Automatic Calculation of SUSY Particle Production with GRACE/SUSY/1LOOP

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1. Introduction
2. Tree level system
3. 1-loop level system
4. Outlook

The 7th ACFA Workshop

on Physics & Detector at the Linear Collider

NTU, Taipei, Taiwan, 10 November, 2004

1. Introduction

Automatic calculation of amplitudes

➛ important @ HE colliders LHC & ILC

* many body final states
* possible many new particles

Systems of automatic calculation

GRACE (Ours) — Prog. Theor. Phys. Suppl. 138 (2000) 18
Comput.Phys.Commun. 153 (2003) 106

CompHEP — hep-ph/0205020, hep-ph/0111291, hep-ph/0101232
Bėlanger et al. MicroOmega, hep-ph/0210327

Feyn series — Hahn, Comput.Phys.Commun. 140 (2001) 418; 143 (2002) 54

MADGRAPH/MADEVENT — Maltoni and Stelzer, JHEP 0302 (2003) 027

2. Tree level system (GRACE/SUSY)

Model: MSSM

particle	variable name
photon	photon
$W^+(W^-)$	W-plus (W-minus)
Z	Z
gluon	gluon
$\nu_e(\overline{\nu_e})$	nu-e (nu-e-bar)
$e^-(e^+)$	electron (positron)
$\nu_\mu(\overline{\nu_\mu})$	nu-mu (nu-mu-bar)
$\mu^-(\mu^+)$	muon (anti-muon)
$\nu_\tau(\overline{\nu_\tau})$	nu-tau (nu-tau-bar)
$\tau^-(\tau^+)$	tau (anti-tau)
$u(\bar u)$	u (u-bar)
$d(\bar d)$	d (d-bar)
$c(\bar c)$	c (c-bar)
$s(\bar s)$	s (s-bar)
$t(\bar t)$	t (t-bar)
$b(\bar b)$	b (b-bar)
h^0	Higgs1
H^0	Higgs2
A^0	Higgs3
$H^+(H^-)$	Higgs-plus (Higgs-minus)

particle	variable name
$\tilde\chi_1^+(\tilde\chi_1^-)$	chargino1 (anti-chargino1)
$\tilde\chi_2^+(\tilde\chi_2^-)$	chargino2 (anti-chargino2)
$\tilde\chi_1^0$	neutralino1
$\tilde\chi_2^0$	neutralino2
$\tilde\chi_3^0$	neutralino3
$\tilde\chi_4^0$	neutralino4
$\tilde\nu_e(\overline{\tilde\nu_e})$	snu-e (anti-snu-e)
$\tilde\nu_\mu(\overline{\tilde\nu_\mu})$	snu-mu (anti-snu-mu)
$\tilde\nu_\tau(\overline{\tilde\nu_\tau})$	snu-tau (anti-snu-tau)
$\tilde e_1^-(\tilde e_1^+)$	selectron1 (anti-selectron1)
$\tilde e_2^-(\tilde e_2^+)$	selectron2 (anti-selectron2)
$\tilde\mu_1^-(\tilde\mu_1^+)$	smuon1 (anti-smuon1)
$\tilde\mu_2^-(\tilde\mu_2^+)$	smuon2 (anti-smuon2)
$\tilde\tau_1^-(\tilde\tau_1^+)$	stau1 (anti-stau1)
$\tilde\tau_2^-(\tilde\tau_2^+)$	stau2 (anti-stau2)
$\tilde u_1(\overline{\tilde u_1})$	su1 (anti-su1)
$\tilde u_2(\overline{\tilde u_2})$	su2 (anti-su2)
$\tilde d_1(\overline{\tilde d_1})$	sd1 (anti-sd1)
$\tilde d_2(\overline{\tilde d_2})$	sd2 (anti-sd2)
$\tilde c_1(\overline{\tilde c_1})$	sc1 (anti-sc1)
$\tilde c_2(\overline{\tilde c_2})$	sc2 (anti-sc2)
$\tilde s_1(\overline{\tilde s_1})$	ss1 (anti-ss1)
$\tilde s_2(\overline{\tilde s_2})$	ss2 (anti-ss2)
$\tilde t_1(\overline{\tilde t_1})$	st1 (anti-st1)
$\tilde t_2(\overline{\tilde t_2})$	st2 (anti-st2)
$\tilde b_1(\overline{\tilde b_1})$	sb1 (anti-sb1)
$\tilde b_2(\overline{\tilde b_2})$	sb2 (anti-sb2)

Input parameters:

Higgs & Gauginos

$$\alpha_e, \alpha_s, M_W, M_Z, \tan\beta, M_{A^0}, \mu, M_1, M_2, M_3.$$

Sfermions

sfermion masses	$m_{\tilde u_i}, m_{\tilde c_i}, m_{\tilde t_i}$	amsu(1,i), amsu(2,i), amsu(3,i)
	$m_{\tilde d_i}, m_{\tilde s_i}, m_{\tilde b_i}$	amsd(1,i), amsd(2,i), amsd(3,i)
	$m_{\tilde\nu_e}, m_{\tilde\nu_\mu}, m_{\tilde\nu_\tau}$	amsn(1), amsn(2), amsn(3)
	$m_{\tilde e_i}, m_{\tilde\mu_i}, m_{\tilde\tau_i}$	amsl(1,i), amsl(2,i), amsl(3,i)
sfermion widths	$\Gamma_{\tilde u_i}, \Gamma_{\tilde c_i}, \Gamma_{\tilde t_i}$	agsu(1,i), agsu(2,i), agsu(3,i)
	$\Gamma_{\tilde d_i}, \Gamma_{\tilde s_i}, \Gamma_{\tilde b_i}$	agsd(1,i), agsd(2,i), agsd(3,i)
	$\Gamma_{\tilde\nu_e}, \Gamma_{\tilde\nu_\mu}, \Gamma_{\tilde\nu_\tau}$	agsn(1), agsn(2), agsn(3)
	$\Gamma_{\tilde e_i}, \Gamma_{\tilde\mu_i}, \Gamma_{\tilde\tau_i}$	agsl(1,i), agsl(2,i), agsl(3,i)
SUSY-breaking parameters	$m_u A_u, m_c A_c, m_t A_t$	xauq(1), xauq(2), xauq(3)
	$m_d A_d, m_s A_s, m_b A_b$	xadq(1), xadq(2), xadq(3)
	$m_e A_e, m_\mu A_\mu, m_\tau A_\tau$	xalp(1), xalp(2), xalp(3)
sfermion mixing	$\sin\theta_u, \sin\theta_c, \sin\theta_t$	sbuq(1), sbuq(2), sbuq(3)
	$\cos\theta_u, \cos\theta_c, \cos\theta_t$	cbuq(1), cbuq(2), cbuq(3)
	$\sin\theta_d, \sin\theta_s, \sin\theta_b$	sbdq(1), sbdq(2), sbdq(3)
	$\cos\theta_d, \cos\theta_s, \cos\theta_b$	cbdq(1), cbdq(2), cbdq(3)
	$\sin\theta_e, \sin\theta_\mu, \sin\theta_\tau$	sblp(1), sblp(2), sblp(3)
	$\cos\theta_e, \cos\theta_\mu, \cos\theta_\tau$	cblp(1), cblp(2), cblp(3)

M. Kuroda, Complete Langarian of MSSM, hep-ph/9902340
J. Fujimoto et al., Comput.Phys.Commun. 153 (2003) 106

Example

$$e^- e^+ \rightarrow \gamma \tilde{\chi}_1^+ \tilde{\chi}_1^-$$

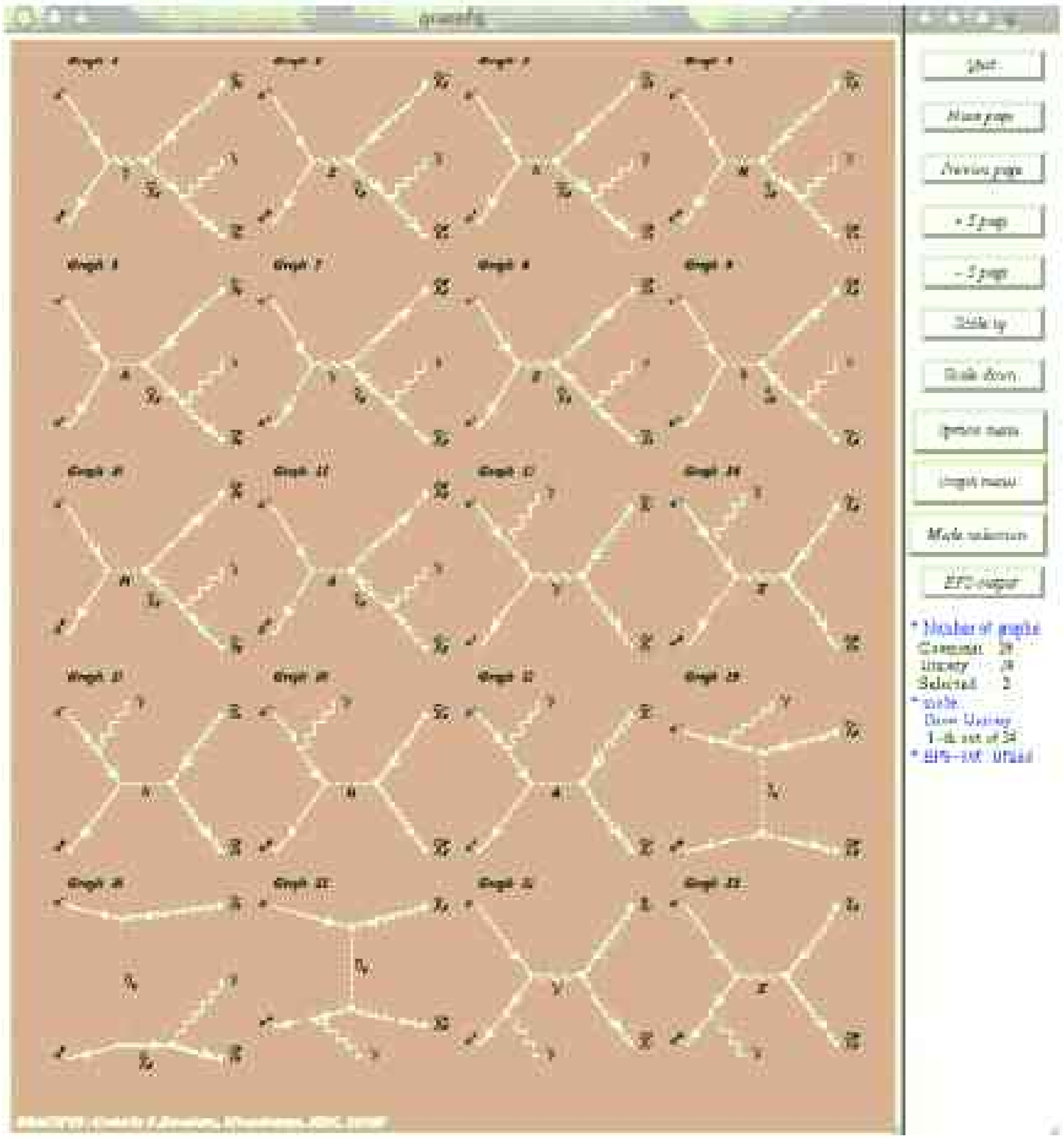
Input file 'in.prc'

```
Model="mssm.mdl";
Process;
ELWK=3;
QCD=0;
 Initial={electron, positron};
 Final ={photon,chargino1,anti-chargino1};
Kinem="2302"
Pend;
```

Feynman diagrams generated by 'grc'

Fortran codes generated by 'grcfort'

Feynman diagrams drawn by 'gracefig'



Gauge invariance check

R_ξ gauge, quadruple-precision at 1-point in phase space

ans1 = 0.139175455829902   covariant gauge
ans2 = 0.139175455829902   unitary gauge
ans1/ans2 - 1 = -2.220446049250313E-016

Integration by 'bases'

```
             Convergency Behavior for the Integration Step
 ------------------------------------------------------------------------
 <- Result of  each iteration ->  <-     Cumulative Result      -> < CPU  time >
  IT Eff R_Neg   Estimate  Acc %  Estimate(+- Error )order   Acc % ( H: M: Sec )
 ------------------------------------------------------------------------
   1  92  0.00  1.145E-01  0.514  1.145749(+-0.005887)E-01  0.514   0: 0:37.68
   2  92  0.00  1.151E-01  0.519  1.149243(+-0.004311)E-01  0.375   0: 0:44.35
   3  91  0.00  1.143E-01  0.515  1.147839(+-0.003478)E-01  0.303   0: 0:51.01
   4  91  0.00  1.137E-01  0.524  1.144273(+-0.002972)E-01  0.260   0: 0:57.66
   5  91  0.00  1.135E-01  0.485  1.142809(+-0.002615)E-01  0.229   0: 1: 4.33
 ------------------------------------------------------------------------

                    ****** END OF BASES *********


    <<   Computing Time Information   >>

          (1) For BASES                  H: M:  Sec
              Overhead           :       0: 0: 0.00
              Grid Optim. Step   :       0: 0:31.00
              Integration Step   :       0: 0:33.33
              Go time for all    :       0: 1: 4.33

          (2) Expected event generation time
              Expected time for 1000 events :      1.10 Sec
```

GRACE/SUSY (tree-level) system is

COMPLETED!

We have checked the gauge invariance with quadruple-precision

SUSY processes with up to 6 external particles

582,102 processes

→ DONE!

The system can be obtained at

http://minami-home.kek.jp/

3. 1-loop level system (GRACE/SUSY/1LOOP)

Renormalization scheme of the MSSM

<u>On mass-shell renormalization</u>

Gauge-boson sector: (conventional approach)

Renormalization constants of wavefunctions → Unmixed bare states

Mass counterterms → Mixed mass eigenstates

Higgs-boson sector:

Renormalization constants of wavefunctions → Unmixed bare states

Chargino sector and Neutralino sector:

Renormalization constants of wavefunctions → Unmixed bare states

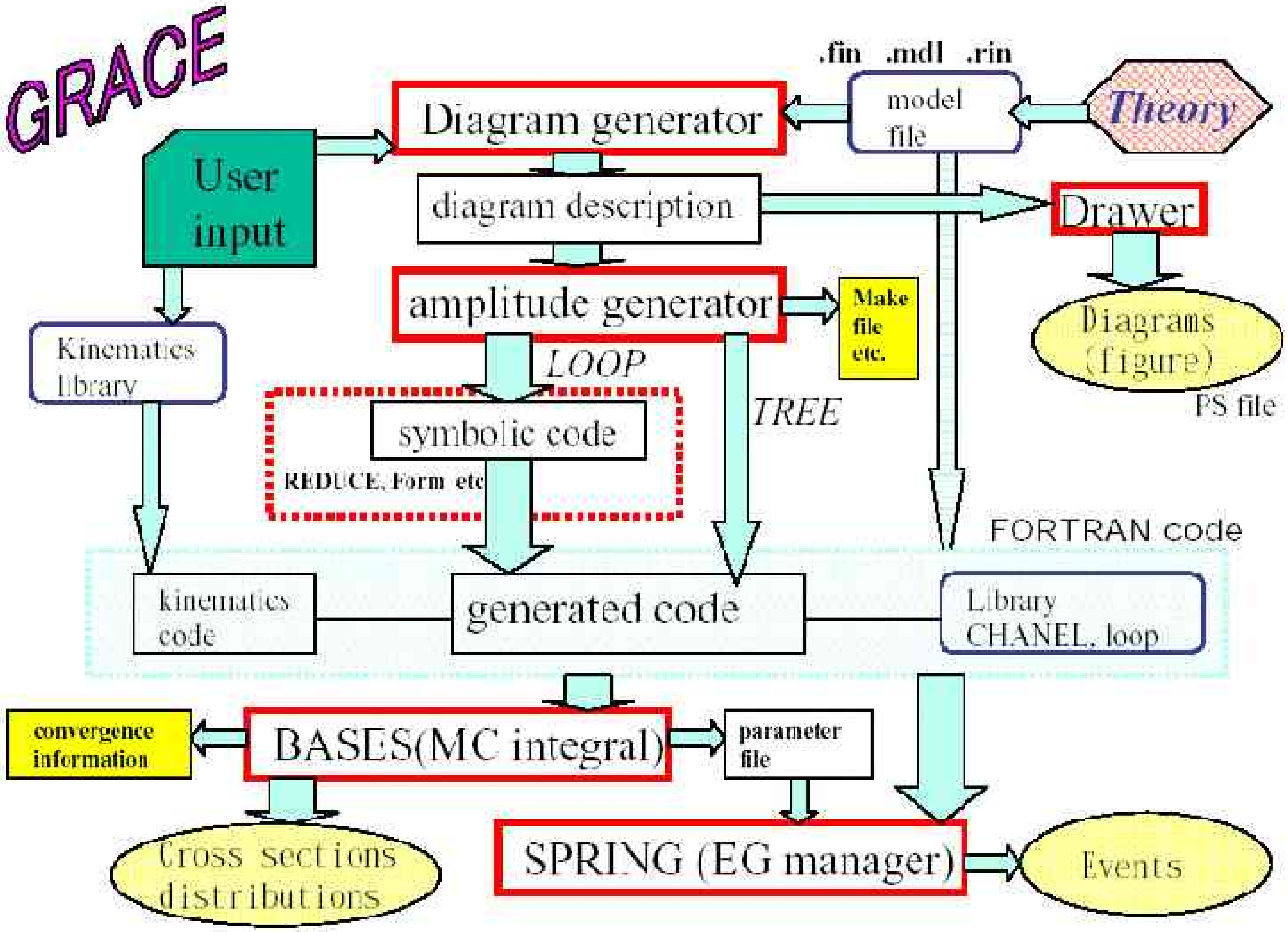
M. Kuroda, in Research report to the Ministry of Education, Science and Culture, Japan, the Grant-in-Aid for Scientific Research C (No.08640391), (1999) 127

T. Fritzsche and W. Hollik, Eur. Phys. J. C24 (2002) 619

Matter-fermion sector and Sfermion sector:

Renormalization constants of wavefunctions → Mixed mass eigenstates

K-I. Aoki, Z. Hioki, R. Kawabe, M. Konuma and T. Muta, Prog. Theor. Phys. Suppl. 73 (1982) 1


GRACE
User input
Diagram generator
.fin .mdl .rin
model file
Theory
diagram description
Drawer
amplitude generator
Make file etc.
Diagrams (figure)
PS file
Kinematics library
LOOP
TREE
symbolic code
REDUCE, Form etc
FORTRAN code
kinematics code
generated code
Library CHANEL, loop
convergence information
BASES(MC integral)
parameter file
Cross sections distributions
SPRING (EG manager)
Events

Example

$$e^- e^+ \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$$

Refs.
M. A. Diaz, S. F. King and A. Ross, Nucl. Phys. B529 (1998) 23, hep-ph/0008117
T. Blank and W. Hollik, hep-ph/0011092
W. Öller, H. Eberl, W. Majerotto and C. Weber, hep-ph/0304006

* Full Electroweak correction

→ 1935 1-loop level diagrams × 7 tree-level diagrams

Input file 'in.prc'

```
Model="mssmnlg.mdl";
Process;
 ELWK={4,2};
 QCD=0;
 Initial ={electron positron};
 Final ={chargino1 anti-chargino1};
 Kinem="2001";
 Expand=Yes;
 Block=No;
 AnyCT=Yes;
 Extself=Yes;
Pend;
```

→ 'grc' → Feynman diagrams

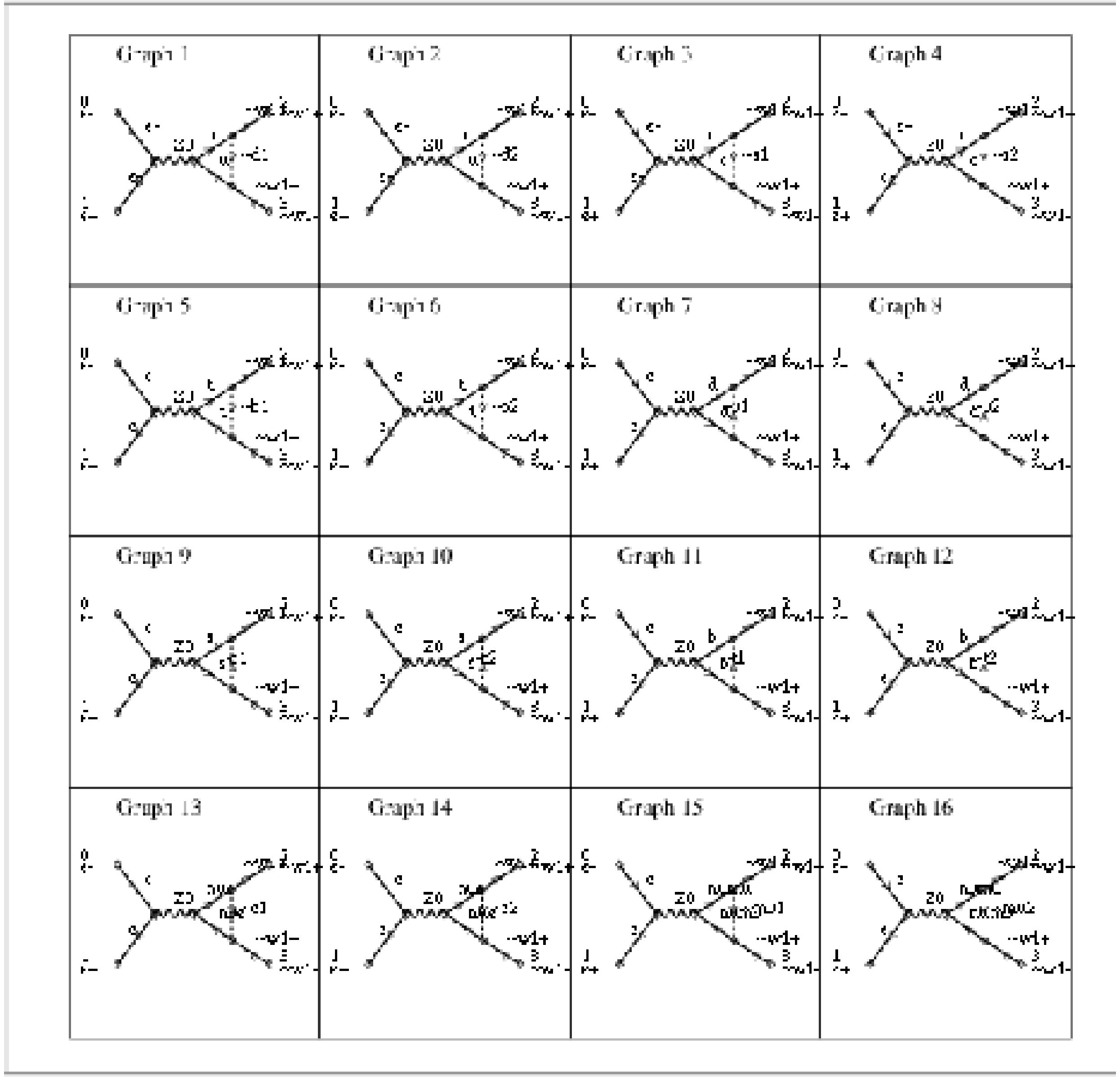
↓ 'grcred'

REDUCE source codes

↓ 'make'

Fortran codes & Executable files

Feynman diagrams printed to ps-files by 'grcplot'



How you can believe the numbers produced by an automated system?

UV finiteness

Check → varing the UV constant ($C_{\rm UV}$)

IR finiteness

Check → varing the fictitious photon mass (λ)
[1-loop + soft poton]

gauge invariance

Check → varing the non-linear gauge parameters
($\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}, \tilde{\varepsilon}, \tilde{\kappa}$)

* Checking GRACE with the non-linear gauge has already been done in the SM

G. Bélanger, F. Boudjema, J. Fujimoto, T. Ishikawa, T. Kaneko, K. Kato and Y. Shimizu, LAPTH-982-03, KEK-CP-138 (2003) hep-ph/0308080

Non-linear gauge in MSSM

- Numerator structure is the same as Feynman gauge $g^{\mu\nu}$ (for $\xi = 1$)
- Vertices modified $\tilde{\alpha} = 1 \Rightarrow$ no AWG
- New vertices (ghost sector) appear

Non-linear gauge fixing terms

$$F_{W^\pm} = (\partial_\mu \pm ie\tilde{\alpha}A_\mu \pm igc_W\tilde{\beta}Z_\mu)W^{\pm\mu}$$

$$\pm i\xi_W \frac{g}{2}(v + \tilde{\delta}_H H^0 + \tilde{\delta}_h h^0 \pm i\tilde{\kappa}G^0)G^\pm$$

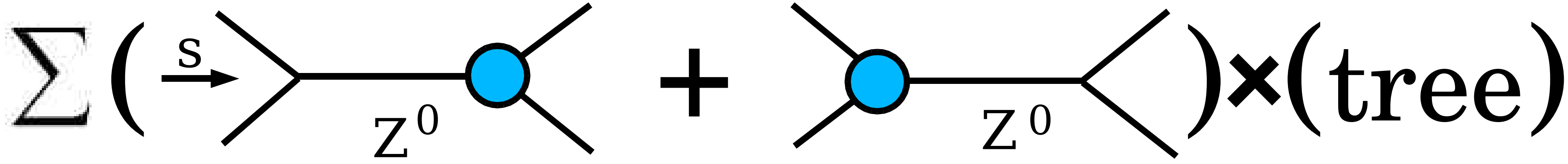
$$F_Z = \partial_\mu Z^\mu + \xi_Z \frac{g_Z}{2}(v + \tilde{\varepsilon}_H H^0 + \tilde{\varepsilon}_h h^0)G^0$$

$$F_\gamma = \partial_\mu A^\mu$$

Results of checks ($e^- e^+ \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$)

UV check

$C_{UV} = 0, 100$



zsum0 0 255 (-2.4238440460988892389568132161782622e-0002,
4.8670226801714368832289586855722879e-0003)

zsumc 0 255 (-2.4238440460988892389568132161777729e-0002,
4.8670226801714368832289586855722879e-0003)

(30 digits)

•
•
•

Total

Zall0 (-0.1371430882438220085000151895773909**3**,
2.9534974780222292111693636042692019e-0002)

Zallc (-0.13714308824382200850001518957737294,
2.9534974780222292111693636042692019e-0002)

(31 digits)

IR check (for selected graphs)

$\lambda = 10^{-18}$

ANS = -8.482168085150522e-0002

$\lambda = 10^{-24}$ (9 digits)

ANS = -8.482168087342838e-0002

[Ommited e-e-scalar]

gauge invariance check NLG parameters

$$\tilde{\alpha}$$

```
alpha
--------------------------
<<selected graph>>42
--------------------------
IU no. T : @ = ^2, # = ^3
RV
         |      a^4        |      a^3      |     a^2      |      a^1       |     a^0
--------------------------
  226V                                                    | -0.2651979e-07 |  0.2651979e-07
  227V                                                    |  0.9541715e-07 | -0.9541715e-07
  228V                                                    |  0.9308935e-07 | -0.9308935e-07
  229V                                                    |  0.3661252e-08 | -0.3661252e-08
  230V                                                    | -0.2651979e-07 |  0.2651979e-07
                                   •
                                   •
                                   •
 1931S                                                    |  0.3902432e-15 |  0.2084935e-
14
 1932SQ| -0.5294619e-50 |  0.1057452e-49 |  0.5338774e-50 | -0.3820339e-49 |  0.2758471e-
49
 ---------------------------------------------------------------------
cnt                1               0               0              25
tot          0.20977e-01     0.20977e-01     0.20977e-01     0.20977e-01     0.20977e-01
sum1         0.65123e-34    -0.47138e-34    -0.32167e-33    -0.77400e-15     0.20977e-01
max          0.42898e-34     0.22914e-34     0.21894e-33     0.81660e-03     0.12824e-01
```

$\tilde{\beta}$

beta

<<selected graph>>41

IU no. T : @ = ^2, # = ^3

RV	a^4	a^3	a^2	a^1	a^0
158V				-0.1404845e-07	0.2651979e-07
159V				0.4166858e-07	-0.9541715e-07
160V				0.3906425e-07	-0.9308935e-07
161V				0.1964962e-08	-0.3661252e-08
166V				-0.1404845e-07	-0.4044929e-08
⋮					
1931S				-0.5221061e-15	0.2084935e-14
1932SQ	-0.2759842e-52	-0.1103847e-52	0.1159122e-51	0.5519367e-52	0.2758471e-49
cnt	1	0	0	20	
tot	0.18567e-01	0.18567e-01	0.18567e-01	0.18567e-01	0.18567e-01
sum1	-0.15159e-34	-0.41344e-34	0.67172e-34	0.10355e-14	0.18567e-01
max	0.61753e-35	0.13166e-34	0.19059e-34	0.96369e-03	0.12824e-01

epsln1

<<selected graph>>47

IU no. T : @ = ^2, # = ^3

$$\tilde{\varepsilon}_{h^0}$$

RV	a^4	a^3	a^2	a^1	a^0
132V				0.4131154e-17	-0.9419811e-07
133V				0.2199380e-18	0.3210661e-04
150V				0.4131154e-17	-0.9419811e-07
151V				0.2199380e-18	0.3210661e-04
276V				-0.5827019e-15	0.2976493e-15
⋮					
1931S@			0.2161744e-15	0.5510489e-16	0.2084935e-14
1933S				-0.6013497e-14	0.7254471e-13
1934S@			-0.3242617e-15	0.1240086e-13	-0.4383777e-12

	a^4	a^3	a^2	a^1	a^0
cnt	0	0	4	43	
tot	0.38631e-03	0.38631e-03	0.38631e-03	0.38631e-03	0.38631e-03
sum1	0.23510e-37	0.10777e-37	-0.10394e-36	-0.37361e-37	0.38631e-03
max	0.23510e-37	0.11755e-37	0.32426e-15	0.50786e-13	0.32229e-03

4. Outlook

More processes

decays, final 2-bodies, 3-bodies, ...

e.g. $e^- e^+ \to \gamma \tilde{\chi}_1^0 \tilde{\chi}_1^0$

25126 1-loop level diagrams

$\times$

22 tree-level diagrams!