Implementation of non-linear gauge in GRACE

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Introduction

- Systems for Automatic Computation of cross sections → essential tools in HEP
- Complicated calculation

  EW, susy : many particles and vertices

  final states: multi-body

  high statistics: higher-order(loops)

→ Beyond man-power

Automatic systems

- Diagram generation for the input process
- Amplitude/Matrix element generation
- Kinematics and Integration (efficiency)
- Event generation (efficiency & weight)
- Peripheral tools: rule generator, diagram selection, QED radiation, PDF, loop integral library, multi-process, color flow and interface for hadronization, etc.

Sugawara, ICHEP2000

Automatic Computation

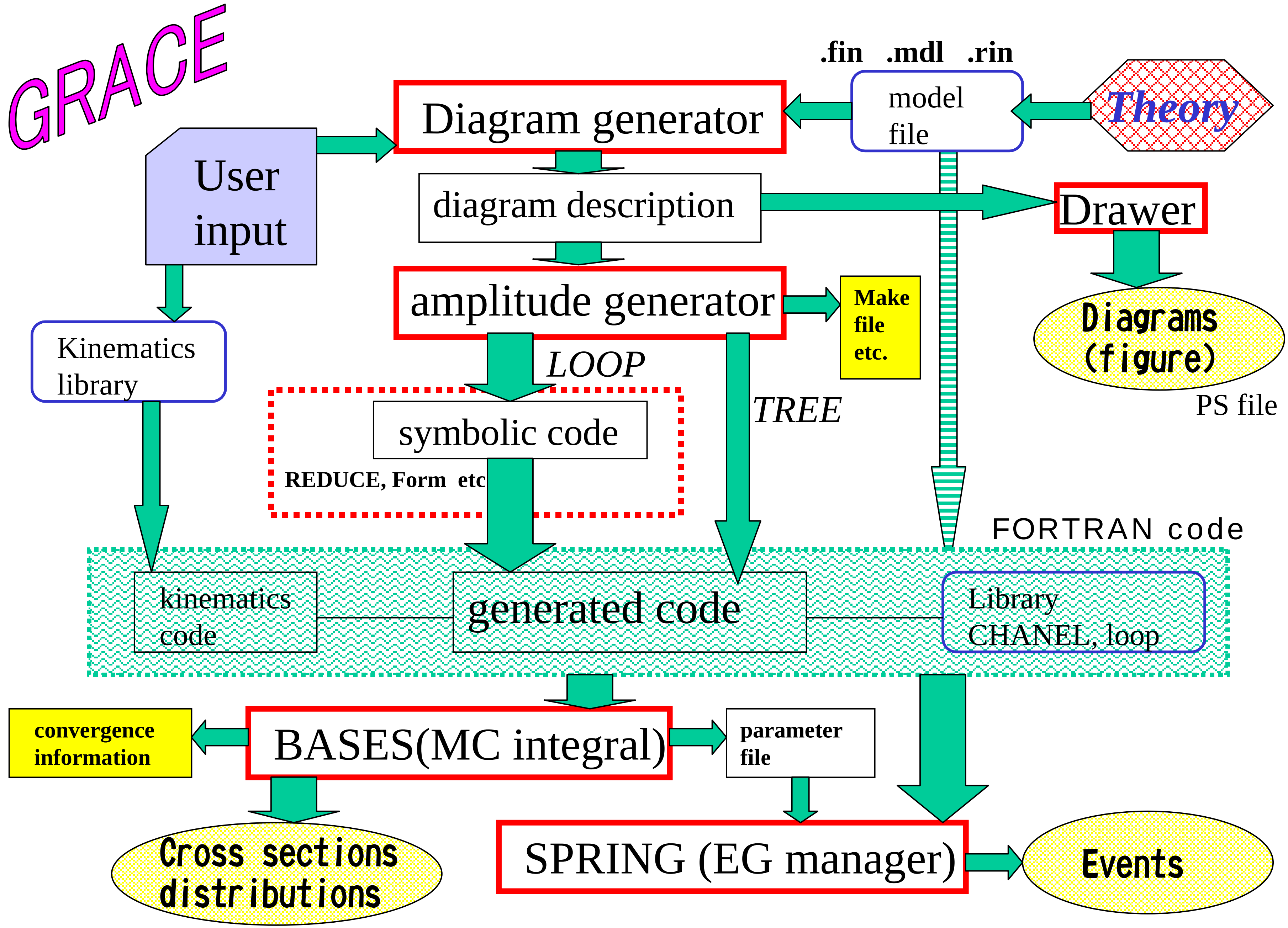
⇒ Automatic calculation of cross sections in HEP.
⇒ Large scale computation beyond man-power.
⇒ Essential tools for current and future HEP.

1. Automatic computation systems working in the world

   `ALPHA`(Italy), `CompHEP`(Russia), `FDC`(China), `FeynArts/FeynCalc series`(Germany), `GEFICOM`(Germany/Russia), `GRACE`(Japan), `MadGraph`(USA), `NIKHEF setup`(Holland) ...

2. Examples of Achievements

   - 4-fermion generators(76 processes) for LEP-2 experiments(`ALPHA`,`CompHEP`, `GRACE`).
   - $e^-e^+ \to$ 6-fermion(`ALPHA`,`GRACE`), $e^-e^+ \to \tilde{\chi}_1^0\tilde{\chi}_1^0 q_1\bar{q}_2 q_3\bar{q}_4$ (`GRACE`), $\gamma\gamma \to$ 4-fermion(`CompHEP`).
   - $ep \to el^+l^-X$(`GRACE`).
   - $p\bar{p} \to Wb\bar{b}$j(`CompHEP`), $pp \to W^+W^-b\bar{b}j$ (`MadGraph`), $gg, q\bar{q} \to 8g$(`ALPHA`).
   - 1-loop calculation for $e^-e^+ \to W^-W^+$, $\gamma\gamma \to W^+W^-$, $W^+W^- \to W^+W^-$ (`FeynArts/FeynCalc`,`GRACE`), $e^-e^+ \to W^+\mu^-\bar{\nu}_\mu$ (`GRACE`).
   - Hadronic Higgs decay in $O(\alpha_s^2)$, $O(\alpha\alpha_s)$ corrections to $Z \to b\bar{b}$, etc. (`GEFICOM`).
   - 4-loop β-function(∼50,000 diagrams) (`NIKHEF setup`).


GRACE
.fin .mdl .rin
Diagram generator
model file
Theory
User input
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

Introduction

- How to check (or how to believe) the results of automated systems ?
- Consistency checks:
  Change particle assignment (kinematical),
  Renormalization, IR cancellation,
  Gauge invariance, ...

Very Powerful

NOTE:*Best check* comparison between systems == International collaboration

Check by gauge invariance

- Tree case : Unitary gauge vs. covarinat gauge.
- Loop case: Unitary gauge $-g^{\mu\nu}+(1-\xi)\frac{p^{\mu}p^{\nu}}{p^{2}-\xi M^{2}}$ is no good for loop integrals (Loop system includes loop integral libraries. The ‘tHooft-Feynman gauge would be the unique choice.)

$\gamma\gamma \to$ WWZ

Tree

Covariant gauge vs. unitary gauge calculation

ans1/ans2−1
=−9.992 ∗ 10^{-16}

double precision

The report from gauge check for the process $\gamma\gamma \to W^+W^-Z$(tree).

```
ans1   =  697.3329568147916
ans2   =  697.3329568147923
ans1/ans2 - 1 =  -9.992007221626409E-16
```

Squared values of each amplitude are shown below. Here gauge parameters are $\xi_W = 2, \xi_Z = 3, \xi_A = 4, \xi_\phi = 5$ for the covariant gauge and all $\xi \to \infty$ in the unitary gauge.

Graph	Covariant G.	Unitary G.
1	21528.57045977585	18564.51167868807
2	.1460009958034371	--
3	2.692211734656595E-02	--
4	.1599975851326383	--
5	19057.88659999488	17008.20822853434
6	4.500684937408190E-03	--
7	3.373657195693665E-03	--
8	2.387622808895325E-02	--
9	323738.2044061869	470708.2532091573
10	.1600687342398619	--
11	9.569409743430992E-02	--
12	6.56115147597876	--
13	76805.68964151866	96110.62012296795
14	1.43800275181183	--
15	.701986206743452	--
16	.2135934480883664	--
17	26658.66122539515	37143.11975960149
18	.1397980786507487	--
19	3.933033557902666E-02	--
20	.2337393687908884	--
21	13193.5606871605	20773.43462811679
22	.180736158674087	--
23	4.112975720574200E-04	--
24	2.820012669875999E-02	--
25	5413.970868959231	4726.365323333212
26	103878.9857062928	155477.022786 222
27	2561.394063080011	4068.109238953077
28	5003.08499786053	9580.555716575343
29	4947.7452831425	4903.632157535491
30	12619.4389111047	16208.36717994843

Non-linear gauge

- Include several gauge parameters

$$\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}, \tilde{\varepsilon}, \tilde{\kappa}$$

- Numerator structure is the same as Feynman gauge $\mathrm{g}^{\mu\nu}$ (for $\xi = 1$)

- Vertices modified (e.g. $\tilde{\alpha} = 1 \Rightarrow$ no AWχ)
- New vertices (ghost sector) appear

Non-linear gauge fixing terms

$$L_{GF} = -\frac{1}{\xi_W} F^+ F^- - \frac{1}{2\xi_Z} \left(F^Z\right)^2 - \frac{1}{2\xi} \left(F^A\right)^2$$

$$F^{\pm} = \left(\partial^{\mu} \mp ie\tilde{\alpha} A^{\mu} \mp i \frac{ec_W}{s_W} \tilde{\beta} Z^{\mu} \right) W^{\pm}_{\mu} \qquad F^A = \partial^{\mu} A_{\mu}$$

$$+ \xi_W \left(M_W \chi^{\pm} + \frac{e}{2s_W} \tilde{\delta} H \chi^{\pm} \pm i \frac{e}{2s_W} \tilde{\kappa} \chi_3 \chi^{\pm} \right)$$

$$F^Z = \partial^{\mu} Z_{\mu} + \xi_Z \left(M_W \chi_3 + \frac{e}{2s_W c_W} \tilde{\varepsilon} H \chi_3 \right)$$

Samples of NLG Feynman rules

$W - W - A$

$$e[g^{\mu\nu}(p_1 - p_2)^\rho$$
$$+ (1 + \tilde{\alpha}/\xi_W)(p_3^\nu g^{\mu\rho} - p_3^\mu g^{\nu\rho})$$
$$+ (1 + \tilde{\alpha}/\xi_W)(p_2^\mu g^{\nu\rho} - p_1^\nu g^{\mu\rho})]$$

$W - \chi - A$

$$\mp ieM_W(1 - \tilde{\alpha})g^{\mu\nu}$$

modified

$\bar{c}^{\mp} - c^A - A - W^{\pm}$

$$-e^2\tilde{\alpha}g^{\mu\nu}$$

$\bar{c}^{\mp} - c^A - \chi^{\pm} - H$

$$\mp ie^2 \frac{1}{2s_W}\tilde{\delta}\xi_W$$

New:ghost-ghost- VV/SS

Examples of results(1-loop)

W=500GeV, $\cos\theta$ = 0.985, k_{cut}= 10GeV
M_z=91.187GeV,M_w=80.37,M_t=174,M_H=100, λ =1.d-15

$$\mathrm{NLG}: \tilde{\alpha} = 2, \tilde{\beta} = 3, \tilde{\delta} = 4, \tilde{\varepsilon} = 5, \tilde{\kappa} = 6$$

$e^+e^- \rightarrow t\bar{t}$

TREE 0.5194160300
LG, Cuv=0 : −0.168187331181333555
NLG, Cuv=10 : −0.168187331181313571

#graphs
tree : 4
1-loop:150

$$\frac{d\sigma}{d\cos\theta}\text{(pb)}$$

Examples of results(1-loop)

W=500GeV, cos θ = 0.985, k_{cut}= 10GeV
M_z=91.187GeV,M_w=80.37,M_t=174,M_H=100, λ =1.d-15

$$\mathrm{NLG}: \tilde{\alpha} = 2, \tilde{\beta} = 3, \tilde{\delta} = 4, \tilde{\varepsilon} = 5, \tilde{\kappa} = 6$$

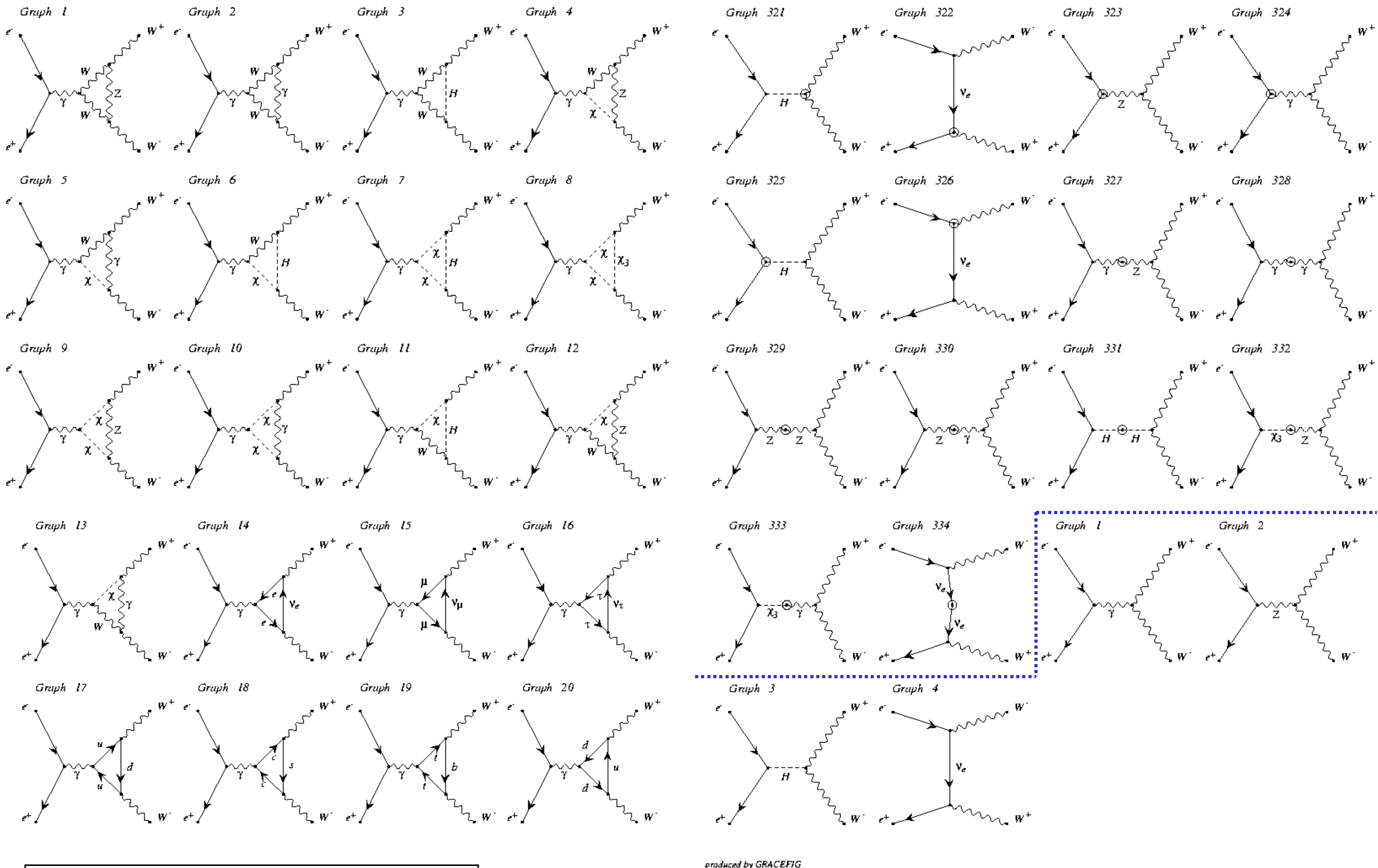
$W^+\gamma \to t\bar{b}$

TREE 22.36869289
LG, CUV=0 : 0.83292500603162400
NLG, CUV=10: 0.83292500610184294

#graphs
tree : 4
1-loop:239

$$\frac{d\sigma}{d\cos\theta}\,(\mathrm{pb})$$

diagrams drawn by GRACEFIG



$$e^-e^+ \rightarrow W^-W^+$$

$e^- e^+ \to W^- W^+$

TREE (TOTAL) : 75.071649720

LG, Cuv = 0 : −15.4257567057010476

NLG, Cuv = 10 : −15.4257562685176595

#graphs

tree : 4

1-loop:334

		LG	NLG
1)	final vtx A	: -0.110232876612731998	-0.962735342032220331
2)	final vtx Z	: -0.176836959641807318	-1.45399925309897249
3)	final vtx H	: -0.731865348125769495E-011	-0.486300610973687554E-011
4)	final vtx X3	: -0.14768555367555172E-013	-0.14768555367554793E-013
5)	t-channel e+	: -102.919001290744660	-136.855066683011671
6)	init vtx Z	: -6.93496613930373318	-6.82256179700717080
7)	init vtx A	: -4.28572899550046760	-4.26803489737576847
8)	init vtx H	: -0.136320409418589835E-009	-0.135363696968451092E-009
9)	box	: -32.3611802623685705	37.7599169853874841
10)	t-channel e-	: -102.919001309649019	-136.855066697757337
11)	Renorm. SE:	0.191341031608370238	-0.580586801361939048E-001

Conclusion

- NLG is implemented into GRACE 1-loop system.
- Performance is good for the check of complicated calculation.
- To be used for the large scale calculation to confirm the output.