# FeynArts

## An Introduction to Mathematica Tools for HEP

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# What is FeynArts (FA) ?

FeynArts is a Mathematica package for the generation and visualization of Feynman diagrams and amplitudes.

-Allows model files generated by the user in FeynRules (SM already implemented in FA).

-Diagrams at tree-level, one-loop level, etc.

-Restrictions on which fields are allowed in a diagram.

# Preface

We count with three main tools to understand FeynArts, FeynCalc, FeynRules, etc:

1. User Guide provided by the creators. FA Guide: https://feynarts.de/FA3Guide.pdf
2. Command InputForm[X] in Mathematica. Shows how Mathematica understands the expression X.
3. Command ?X . Shows the definition of X.

# Using InputForm

Typical amplitude for a Feynman diagram

```
hhtohhtreeamp2 = PickLevel[Particles][hhtohhtreeamp] // ToFA1Conventions
```

$$\text{FAFeynAmpList}\left(\text{Process} \to \begin{pmatrix} S(1) & p1 & FCGV(MH) & \{\} \\ S(1) & p2 & FCGV(MH) & \{\} \end{pmatrix} \to \begin{pmatrix} S(1) & k1 & FCGV(MH) & \{\} \\ S(1) & k2 & FCGV(MH) & \{\} \end{pmatrix}\right), \text{Model} \to \{\text{SM}\}, \text{GenericModel} \to \{\text{Lorentz}\}, \text{AmplitudeLevel} \to \{\text{Particles}\}, \text{ExcludeParticles} \to \{\}, \text{ExcludeFieldPoints} \to \{\}, \text{LastSelections} \to \{\}\Bigg)$$

$$\left(\text{FAFeynAmp}\left(\text{GraphName}(, \text{T1}, \text{G1C1P1}, \text{N1}), -\frac{3\,FCGV(EL)^2\,FCGV(MH)^2}{4\,FCGV(MW)^2\,FCGV(SW)^2}\right), \text{FAFeynAmp}\left(\text{GraphName}(, \text{T2}, \text{G1C2P1}, \text{N2}), -\frac{9\,FCGV(EL)^2\,FCGV(MH)^4\,\frac{1}{(k1+k2)^2-FCGV(MH)^2}}{4\,FCGV(MW)^2\,FCGV(SW)^2}\right),\right.$$

$$\left.\text{FAFeynAmp}\left(\text{GraphName}(, \text{T3}, \text{G1C3P1}, \text{N3}), -\frac{9\,FCGV(EL)^2\,FCGV(MH)^4\,\frac{1}{(k2-p2)^2-FCGV(MH)^2}}{4\,FCGV(MW)^2\,FCGV(SW)^2}\right), \text{FAFeynAmp}\left(\text{GraphName}(, \text{T4}, \text{G1C4P1}, \text{N4}), -\frac{9\,FCGV(EL)^2\,FCGV(MH)^4\,\frac{1}{(k1-p2)^2-FCGV(MH)^2}}{4\,FCGV(MW)^2\,FCGV(SW)^2}\right)\right)$$

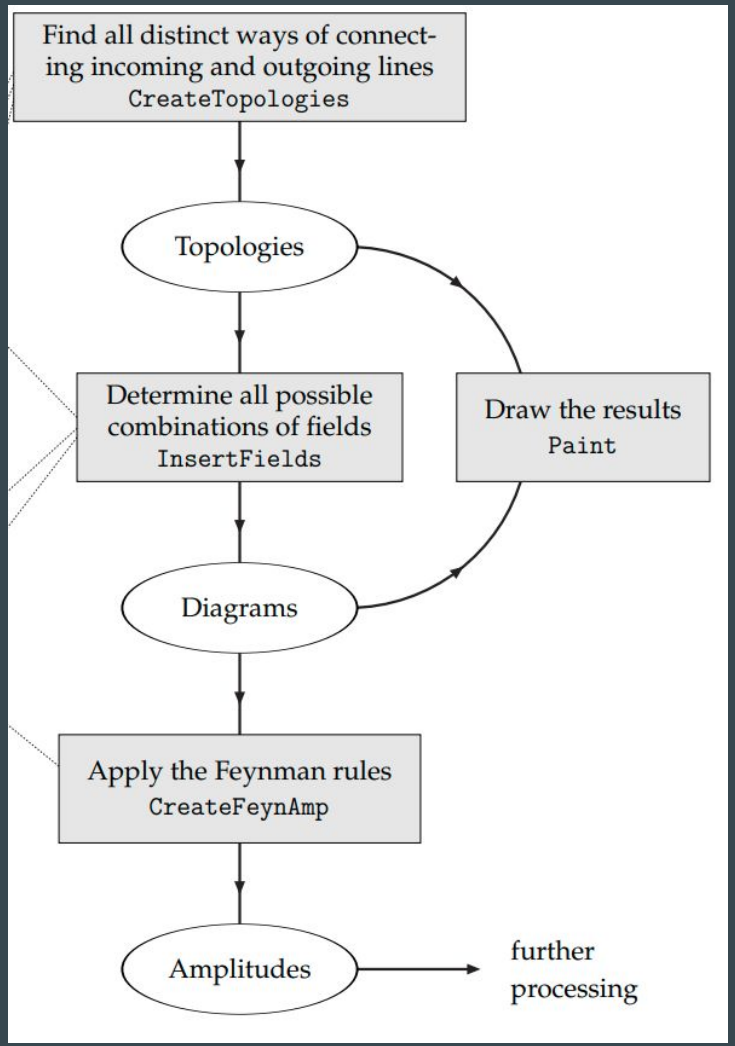
```
InputForm[hhtohhtreeamp2]
```

forma de entrada

```
InputForm=
FAFeynAmpList[Process -> {{S[1], p1, FCGV["MH"], {}}, {S[1], p2, FCGV["MH"], {}}} -> {{S[1], k1, FCGV["MH"], {}}, {S[1], k2, FCGV["MH"], {}}}, Model -> {"SM"}, GenericModel -> {"Lorentz"},
  AmplitudeLevel -> {Particles}, ExcludeParticles -> {}, ExcludeFieldPoints -> {}, LastSelections -> {}][FAFeynAmp[GraphName["", "T1", "G1C1P1", "N1"],
  (-3*FCGV["EL"]^2*FCGV["MH"]^2)/(4*FCGV["MW"]^2*FCGV["SW"]^2)], FAFeynAmp[GraphName["", "T2", "G1C2P1", "N2"], (-9*FAPropagatorDenominator[k1 + k2, FCGV["MH"]]*FCGV["EL"]^2*FCGV["MH"]^4)/
  (4*FCGV["MW"]^2*FCGV["SW"]^2)], FAFeynAmp[GraphName["", "T3", "G1C3P1", "N3"], (-9*FAPropagatorDenominator[k2 - p2, FCGV["MH"]]*FCGV["EL"]^2*FCGV["MH"]^4)/(4*FCGV["MW"]^2*FCGV["SW"]^2)],
 FAFeynAmp[GraphName["", "T4", "G1C4P1", "N4"], (-9*FAPropagatorDenominator[k1 - p2, FCGV["MH"]]*FCGV["EL"]^2*FCGV["MH"]^4)/(4*FCGV["MW"]^2*FCGV["SW"]^2)]]
```

This allows us to write substitutions /. FCGV[“MH”] -> MH

# How does it work?



# Getting started: Creating Topologies

| | |
|---|---|
| `CreateTopologies[`$l$`, `$i$` -> `$o$`]` | create topologies with $l$ loops, $i$ incoming, and $o$ outgoing legs |
| `CreateTopologies[`$l$`, `$e$`]` | create topologies with $l$ loops and $e$ external legs |

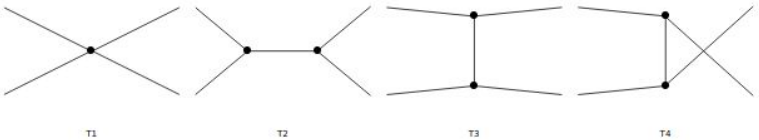
```
t22 = CreateTopologies[0, 2 → 2]
```

TopologyList(Topology(1)(Propagator(Incoming)(Vertex(1)(1), Vertex(4)(5)), Propagator(Incoming)(Vertex(1)(2), Vertex(4)(5)), Propagator(Outgoing)(Vertex(1)(3), Vertex(4)(5)), Propagator(Outgoing)(Vertex(1)(4), Vertex(4)(5))),
Topology(1)(Propagator(Incoming)(Vertex(1)(1), Vertex(3)(5)), Propagator(Incoming)(Vertex(1)(2), Vertex(3)(5)), Propagator(Outgoing)(Vertex(1)(3), Vertex(3)(6)), Propagator(Outgoing)(Vertex(1)(4), Vertex(3)(6)), Propagator(Internal)(Vertex(3)(5), Vertex(3)(6))),
Topology(1)(Propagator(Incoming)(Vertex(1)(1), Vertex(3)(5)), Propagator(Incoming)(Vertex(1)(2), Vertex(3)(6)), Propagator(Outgoing)(Vertex(1)(3), Vertex(3)(5)), Propagator(Outgoing)(Vertex(1)(4), Vertex(3)(6)), Propagator(Internal)(Vertex(3)(5), Vertex(3)(6))),
Topology(1)(Propagator(Incoming)(Vertex(1)(1), Vertex(3)(5)), Propagator(Incoming)(Vertex(1)(2), Vertex(3)(6)), Propagator(Outgoing)(Vertex(1)(3), Vertex(3)(6)), Propagator(Outgoing)(Vertex(1)(4), Vertex(3)(5)), Propagator(Internal)(Vertex(3)(5), Vertex(3)(6))))

```
Paint[t22, ColumnsXRows → 4]
```

> Top. 1 aebe/cede/0.m, 0 diagrams
> Top. 2 aebe/cfdf/ef .m, 0 diagrams
> Top. 3 aebf/cedf/ef .m, 0 diagrams
> Top. 4 aebf/cfde/ef .m, 0 diagrams

2 → 2




At this level there are not particles.
Only topologies

# Inserting fields in the topologies

We can insert, for example, a general scalar, a class of scalars, and a particular scalar

| | |
|---|---|
| `Generic, Classes, Particles` | field levels in *FeynArts* |

| | |
|---|---|
| `F, S, V, U, T` | basic field types: fermion, scalar, vector, ghost, and tensor fields |
| `Mix[`$g_1$`,` $g_2$`]` | $g_1$–$g_2$ mixing field |

General variables for fields

`InsertFields[`$t$`, {`$i_1, i_2, \ldots$`} -> {`$o_1, o_2, \ldots$`}]`

insert fields into the `TopologyList` $t$ where the incoming fields are $i_1, i_2, \ldots$ and the outgoing fields are $o_1, o_2, \ldots$

-Minimum information to define a Feynman Diagram. Incoming and outgoing particles.

-If a model is not specific, FeynArts uses the SM.mod.

# Fields of the SM model file (SM.mod)

-The field content is specific to each model file.

| *class* | *self-conj.* | *indices* | *members* | | *mass* |
|---|---|---|---|---|---|
| F[1] | no | Generation | F[1, {1}] | $\nu_e$ | 0 |
| (neutrinos) | | | F[1, {2}] | $\nu_\mu$ | 0 |
| | | | F[1, {3}] | $\nu_\tau$ | 0 |
| F[2] | no | Generation | F[2, {1}] | $e$ | ME |
| (massive leptons) | | | F[2, {2}] | $\mu$ | MM |
| | | | F[2, {3}] | $\tau$ | ML |
| F[3] | no | Generation | F[3, {1, $o$}] | $u$ | MU |
| (up-type quarks) | | Colour | F[3, {2, $o$}] | $c$ | MC |
| | | | F[3, {3, $o$}] | $t$ | MT |
| F[4] | no | Generation | F[4, {1, $o$}] | $d$ | MD |
| (down-type quarks) | | Colour | F[4, {2, $o$}] | $s$ | MS |
| | | | F[4, {3, $o$}] | $b$ | MB |
| V[1] | yes | | V[1] | $\gamma$ | 0 |
| V[2] | yes | | V[2] | $Z$ | MZ |
| V[3] | no | | V[3] | $W^-$ | MW |
| V[4] (mixing field)† | yes | | V[4] | $\gamma$–$Z$ | MAZ |
| S[1] | yes | | S[1] | $H$ | MH |
| S[2] | yes | | S[2] | $G^0$ | MG0 |
| S[3] | no | | S[3] | $G^-$ | MGp |
| U[1] | no | | U[1] | $u_\gamma$ | 0 |
| U[2] | no | | U[2] | $u_Z$ | MZ |
| U[3] | no | | U[3] | $u_-$ | MW |
| U[4] | no | | U[4] | $u_+$ | MW |
| SV[2] (mixing field)‡ | yes | | SV[2] | $G^0$–$Z$ | MZ |
| SV[3] (mixing field)‡ | no | | SV[3] | $G^-$–$W^-$ | MW |

# Generation of Goldstone scattering

```
omegaomegatoomegaomega = InsertFields[t22, {S[3], S[3]} → {S[3], S[3]}, Model → "HEFT3_FA", GenericModel → "HEFT3_FA", InsertionLevel → Particles]
```


```
omegaomegatoomegaomega = InsertFields[t22, {S[3], S[3]} → {S[3], S[3]}, Model → "HEFT3_FA", GenericModel → "HEFT3_FA", InsertionLevel → Particles]
```


inserting at level(s) {Generic, Classes, Particles}

> Top. 1: 1 Generic, 1 Classes, 1 Particles insertions

> Top. 2: 1 Generic, 1 Classes, 1 Particles insertions

> Top. 3: 1 Generic, 1 Classes, 1 Particles insertions

> Top. 4: 1 Generic, 1 Classes, 1 Particles insertions

in total: 4 Generic, 4 Classes, 4 Particles insertions

TopologyList(Process → {*S*(3), *S*(3)} → {*S*(3), *S*(3)}, Model → {HEFT3_FA}, GenericModel → {HEFT3_FA}, InsertionLevel → {Generic, Classes, Particles}, ExcludeParticles → {}, ExcludeFieldPoints → {}, LastSelections → {})

(Topology(1)(Propagator(Incoming)(Vertex(1)(1), Vertex(4)(5), Field(1)), Propagator(Incoming)(Vertex(1)(2), Vertex(4)(5), Field(2)), Propagator(Outgoing)(Vertex(1)(3), Vertex(4)(5), Field(3)), Propagator(Outgoing)(Vertex(1)(4), Vertex(4)(5), Field(4))) →
Insertions(Generic)(FeynmanGraph(1, Generic = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3)) →
Insertions(Classes)(FeynmanGraph(1, Classes = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3)) → Insertions(Particles)(FeynmanGraph(1, Particles = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3))))),

Topology(1)(Propagator(Incoming)(Vertex(1)(1), Vertex(3)(5), Field(1)), Propagator(Incoming)(Vertex(1)(2), Vertex(3)(5), Field(2)), Propagator(Outgoing)(Vertex(1)(3), Vertex(3)(6), Field(3)), Propagator(Outgoing)(Vertex(1)(4), Vertex(3)(6), Field(4)),
Propagator(Internal)(Vertex(3)(5), Vertex(3)(6), Field(5))) → Insertions(Generic)(FeynmanGraph(1, Generic = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3), Field(5) → *S*) → Insertions(Classes)
(FeynmanGraph(1, Classes = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3), Field(5) → *S*(4)) → Insertions(Particles)(FeynmanGraph(1, Particles = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3), Field(5) → *S*(4))))),

Topology(1)(Propagator(Incoming)(Vertex(1)(1), Vertex(3)(5), Field(1)), Propagator(Incoming)(Vertex(1)(2), Vertex(3)(6), Field(2)), Propagator(Outgoing)(Vertex(1)(3), Vertex(3)(5), Field(3)), Propagator(Outgoing)(Vertex(1)(4), Vertex(3)(6), Field(4)),
Propagator(Internal)(Vertex(3)(5), Vertex(3)(6), Field(5))) → Insertions(Generic)(FeynmanGraph(1, Generic = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3), Field(5) → *S*) → Insertions(Classes)
(FeynmanGraph(1, Classes = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3), Field(5) → *S*(4)) → Insertions(Particles)(FeynmanGraph(1, Particles = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3), Field(5) → *S*(4))))),

Topology(1)(Propagator(Incoming)(Vertex(1)(1), Vertex(3)(5), Field(1)), Propagator(Incoming)(Vertex(1)(2), Vertex(3)(6), Field(2)), Propagator(Outgoing)(Vertex(1)(3), Vertex(3)(6), Field(3)), Propagator(Outgoing)(Vertex(1)(4), Vertex(3)(5), Field(4)),
Propagator(Internal)(Vertex(3)(5), Vertex(3)(6), Field(5))) → Insertions(Generic)(FeynmanGraph(1, Generic = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3), Field(5) → *S*) → Insertions(Classes)
(FeynmanGraph(1, Classes = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3), Field(5) → *S*(4)) → Insertions(Particles)(FeynmanGraph(1, Particles = 1)(Field(1) → *S*(3), Field(2) → *S*(3), Field(3) → *S*(3), Field(4) → *S*(3), Field(5) → *S*(4)))))

```
Paint[omegaomegatoomegaomega, PaintLevel → {Particles}, ImageSize → 500]
```
tamaño de imagen

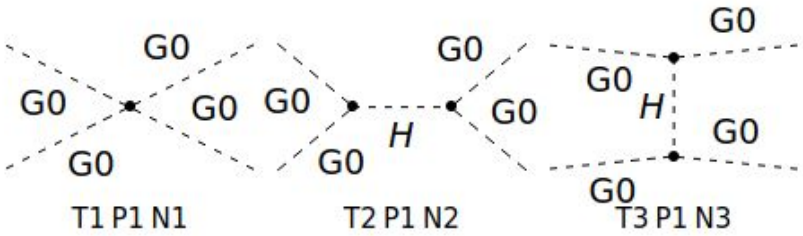
> Top. 1 aebe/cede/0.m, 0 diagrams

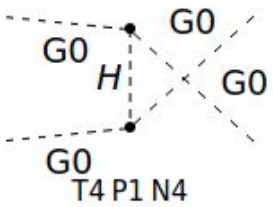
> Top. 2 aebe/cfdf/ef .m, 0 diagrams

> Top. 3 aebf/cedf/ef .m, 0 diagrams

> Top. 4 aebf/cfde/ef .m, 0 diagrams

## G0G0 → G0G0



# Creating a Feynman amplitude

| | |
|---|---|
| `CreateFeynAmp[`*i*`]` | translate the inserted topologies *i* into Feynman amplitudes |

| *option* | *default value* | |
|---|---|---|
| `AmplitudeLevel` | `InsertionLevel` | level specification (see end of Sect. 4.1) |
| `PreFactor` | `-I (2 Pi)^ (-4 LoopNumber)` | overall factor of the amplitude |
| `Truncated` | `False` | whether to remove external wave functions |
| `GaugeRules` | `_GaugeXi -> 1` | rules to enforce a particular choice of gauge |
| `MomentumConservation` | `True` | whether to enforce momentum conservation at each vertex |
| `GraphInfoFunction` | `(1 &)` | a function for adding graph information to the amplitude |

```
omegaomegatoomegaomegaamp = CreateFeynAmp[omegaomegatoomegaomega, AmplitudeLevel → Particles, GaugeRules → {}]  /. M$FACouplingsHEFT
```

```
omegaomegatoomegaomegaamp = CreateFeynAmp[omegaomegatoomegaomega, AmplitudeLevel → Particles, GaugeRules → {}]  /. M$FACouplingsHEFT

creating amplitudes at level(s) {Generic, Classes, Particles}
> Top. 1: 1 Generic, 1 Classes, 1 Particles amplitudes
> Top. 2: 1 Generic, 1 Classes, 1 Particles amplitudes
> Top. 3: 1 Generic, 1 Classes, 1 Particles amplitudes
> Top. 4: 1 Generic, 1 Classes, 1 Particles amplitudes
in total: 4 Generic, 4 Classes, 4 Particles amplitudes
```

$$\text{FAFeynAmpList}\left(\text{Process} \to \begin{pmatrix} S(3) & p1 & Mz & \{\} \\ S(3) & p2 & Mz & \{\} \end{pmatrix} \to \begin{pmatrix} S(3) & k1 & Mz & \{\} \\ S(3) & k2 & Mz & \{\} \end{pmatrix}, \text{Model} \to \{\text{HEFT3_FA}\}, \text{GenericModel} \to \{\text{HEFT3_FA}\}, \text{AmplitudeLevel} \to \{\text{Generic, Classes, Particles}\}, \text{ExcludeParticles} \to \{\}, \text{ExcludeFieldPoints} \to \{\}, \text{LastSelections} \to \{\}\right)$$

$$\Big(\text{FAFeynAmp}\Big(\text{GraphID}(\text{Topology} = 1, \text{Generic} = 1), \text{Integral}[], -i\ \text{RelativeCF}\ \Big(G^{(0)}_{SSSS}(1) + (p1).(p2)\ G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(2)) + (p1).(-(k1))\ G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(3)) + (p1).(-(k2))\ G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(4)) + (p2).(-(k1))\ G^{(0)}_{SSSS}(\text{Mom}(2).\text{Mom}(3)) +$$

$$(p1).(-(k2))\ (p2).(-(k1))\ G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(4)\ \text{Mom}(2).\text{Mom}(3)) + (p2).(-(k2))\ G^{(0)}_{SSSS}(\text{Mom}(2).\text{Mom}(4)) + (p1).(-(k1))\ (p2).(-(k2))\ G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(3)\ \text{Mom}(2).\text{Mom}(4)) + (-(k1)).(-(k2))\ G^{(0)}_{SSSS}(\text{Mom}(3).\text{Mom}(4)) + (p1).(p2)\ (-(k1)).(-(k2))\ G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(2)\ \text{Mom}(3).\text{Mom}(4))\Big),$$

$$\Big\{G^{(0)}_{SSSS}(1), G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(2)), G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(3)), G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(4)), G^{(0)}_{SSSS}(\text{Mom}(2).\text{Mom}(3)), G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(4)\ \text{Mom}(2).\text{Mom}(3)), G^{(0)}_{SSSS}(\text{Mom}(2).\text{Mom}(4)), G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(3)\ \text{Mom}(2).\text{Mom}(4)), G^{(0)}_{SSSS}(\text{Mom}(3).\text{Mom}(4)),$$

$$G^{(0)}_{SSSS}(\text{Mom}(1).\text{Mom}(2)\ \text{Mom}(3).\text{Mom}(4)), \text{RelativeCF}\Big\} \to \text{Insertions}(\text{Classes})\Big(\Big\{0, -\frac{2\,i}{v^2}, -\frac{2\,i}{v^2}, -\frac{2\,i}{v^2}, -\frac{2\,i}{v^2}, \frac{8\,i\,(a4+a5)}{v^4}, -\frac{2\,i}{v^2}, \frac{8\,i\,(a4+a5)}{v^4}, -\frac{2\,i}{v^2}, \frac{8\,i\,(a4+a5)}{v^4}, 1\Big\} \to \text{Insertions}(\text{Particles})\Big(\Big\{0, -\frac{2\,i}{v^2}, -\frac{2\,i}{v^2}, -\frac{2\,i}{v^2}, -\frac{2\,i}{v^2}, \frac{8\,i\,(a4+a5)}{v^4}, -\frac{2\,i}{v^2}, \frac{8\,i\,(a4+a5)}{v^4}, -\frac{2\,i}{v^2}, \frac{8\,i\,(a4+a5)}{v^4}, 1\Big\}\Big)\Big)\Big),$$

$$\text{FAFeynAmp}\Big(\text{GraphID}(\text{Topology} = 2, \text{Generic} = 1), \text{Integral}[], \text{RelativeCF}\ \frac{1}{(k1+k2)^2 - (\text{xiSubscript}[S(\text{Gen5})])\,\text{Mass}(S(\text{Gen5}))^2}\ \Big(G^{(0)}_{SSS}(1) + (p1).(p2)\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)) + (p1).(-(k1) - k2)\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)) + (p2).(-(k1) - k2)\ G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3))\Big)$$

$$\Big(G^{(0)}_{SSS}(1) + (-(k1)).(-(k2))\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)) + (-(k1)).(k1+k2)\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)) + (-(k2)).(k1+k2)\ G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3))\Big),$$

$$\Big\{\text{xiSubscript}[S(\text{Gen5})], \text{Mass}(S(\text{Gen5})), G^{(0)}_{SSS}(1), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)), G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3)), G^{(0)}_{SSS}(1), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)), G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3)), \text{RelativeCF}\Big\} \to$$

$$\text{Insertions}(\text{Classes})\Big(\Big\{\text{xiSubscript}[S(4)], \text{FCGV}(\text{MH}), 0, -\frac{2\,i\,a}{v}, 0, 0, 0, -\frac{2\,i\,a}{v}, 0, 0, 1\Big\} \to \text{Insertions}(\text{Particles})\Big(\Big\{\text{xiSubscript}[S(4)], \text{FCGV}(\text{MH}), 0, -\frac{2\,i\,a}{v}, 0, 0, 0, -\frac{2\,i\,a}{v}, 0, 0, 1\Big\}\Big)\Big)\Big),$$

$$\text{FAFeynAmp}\Big(\text{GraphID}(\text{Topology} = 3, \text{Generic} = 1), \text{Integral}[], \text{RelativeCF}\ \frac{1}{(k2-p2)^2 - (\text{xiSubscript}[S(\text{Gen5})])\,\text{Mass}(S(\text{Gen5}))^2}\ \Big(G^{(0)}_{SSS}(1) + (p1).(-(k1))\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)) + (p1).(p2-k2)\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)) + (-(k1)).(p2-k2)\ G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3))\Big)$$

$$\Big(G^{(0)}_{SSS}(1) + (p2).(-(k2))\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)) + (p2).(k2-p2)\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)) + (-(k2)).(k2-p2)\ G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3))\Big),$$

$$\Big\{\text{xiSubscript}[S(\text{Gen5})], \text{Mass}(S(\text{Gen5})), G^{(0)}_{SSS}(1), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)), G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3)), G^{(0)}_{SSS}(1), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)), G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3)), \text{RelativeCF}\Big\} \to$$

$$\text{Insertions}(\text{Classes})\Big(\Big\{\text{xiSubscript}[S(4)], \text{FCGV}(\text{MH}), 0, -\frac{2\,i\,a}{v}, 0, 0, 0, -\frac{2\,i\,a}{v}, 0, 0, 1\Big\} \to \text{Insertions}(\text{Particles})\Big(\Big\{\text{xiSubscript}[S(4)], \text{FCGV}(\text{MH}), 0, -\frac{2\,i\,a}{v}, 0, 0, 0, -\frac{2\,i\,a}{v}, 0, 0, 1\Big\}\Big)\Big)\Big),$$

$$\text{FAFeynAmp}\Big(\text{GraphID}(\text{Topology} = 4, \text{Generic} = 1), \text{Integral}[], \text{RelativeCF}\ \frac{1}{(k1-p2)^2 - (\text{xiSubscript}[S(\text{Gen5})])\,\text{Mass}(S(\text{Gen5}))^2}\ \Big(G^{(0)}_{SSS}(1) + (p1).(-(k2))\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)) + (p1).(p2-k1)\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)) + (p2-k1).(-(k2))\ G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3))\Big)$$

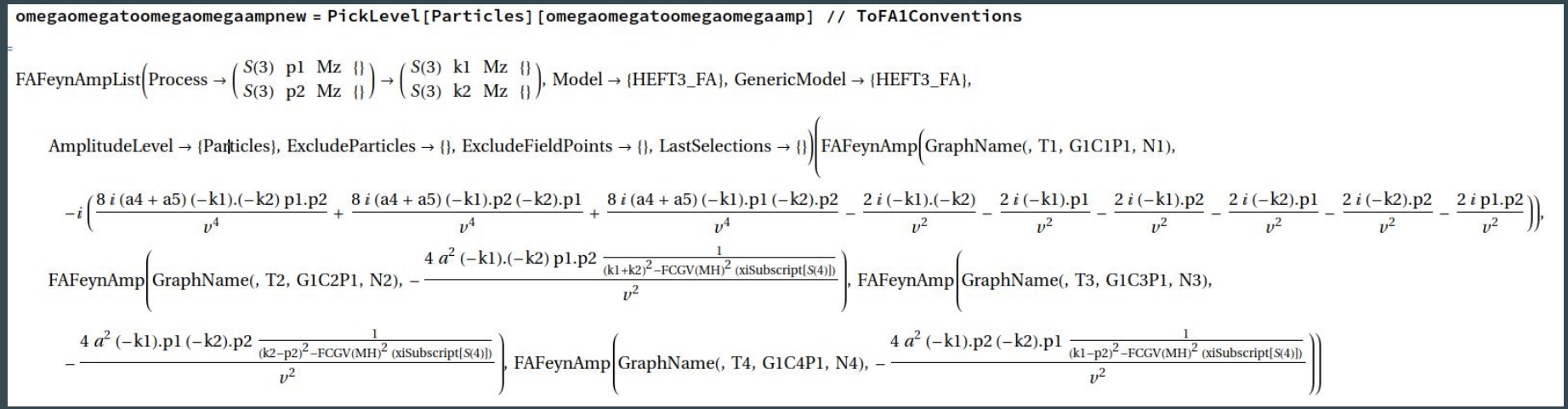
$$\Big(G^{(0)}_{SSS}(1) + (p2).(-(k1))\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)) + (p2).(k1-p2)\ G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)) + (-(k1)).(k1-p2)\ G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3))\Big),$$

$$\Big\{\text{xiSubscript}[S(\text{Gen5})], \text{Mass}(S(\text{Gen5})), G^{(0)}_{SSS}(1), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)), G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3)), G^{(0)}_{SSS}(1), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(2)), G^{(0)}_{SSS}(\text{Mom}(1).\text{Mom}(3)), G^{(0)}_{SSS}(\text{Mom}(2).\text{Mom}(3)), \text{RelativeCF}\Big\} \to$$

$$\text{Insertions}(\text{Classes})\Big(\Big\{\text{xiSubscript}[S(4)], \text{FCGV}(\text{MH}), 0, -\frac{2\,i\,a}{v}, 0, 0, 0, -\frac{2\,i\,a}{v}, 0, 0, 1\Big\} \to \text{Insertions}(\text{Particles})\Big(\Big\{\text{xiSubscript}[S(4)], \text{FCGV}(\text{MH}), 0, -\frac{2\,i\,a}{v}, 0, 0, 0, -\frac{2\,i\,a}{v}, 0, 0, 1\Big\}\Big)\Big)\Big)\Big)$$

# Output for FeynCalc

```
omegaomegatoomegaomegaampnew = PickLevel[Particles][omegaomegatoomegaomegaamp] // ToFA1Conventions
```



# One-loop

```
t11loop = CreateTopologies[1, 1 → 1]
```

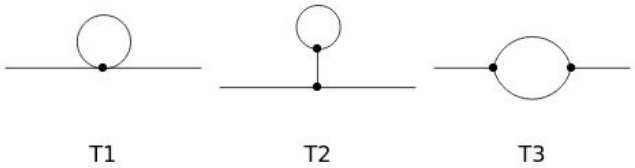
```
Paint[t11loop, ColumnsXRows → 3]
```

> Top. 1 ac/bc/cc.m, 0 diagrams

> Top. 2 ac/bc/cddd.m, 0 diagrams

> Top. 3 ac/bd/cdcd.m, 0 diagrams

$1 \to 1$



# Higgs self-energy

```
hhselfenergy = InsertFields[t1loop, {S[1]} → {S[1]}, InsertionLevel → Particles]
```

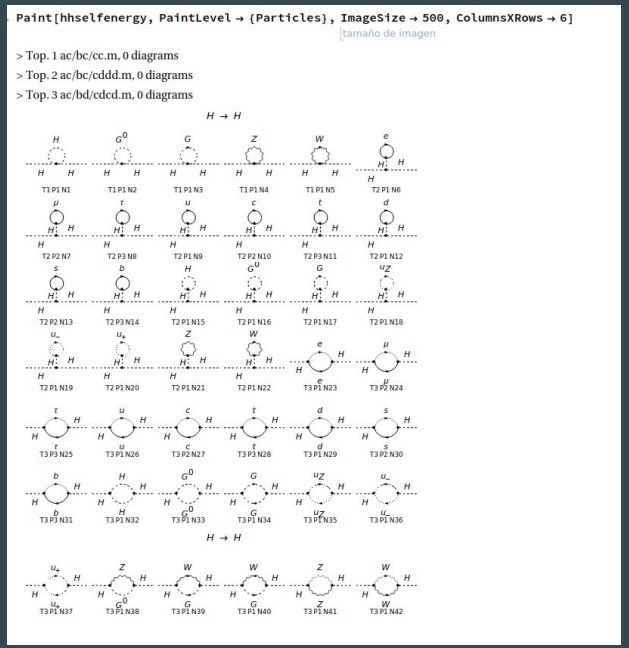
```
Paint[hhselfenergy, PaintLevel → {Particles}, ImageSize → 500, ColumnsXRows → 6]
```

[tamaño de imagen]

> Top. 1 ac/bc/cc.m, 0 diagrams

> Top. 2 ac/bc/cddd.m, 0 diagrams

> Top. 3 ac/bd/cdcd.m, 0 diagrams



# Imposing restrictions

-We will only allow Higgs bosons in the loop

```
hhselfenergy2 = InsertFields[t11loop, {S[1]} → {S[1]}, InsertionLevel → Particles, ExcludeParticles → {V, F, S[2], S[3], U}, LastSelections → {S[1]}]
```

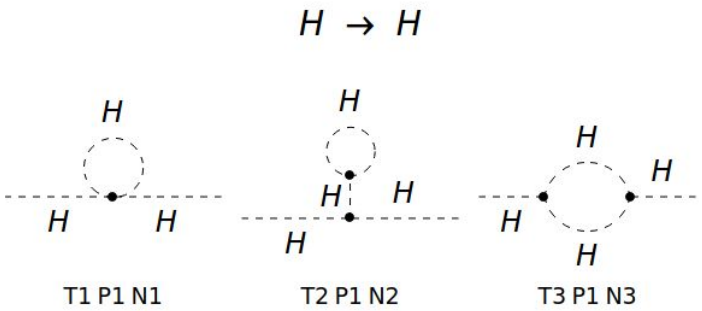
```
Paint[hhselfenergy2, PaintLevel → {Particles}, ImageSize → 500]
```

tamaño de imagen

> Top. 1 ac/bc/cc.m, 0 diagrams

> Top. 2 ac/bc/cddd.m, 0 diagrams

> Top. 3 ac/bd/cdcd.m, 0 diagrams



Then again we can create the amplitude of this

```
hhselfenergy2amp = CreateFeynAmp[hhselfenergy2, AmplitudeLevel → Particles, GaugeRules → {}]
```

```
hhselfenergy2ampnew = PickLevel[Particles][hhselfenergy2amp] // ToFA1Conventions
```

That is the expression that we can feed to FeynCalc.

# Hands on!

Exercise 1:

- Create a topology 2-> 2 in the SM
- Insert the fields for the process hh-> hh
- Draw the diagrams for this process. How many diagrams do we have?

Exercise 2:

- Create a topology 2-> 2 in the SM
- Insert the fields for the process WW-> hh
- Draw the diagrams for this process. How many diagrams?

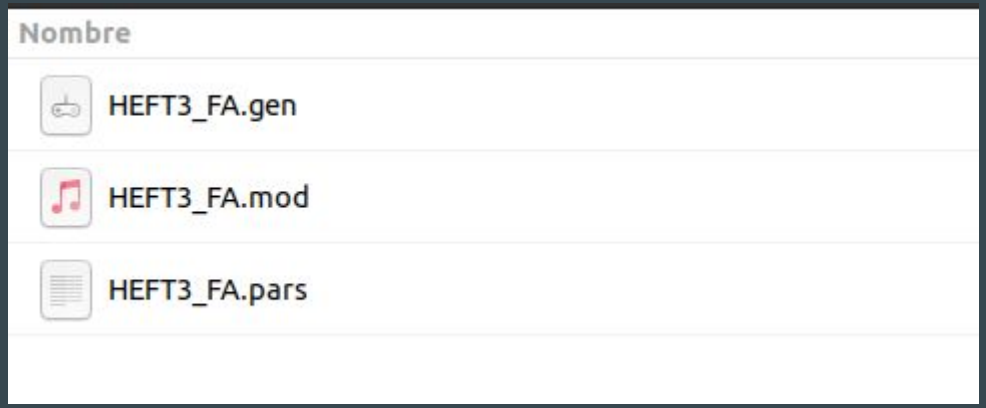
- Now remove vector fields from the intermediate fields
- Draw the diagrams for this process again. How many diagrams do we have now?

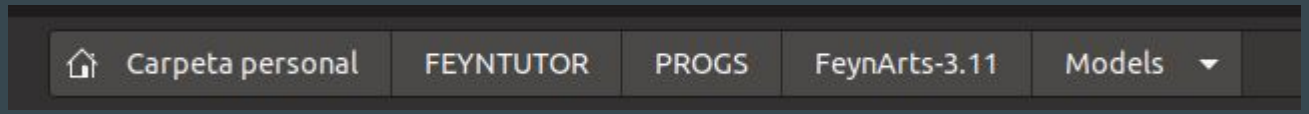
Exercise 3:

- Create a topology 1-> 1 at one loop in the SM.
- Insert the fields for the process h-> h
- Draw the diagrams for this process. How many diagrams?

- Now remove vector, ghosts and fermions and only allow the Higgs in the loop
- Draw the diagrams for this process again. How many diagrams do we have now?

# EXTRA: HEFT model



Exercise 4 (extra):

- Create a topology 2-> 2 in HEFT
- Insert the fields for the process G0G0 -> G0 G0
- Draw the diagrams for this process. How many diagrams?