

# GoSam 2.0.4: $gg \rightarrow hh$

lscyboz

2019-06-17 (17:37:15)

## Abstract

This process consists of 2 tree-level diagrams and 10 NLO diagrams. GoSam has identified 3 groups of NLO diagrams by analyzing their one-loop integrals.

# Contents

<b>1</b>	<b>Helicities</b>	<b>3</b>
<b>2</b>	<b>Wave Functions</b>	<b>3</b>
<b>3</b>	<b>Colour Basis</b>	<b>3</b>
<b>4</b>	<b>Tree Diagrams</b>	<b>4</b>
<b>5</b>	<b>One-Loop Diagrams</b>	<b>5</b>
5.1	Group 0 (4-Point) . . . . .	6
5.1.1	Diagrams (2) . . . . .	7
5.2	Group 1 (4-Point) . . . . .	7
5.2.1	Diagrams (6) . . . . .	8
5.3	Group 2 (4-Point) . . . . .	9
5.3.1	Diagrams (2) . . . . .	9
<b>6</b>	<b>Related Work</b>	<b>10</b>

## 1 Helicities

Index	1	2	3	4
0	−	−	0	0
$1 \rightarrow 0$	+	−	0	0
$2 \rightarrow 0$	−	+	0	0
$3 \rightarrow 0$	+	+	0	0

## 2 Wave Functions

In this section, we use  $l_i = k_i$  for massless particles; in spinors  $|i\rangle$  (resp.  $|i]$ ) denote  $|l_i\rangle$  (resp.  $|l_i]$ ). For the massive particles we have:

$$l_3 = k_3 - \frac{mdlMh^2}{2k_3 \cdot k_2} k_2 \quad (1)$$

$$l_4 = k_4 - \frac{mdlMh^2}{2k_4 \cdot k_2} k_2 \quad (2)$$

All helicity amplitudes are defined in terms of the following wave functions:

- $g(k_1)$

$$\varepsilon_+^\mu(k_1) = \frac{\langle 2|\gamma^\mu|1\rangle}{\sqrt{2}\langle 2|1\rangle} \quad (3)$$

$$\varepsilon_-^\mu(k_1) = \frac{[2|\gamma^\mu|1\rangle}{\sqrt{2}[1|2]} \quad (4)$$

- $g(k_2)$

$$\varepsilon_+^\mu(k_2) = \frac{\langle 1|\gamma^\mu|2\rangle}{\sqrt{2}\langle 1|2\rangle} \quad (5)$$

$$\varepsilon_-^\mu(k_2) = \frac{[1|\gamma^\mu|2\rangle}{\sqrt{2}[2|1]} \quad (6)$$

- $h(k_3)$

$$\epsilon(k_3) = 1 \quad (7)$$

- $h(k_4)$

$$\epsilon(k_4) = 1 \quad (8)$$

## 3 Colour Basis

$$|c_1\rangle = g_{(1)}^{A_1} g_{(2)}^{A_2} \text{tr} \{T^{A_2} T^{A_1}\} \quad (9)$$

## 4 Tree Diagrams

QGraf Setup

---

qgraf-3.1.4

---

```
output = 'diagrams-0.hh';
style = 'form.sty';
model = 'model';
in = part21[k1], part21[k2];
out = part25[k3], part25[k4];
loops=0;
loop_momentum=p;
options=onshell, notadpole, nosnail;
true=chord[part5,part25,0,0];
true=vsum[QL,1,1];
```

---

---

warning: model splits into disjoint components

---

---



---

---

warning: model contains at least one non-interacting field

---

---



---

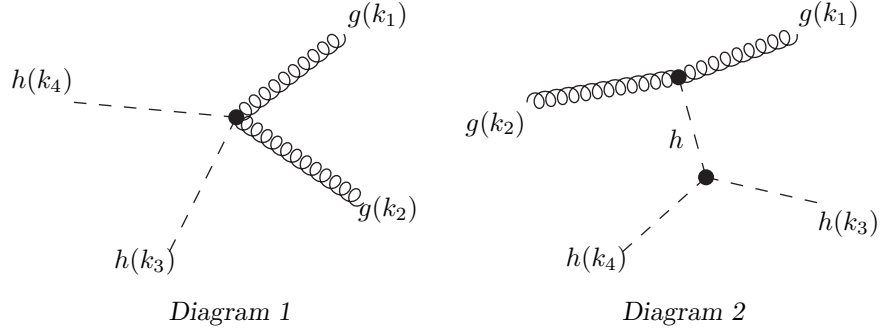
24P — 7+ 17- — 5N+ 2C+ 17C-

78V — 3^64 4^11 5^2 6^1

---

— 4^1 — — — 1 diagram  
3^2 — — — — 1 diagram

total = 2 diagrams



## 5 One-Loop Diagrams

### General Information

QGraf Setup

qgraf-3.1.4

```
output = 'diagrams-1.hh';
style = 'form.sty';
model = 'model';
in = part21[k1], part21[k2];
out = part25[k3], part25[k4];
loops=1;
loop_momentum=p;
options=onshell, notadpole, nosnail;
true=chord[part5,part25,0,0];
true=vsum[QL,0,0];
```

warning: model splits into disjoint components

warning: model contains at least one non-interacting field

24P — 7+ 17- — 5N+ 2C+ 17C-

78V	—	3^64	4^11	5^2	6^1	
<hr/>						
—	—	—	6^1	—	0	diagrams
3^1	—	5^1	—	—	0	diagrams
—	4^2	—	—	—	0	diagrams
3^2	4^1	—	—	—	3	diagrams
3^4	—	—	—	—	11	diagrams
<hr/>						
total = 14 diagrams						

Loop diagrams are grouped into sets of diagrams which share loop-propagators. A loop integral can be written as

$$\int \frac{d^n k}{i\pi^{\frac{n}{2}}} \frac{\mathcal{N}(q)}{\prod_{j=1}^N [(k+r_j)^2 - (m_j^2 - im_j\Gamma_j) + i\delta]}. \quad (10)$$

For each group we list  $r_j$ ,  $m_j$  and  $\Gamma_j$ . For  $m_j$  and  $\Gamma_j$  only non-vanishing symbols are listed. Furthermore, we give the matrix  $S$  which is defined as

$$S_{\alpha\beta} = (r_\alpha - r_\beta)^2 - (m_\alpha^2 - im_\alpha\Gamma_\alpha) - (m_\beta^2 - im_\beta\Gamma_\beta). \quad (11)$$

For each diagram we denote how the matrix  $S'$  for the specific diagram is obtained from the original  $S$ . The notation

$$S' = S_{Q \rightarrow q'}^{\{l_1, l_2, \dots\}} \quad (12)$$

means, that the rows and columns labeled by  $l_1, l_2, \dots$  should be removed from  $S$  (likewise  $r_{l_1}, r_{l_2}, \dots$  are removed from the list of propagators) and  $\mathcal{N}(q)$  has to be replaced by  $\mathcal{N}(q')$ . The maximum effective rank of a group is the rank that has to be passed to SAMURAI if the whole group is reduced at once; this number is calculated as

$$\max_{\text{diagrams}} \{(\text{rank of diagram}) + (\text{number of pinches})\}. \quad (13)$$

Diagrams with massless closed quark lines are multiplied by a factor **Nfrat** = **Nf**/**Nfgen**. This multiplication is indicated by the symbol  $N_f$  following the rank. By default **Nfrat** evaluates to one but can be changed by modifying **Nf** or **Nfgen** in the model file.

## 5.1 Group 0 (4-Point)

### General Information

The maximum effective rank in this group is 4.

$$r_1 = -k_2 + k_4, \quad m_1 = \text{MT} \quad (14a)$$

$$r_2 = -k_2, \quad m_2 = \text{MT} \quad (14b)$$

$$r_3 = 0, \quad m_3 = \text{MT} \quad (14c)$$

$$r_4 = -k_3, \quad m_4 = \text{MT} \quad (14d)$$

$$S = \begin{pmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{2,1} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{3,1} & S_{3,2} & S_{3,3} & S_{3,4} \\ S_{4,1} & S_{4,2} & S_{4,3} & S_{4,4} \end{pmatrix} \quad (15)$$

$$S_{1,1} = -2MT^2 \quad (16a)$$

$$S_{1,2} = Mh^2 - 2MT^2 \quad (16b)$$

$$S_{1,3} = 2Mh^2 - s_{23} - 2MT^2 - s_{12} \quad (16c)$$

$$S_{1,4} = -2MT^2 \quad (16d)$$

$$S_{2,2} = -2MT^2 \quad (16e)$$

$$S_{2,3} = -2MT^2 \quad (16f)$$

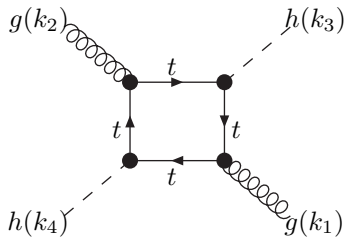
$$S_{2,4} = s_{23} - 2MT^2 \quad (16g)$$

$$S_{3,3} = -2MT^2 \quad (16h)$$

$$S_{3,4} = Mh^2 - 2MT^2 \quad (16i)$$

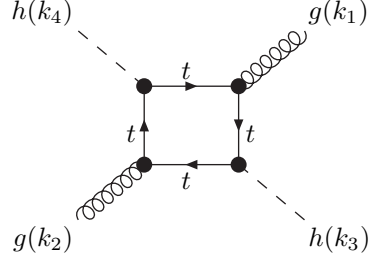
$$S_{4,4} = -2MT^2 \quad (16j)$$

### 5.1.1 Diagrams (2)



-Diagram 13

$$S' = S_{Q \rightarrow -q - (-k3)}, \text{rk} = 4$$



-Diagram 14

$$S' = S_{Q \rightarrow -q - (-k3)}, \text{rk} = 4$$

## 5.2 Group 1 (4-Point)

### General Information

The maximum effective rank in this group is 4.

$$r_1 = -k_3 - k_4, \quad m_1 = MT \quad (17a)$$

$$r_2 = -k_3, \quad m_2 = MT \quad (17b)$$

$$r_3 = 0, \quad m_3 = MT \quad (17c)$$

$$r_4 = -k_2, \quad m_4 = MT \quad (17d)$$

$$S = \begin{pmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{2,1} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{3,1} & S_{3,2} & S_{3,3} & S_{3,4} \\ S_{4,1} & S_{4,2} & S_{4,3} & S_{4,4} \end{pmatrix} \quad (18)$$

$$S_{1,1} = -2MT^2 \quad (19a)$$

$$S_{1,2} = Mh^2 - 2MT^2 \quad (19b)$$

$$S_{1,3} = -2MT^2 + s_{12} \quad (19c)$$

$$S_{1,4} = -2MT^2 \quad (19d)$$

$$S_{2,2} = -2MT^2 \quad (19e)$$

$$S_{2,3} = Mh^2 - 2MT^2 \quad (19f)$$

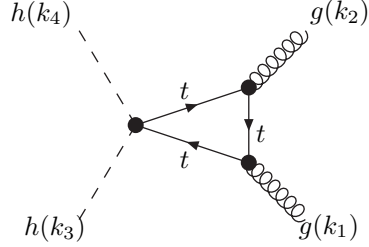
$$S_{2,4} = s_{23} - 2MT^2 \quad (19g)$$

$$S_{3,3} = -2MT^2 \quad (19h)$$

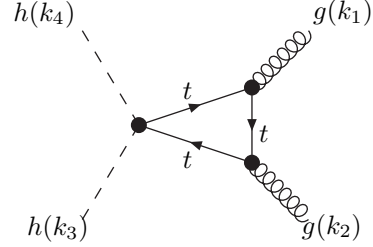
$$S_{3,4} = -2MT^2 \quad (19i)$$

$$S_{4,4} = -2MT^2 \quad (19j)$$

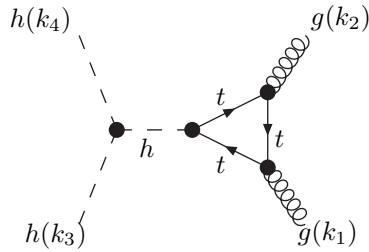
### 5.2.1 Diagrams (6)



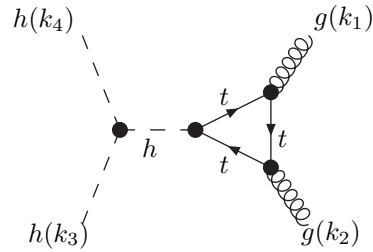
-Diagram 2  
 $S' = S_{Q \rightarrow q-(k2)}^{\{2\}}, \text{rk} = 3$



-Diagram 3  
 $S' = S_{Q \rightarrow q-(k2)}^{\{2\}}, \text{rk} = 3$

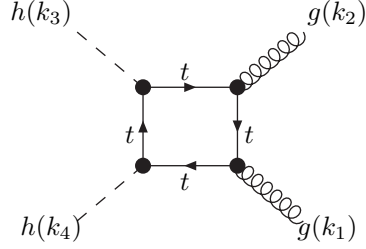


-Diagram 7  
 $S' = S_{Q \rightarrow q-(k2)}^{\{2\}}, \text{rk} = 3$



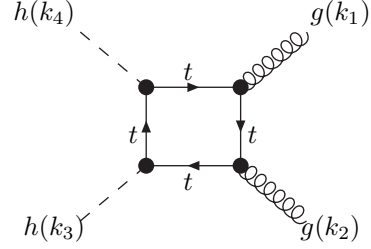
-Diagram 8  
 $S' = S_{Q \rightarrow q-(k2)}^{\{2\}}, \text{rk} = 3$





-Diagram 11

$$S' = S_{Q \rightarrow q-(k2)}, \text{rk} = 4$$



-Diagram 12

$$S' = S_{Q \rightarrow q-(k2)}, \text{rk} = 4$$

### 5.3 Group 2 (4-Point)

#### General Information

The maximum effective rank in this group is 4.

$$r_1 = -k_3 - k_4, \quad m_1 = \text{MT} \quad (20a)$$

$$r_2 = -k_4, \quad m_2 = \text{MT} \quad (20b)$$

$$r_3 = 0, \quad m_3 = \text{MT} \quad (20c)$$

$$r_4 = -k_2, \quad m_4 = \text{MT} \quad (20d)$$

$$S = \begin{pmatrix} S_{1,1} & S_{1,2} & S_{1,3} & S_{1,4} \\ S_{2,1} & S_{2,2} & S_{2,3} & S_{2,4} \\ S_{3,1} & S_{3,2} & S_{3,3} & S_{3,4} \\ S_{4,1} & S_{4,2} & S_{4,3} & S_{4,4} \end{pmatrix} \quad (21)$$

$$S_{1,1} = -2\text{MT}^2 \quad (22a)$$

$$S_{1,2} = \text{Mh}^2 - 2\text{MT}^2 \quad (22b)$$

$$S_{1,3} = -2\text{MT}^2 + s_{12} \quad (22c)$$

$$S_{1,4} = -2\text{MT}^2 \quad (22d)$$

$$S_{2,2} = -2\text{MT}^2 \quad (22e)$$

$$S_{2,3} = \text{Mh}^2 - 2\text{MT}^2 \quad (22f)$$

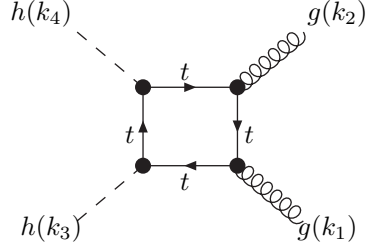
$$S_{2,4} = 2\text{Mh}^2 - s_{23} - 2\text{MT}^2 - s_{12} \quad (22g)$$

$$S_{3,3} = -2\text{MT}^2 \quad (22h)$$

$$S_{3,4} = -2\text{MT}^2 \quad (22i)$$

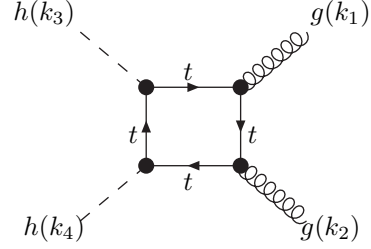
$$S_{4,4} = -2\text{MT}^2 \quad (22j)$$

#### 5.3.1 Diagrams (2)



-Diagram 9

$$S' = S_{Q \rightarrow q-(k2)}, \text{rk} = 4$$



-Diagram 10

$$S' = S_{Q \rightarrow q-(k2)}, \text{rk} = 4$$

## 6 Related Work

If you publish results obtained by using this matrix element code please cite the appropriate papers in the bibliography of this document.

Scientific publications prepared using the present version of GoSAM or any modified version of it or any code linking to GoSAM or parts of it should make a clear reference to the publications [1, 2].

For graph generation we use QGraf [3]. The Feynman diagrams are further processed with the symbolic manipulation program FORM [4, 5] using the FORM library SPINNEY [6]. The Fortran 90 code is generated using FORM [4, 5]. For the reduction of the tensor integrals the code uses an implementation of the Laurent series expansion method [8] from the library Ninja [7]. For the reduction of the tensor integrals, the code uses the package GOLEM95 [9, 10, 11]. The tensor coefficients are obtained using tensorial reconstruction at the integrand level [16].

Please, make sure, you also give credit to the authors of the scalar loop libraries, if you configured the amplitude code such that it calls other libraries than the ones mentioned so far. Depending on your configuration you might use one or more of the following programs for the evaluation of the scalar integrals:

- OneLOop [12],
- QCDDLoop [13], which uses FF [14],
- LoopTools [15], which uses FF [14].
- GOLEM95 [10, 9] which uses OneLOop [12] and may be configured such that it uses LoopTools [15, 14].

## References

- [1] G. Cullen, H. van Deurzen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, E. Mirabella and G. Ossola *et al.*, “GoSam-2.0: a tool for automated one-loop calculations within the Standard Model and beyond,” *Eur. Phys. J. C* **74** (2014) 8, 3001 [arXiv:1404.7096 [hep-ph]].

- [2] G. Cullen, N. Greiner, G. Heinrich, G. Luisoni, P. Mastrolia, G. Ossola, T. Reiter and F. Tramontano, “Automated One-Loop Calculations with GoSam,” *Eur. Phys. J. C* **72** (2012) 1889 [arXiv:1111.2034 [hep-ph]].
- [3] P. Nogueira, “Automatic Feynman graph generation,” *J. Comput. Phys.* **105** (1993) 279.
- [4] J. Kuipers, T. Ueda, J. A. M. Vermaseren and J. Vollinga, “FORM version 4.0,” *Comput. Phys. Commun.* **184** (2013) 1453 [arXiv:1203.6543 [cs.SC]].
- [5] J. A. M. Vermaseren, “New features of FORM,” arXiv:math-ph/0010025.
- [6] G. Cullen, M. Koch-Janusz and T. Reiter, “spinney: A Form Library for Helicity Spinors,” arXiv:1008.0803 [hep-ph].
- [7] T. Peraro, “Ninja: Automated Integrand Reduction via Laurent Expansion for One-Loop Amplitudes,” *Comput. Phys. Commun.* **185** (2014) 2771 [arXiv:1403.1229 [hep-ph]].
- [8] P. Mastrolia, E. Mirabella and T. Peraro, “Integrand reduction of one-loop scattering amplitudes through Laurent series expansion,” *JHEP* **1206** (2012) 095 [Erratum-ibid. **1211** (2012) 128] [arXiv:1203.0291 [hep-ph]].
- [9] J. P. Guillet, G. Heinrich and J. F. von Soden-Fraunhofen, “Tools for NLO automation: extension of the golem95C integral library,” *Comput. Phys. Commun.* **185** (2014) 1828 [arXiv:1312.3887 [hep-ph]].
- [10] T. Binoth, J. P. Guillet, G. Heinrich, E. Pilon and T. Reiter, “Golem95: a numerical program to calculate one-loop tensor integrals with up to six external legs,” *Comput. Phys. Commun.* **180** (2009) 2317 [arXiv:0810.0992 [hep-ph]].
- [11] G. Cullen, J. P. Guillet, G. Heinrich, T. Kleinschmidt, E. Pilon, T. Reiter, M. Rodgers, “Golem95C: A library for one-loop integrals with complex masses,” *Comput. Phys. Commun.* **182** (2011) 2276-2284. [arXiv:1101.5595 [hep-ph]].
- [12] A. van Hameren, “OneLoop: For the evaluation of one-loop scalar functions,” [arXiv:1007.4716 [hep-ph]].
- [13] R. K. Ellis, G. Zanderighi, “Scalar one-loop integrals for QCD,” *JHEP* **0802** (2008) 002. [arXiv:0712.1851 [hep-ph]].
- [14] G. J. van Oldenborgh, “FF: A Package to evaluate one loop Feynman diagrams,” *Comput. Phys. Commun.* **66** (1991) 1-15.
- [15] T. Hahn, M. Perez-Victoria, “Automatized one loop calculations in four-dimensions and D-dimensions,” *Comput. Phys. Commun.* **118** (1999) 153-165. [hep-ph/9807565].
- [16] G. Heinrich, G. Ossola, T. Reiter, F. Tramontano, “Tensorial Reconstruction at the Integrand Level,” *JHEP* **1010** (2010) 105. [arXiv:1008.2441 [hep-ph]].