{q^2 - M_t^2}
\end{aligned}
$$

- The electroweak mixing angle is kept real (FWS):

$$\Rightarrow \sin^2\theta_W = 1 - m_W^2/m_Z^2$$

- Fermion masses are fully taken into account
- Higgs couplings to e, u, d have been neglected
- Results obtained after 10^6 Monte Carlo points

Technicalities

- All calculations done in parallel mode on two SGI Origin 3800 machines at the ZHR Dresden
  - Operating system: IRIX 6.5.17
  - 192 SGI MIPS R12000 64-Bit-CPU with 400 MHz and 8 MB secondary cache
- Compiler: SGI MIPSpro C++ version 7.3

Flags: -O2 -LANG:std -ptused

-OPT:roundoff=2:alias=typed

Top-channels (full-hadronic modes)

$e^+ e^- \to$	$\sqrt{s}$	QCD	AMEGIC++ [fb]	time [h]
$b\,\bar{b}\,u\,\bar{u}\,d\,\bar{d}$	360	yes	32.90(15)	107
	500	yes	49.74(21)	122
	360	no	32.22(34)	75
	500	no	49.42(44)	73
$b\,\bar{b}\,u\,\bar{u}\,g\,g$	360	–	11.23(10)	76
	500	–	9.11(13)	81
$b\,\bar{b}\,g\,g\,g\,g$	360	–	18.82(13)	89
	500	–	24.09(18)	99

- Phase space cuts for the gluons:

$$\theta(g,\mathrm{beam}) > 5^\circ\,, \quad m(g,g') > 10\text{ GeV}$$
$$m(g,q) > 10\text{ GeV}\,, \quad E_g > 10\text{ GeV}$$

Top-channels (full-hadronic modes)

$e^+ e^- \to$	$\sqrt{s}$	QCD	AMEGIC++ [fb]	time [h]
$b\,\bar{b}\,u\,\bar{u}\,d\,\bar{d}$	360	yes	32.90(15)	107
	500	yes	49.74(21)	122
	360	no	32.22(34)	75
	500	no	49.42(44)	73
$b\,\bar{b}\,u\,\bar{u}\,g\,g$	360	–	11.23(10)	76
	500	–	9.11(13)	81
$b\,\bar{b}\,g\,g\,g\,g$	360	–	18.82(13)	89
	500	–	24.09(18)	99

LUSIFER results:
(massless, 10^7 steps)

31.28(8)

48.70(14)

- Phase space cuts for the gluons:

$$\theta(g, \text{beam}) > 5^\circ\,, \qquad m(g,g') > 10\text{ GeV}$$
$$m(g,q) > 10\text{ GeV}\,, \qquad E_g > 10\text{ GeV}$$

Top-channels (semi-leptonic modes)

$e^+ e^- \to$	$\sqrt{s}$	QCD	AMEGIC++ [fb]	LUSIFER† [fb]	time [h]
$b\,\bar{b}\,u\,\bar{d}\,e^-\,\bar{\nu}_e$	360	yes	11.460(36)	11.103(63)	48
	500	yes	17.486(66)	17.037(32)	48
	360	no	11.312(37)	11.127(23)	29
	500	no	17.366(68)	16.957(12)	31
$b\,\bar{b}\,e^+\,\nu_e\,e^-\,\bar{\nu}_e$	360	–	3.902(31)	3.836(9)	84
	500	–	5.954(55)	5.806(11)	80
$b\,\bar{b}\,e^+\,\nu_e\,\mu^-\,\bar{\nu}_\mu$	360	–	3.847(15)	3.821(38)	31
	500	–	5.865(24)	5.747(4)	30
$b\,\bar{b}\,\mu^+\,\nu_\mu\,\mu^-\,\bar{\nu}_\mu$	360	–	3.808(16)	3.819(20)	47
	500	–	5.840(30)	5.727(3)	44

† : 10^7 events, massless approximation

Top-channels (massless, 10^7 steps)

$e^+ e^- \to$	$\sqrt{s}$	QCD	AMEGIC++ [fb]	LUSIFER [fb]	time [h]
$b\,\bar{b}\,u\,\bar{u}\,d\,\bar{d}$	360	no	31.42(3)	31.28(8)	115
	500	no	49.50(39)	48.70(14)	115
$b\,\bar{b}\,u\,\bar{d}\,e^-\,\bar{\nu}_e$	360	yes	11.333(7)	11.103(63)	144
	500	yes	17.391(13)	17.037(32)	136
	360	no	11.235(6)	11.127(23)	85
	500	no	17.284(12)	16.957(12)	84
$b\,\bar{b}\,e^+\,\nu_e\,e^-\,\bar{\nu}_e$	360	–	3.868(7)	3.836(9)	168
($6 \cdot 10^6$ steps)	500	–	5.955(12)	5.806(11)	168
$b\,\bar{b}\,e^+\,\nu_e\,\mu^-\,\bar{\nu}_\mu$	360	–	3.839(2)	3.821(38)	84
	500	–	5.866(4)	5.747(4)	84
$b\,\bar{b}\,\mu^+\,\nu_\mu\,\mu^-\,\bar{\nu}_\mu$	360	–	3.841(12)	3.819(20)	84
	500	–	5.807(10)	5.727(3)	80

Differences seem to stem from the inclusion (AME) / exclusion (LUS) of $H\,b\,\bar{b}$ interactions

Higgs production via vector fusion I

			Higgs on		Higgs off	
$e^+ e^- \to$	$\sqrt{s}$	QCD	AMEGIC++ [fb]	time [h]	AMEGIC++ [fb]	time [h]
$e^- e^+ u \bar{u} d \bar{d}$	360	yes	0.6597(94)	78	0.4838(50)	91
	500	yes	1.237(15)	88	1.0514(97)	99
	360	no	0.6348(69)	72	0.4502(31)	133
	500	no	1.206(14)	76	1.0239(79)	136
$\nu_e \bar{\nu}_e u \bar{u} d \bar{d}$	360	yes	1.232(41)	52	0.15007(53)	52
	500	yes	2.52(10)	51	0.4755(21)	56
	360	no	1.214(47)	48	0.12828(42)	56
	500	no	2.466(36)	48	0.4417(19)	61

Higgs production via vector fusion II

		Higgs on		Higgs off	
$e^+ e^- \to$	$\sqrt{s}$	AMEGIC++ [fb]	time [h]	AMEGIC++ [fb]	time [h]
$e^- e^+ u \bar{u} e^- e^+$	360	0.00636(55)	43	0.003757(98)	26
	500	0.00681(34)	42	0.004082(56)	32
$e^- e^+ u \bar{u} \mu^- \mu^+$	360	0.00924(12)	28	0.005201(61)	35
	500	0.00925(17)	29	0.005805(67)	38
$\nu_e \bar{\nu}_e u \bar{d} e^- \bar{\nu}_e$	360	0.424(12)	29	0.04546(13)	37
	500	0.887(31)	29	0.16237(62)	37
$\nu_e \bar{\nu}_e u \bar{d} \mu^- \bar{\nu}_\mu$	360	0.407(11)	15	0.04230(12)	12
	500	0.898(37)	15	0.14383(53)	13

Higgs production via vector fusion II

		Higgs on		Higgs off	
$e^+ e^- \rightarrow$	$\sqrt{s}$	AMEGIC++ [fb]	time [h]	AMEGIC++ [fb]	time [h]
$e^- e^+ u \bar{u} e^- e^+$	360	0.00636(55)	43	0.003757(98)	26
	500	0.00681(34)	42	0.004082(56)	32
$e^- e^+ u \bar{u} \mu^- \mu^+$	360	0.00924(12)	28	0.005201(61)	35
	500	0.00925(17)	29	0.005805(67)	38
$\nu_e \bar{\nu}_e u \bar{d} e^- \bar{\nu}_e$	360	0.424(12)	29	0.04546(13)	37
	500	0.887(31)	29	0.16237(62)	37
$\nu_e \bar{\nu}_e u \bar{d} \mu^- \bar{\nu}_\mu$	360	0.407(11)	15	0.04230(12)	12
	500	0.898(37)	15	0.14383(53)	13

Errors larger than 5%: More statistics needed.

Higgs production via Higgsstrahlung

			Higgs on		Higgs off	
$e^+ e^- \to$	$\sqrt{s}$	QCD	AMEGIC++ [fb]	time [h]	AMEGIC++ [fb]	time [h]
$\mu^- \mu^+ \mu^+ \nu_\mu e^- \bar{\nu}_e$	360	–	0.03244(27)	46	0.01845(14)	31
	500	–	0.03747(29)	46	0.03054(23)	36
$\mu^- \mu^+ u \bar{d}\, e^- \bar{\nu}_e$	360	–	0.0924(8)	28	0.05284(57)	21
	500	–	0.1106(22)	25	0.08911(53)	24
$\mu^- \mu^+ \mu^+ \mu^- e^- e^+$	360	–	0.002828(67)	32	0.002204(52)	22
	500	–	0.002731(65)	39	0.002280(66)	22
$\mu^- \mu^+ u \bar{u} d \bar{d}$	360	yes	0.2534(24)	93	0.1412(10)	50
	500	yes	0.2634(22)	92	0.2092(12)	65
	360	no	0.2441(23)	61	0.1358(20)	60
	500	no	0.2593(22)	61	0.2040(12)	65
$\mu^- \mu^+ u \bar{u} u \bar{u}$	360	yes	0.011249(81)	65	0.005937(24)	45
	500	yes	0.008767(45)	69	0.006134(29)	49

Higgs production via Higgsstrahlung

			Higgs on		Higgs off	
$e^+ e^- \rightarrow$	$\sqrt{s}$	QCD	AMEGIC++ [fb]	time [h]	AMEGIC++ [fb]	time [h]
$\mu^- \mu^+ \mu^+ \nu_\mu e^- \bar{\nu}_e$	360	–	0.03244(27)	46	0.01845(14)	31
	500	–	0.03747(29)	46	0.03054(23)	36
$\mu^- \mu^+ u \bar{d}\, e^- \bar{\nu}_e$	360	–	0.0924(8)	28	0.05284(57)	21
	500	–	0.1106(22)	25	0.08911(53)	24
$\mu^- \mu^+ \mu^+ \mu^- e^- e^+$	360	–	0.002828(67)	32	0.002204(52)	22
	500	–	0.002731(65)	39	0.002280(66)	22
$\mu^- \mu^+ u \bar{u} d \bar{d}$	360	yes	0.2534(24)	93	0.1412(10)	50
	500	yes	0.2634(22)	92	0.2092(12)	65
$\mu^- \mu^+ u \bar{u} u \bar{u}$	360	yes	0.011249(81)	65	0.005937(24)	45
	500	yes	0.008767(45)	69	0.006134(29)	49
	360	no	0.007929(57)	56	0.002722(10)	50
	500	no	0.006098(35)	58	0.003290(12)	54

Triple Higgs coupling & QGCs

			Higgs on		Higgs off	
$e^+ e^- \to$	$\sqrt{s}$	QCD	AMEGIC++ [fb]	time [h]	AMEGIC++ [fb]	time [h]
$\mu^- \mu^+ b \bar{b} b \bar{b}$	360	yes	0.02560(26)	216	0.00724(22)	63
	500	yes	0.03096(60)	205	0.006651(24)	72
	360	no	0.01711(55)	77	0.002955(11)	54
	500	no	0.0234(12)	83	0.003704(15)	58

Number of Feynman diagrams/Superamplitudes for $e^+ e^- \to \mu^- \mu^+ b \bar{b} b \bar{b}$:

Higgs on : with QCD 2918/382, without QCD 2502/294

Higgs off : with QCD 1440/216, without QCD 1152/144

$e^+ e^- \to$	$\sqrt{s}$	AMEGIC++ [fb]	time [h]
$e^+ \nu_e \mu^- \bar{\nu}_\mu \gamma$	360	11.95(11)	2.3
	500	10.48(13)	2.3

$t\,\bar{t}\,H$ production and SUSY

Status quo:

- Generation of amplitudes in general possible

$b\,\bar{b}\,b\,\bar{b}\,\mu^+\,\nu_\mu\,e^-\,\bar{\nu}_e$	:	42428
$b\,\bar{b}\,b\,\bar{b}\,u\,\bar{d}\,e^-\,\bar{\nu}_e$	:	53632
$\tilde{\chi}^0_1\,\tilde{\chi}^0_1\,u\,\bar{d}\,e^-\,\bar{\nu}_e$	:	11414 $\rightarrow$ 1682 (Superamplitudes)

  $\Rightarrow$ Has been parallelized and accelerated significantly

  $\Rightarrow$ Further acceleration desirable

- Number of phase space channels to large to be handled at the moment

  $\Rightarrow$ Most urgend topic of the next month

Conclusion

- AMEGIC++ capable to calculate six-fermion and six-jet production processes
- Allows to study signal and associated backgrounds in one consistent framework
- Fermion masses can fully be taken into account
- Performance comparable to that of dedicated programs
- The phase space will be revised to face eight-fermion processes