SOFTWARE TOOLS FOR COLLIDER DATA ANALYSES WITHIN THE ELECTROWEAK CHIRAL LAGRANGIAN FRAMEWORK

JAVIER MARTÍNEZ MARTÍN

IN COLLABORATION WITH: JUAN JOSÉ SANZ CILLERO

Work based on J. Martínez-Martín Master Thesis: https://github.com/javomar99/ewet (V 1.0)

UNIVERSIDAD COMPLUTENSE MADRID

IPARCOS

INTRODUCTION

- Introduction
  - The theory
  - The software
- The Lagrangian
  - The fields
  - The operators
- FeynRules
  - The implementation
  - The vertices
- FeynCalc
  - Checks: Vertices
  - Checks: Amplitudes
  - Predictions

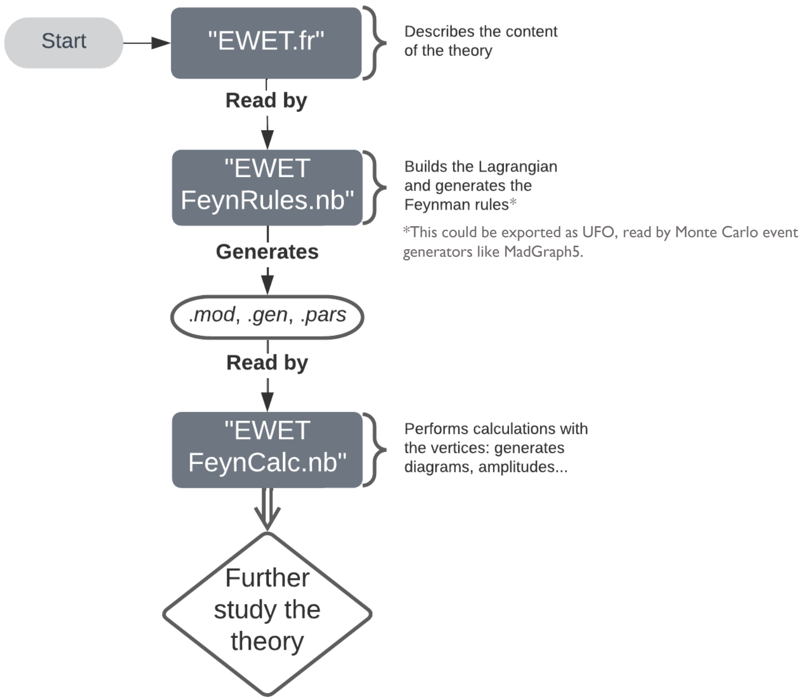
INTRODUCTION

THEORY[1-7]

- $\mathcal{G} \equiv \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{SU}(2)_{\mathrm{R}} \to \mathcal{H} \equiv \mathrm{SU}(2)_{\mathrm{L+R}}$
- $h,\ \pi^a,\ W^{\pm},\ Z,\ A$ (+ fermion / color / ghost / GF terms)
- $\mathcal{L}_{\mathrm{EWET}} = \sum_{\hat{d}\geq 2} \mathcal{L}^{(\hat{d})}\,, \quad \mathcal{L}^{(\hat{d})} = \mathcal{O}(p^{\hat{d}})\,, \quad \mathcal{M} \sim p^{2(L+1)+\sum_{\hat{d}} N_{\hat{d}}(\hat{d}-2)}$
- $\frac{h}{v},\ \frac{\pi^a}{v},\ \frac{W^{a,\mu}}{v},\ \frac{B^\mu}{v} \sim \mathcal{O}(p^0)\,,$

$\partial_\mu,\ m_h,\ m_W,\ m_Z,\ g_W,\ g_1 \sim \mathcal{O}(p)\,,$

SOFTWARE[8-10]



[1] C. KRAUSE, A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ- CILLERO, COLORFUL IMPRINTS OF HEAVY STATES IN THE ELEC- TROWEAK EFFECTIVE THEORY, JOURNAL OF HIGH ENERGY PHYSICS 2019, 10.1007/JHEP05(2019)092 (2019).
[2] A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ-CILLERO, FINGERPRINTS OF HEAVY SCALES IN ELECTROWEAK EFFECTIVE LAGRANGIANS, JOURNAL OF HIGH ENERGY PHYSICS 2017, 10.1007/JHEP04(2017)012 (2017).
[3] A. C. LONGHITANO, HEAVY HIGGS BOSONS IN THE WEINBERG- SALAM MODEL, PHYS. REV. D 22, 1166 (1980).
[4] A. C. LONGHITANO, LOW-ENERGY IMPACT OF A HEAVY HIGGS BOSON SECTOR, NUCLEAR PHYSICS B 188, 118 (1981).
[5] G. BUCHALLA, O. CATÀ, AND C. KRAUSE, COMPLETE ELECTROWEAK CHIRAL LAGRANGIAN WITH A LIGHT HIGGS AT NLO, NU- CLEAR PHYSICS B 880, 552 (2014).
[6] G. BUCHALLA, O. CATÀ , A. CELIS, M. KNECHT, AND C. KRAUSE, HIGGS-ELECTROWEAK CHIRAL LAGRANGIAN: ONE-LOOP RENORMALIZATION GROUP EQUATIONS, PHYSICAL REVIEW D 104, 10.1103/PHYSREVD.104.076005 (2021)
[7] R. ALONSO, M. B. GAVELA, L. MERLO, S. RIGOLINI AND J. YEPES, THE EFFECTIVE CHIRAL LAGRANGIAN FOR A LIGHT DYNAMICAL "HIGGS PARTICLE", 1212.3305 [HEP-PH] (2013)
[8] A. ALLOUL, N. D. CHRISTENSEN, C. DEGRANDE, C. DUHR, AND B. FUKS, FEYNRULES 2.0 — A COMPLETE TOOLBOX FOR TREE-LEVEL PHENOMENOLOGY, COMPUTER PHYSICS COMMUNI- CATIONS 185, 2250 (2014).
[9] T. HAHN, GENERATING FEYNMAN DIAGRAMS AND AMPLITUDES WITH FEYNARTS 3, COMPUTER PHYSICS COMMUNICATIONS 140, 418 (2001).
[10] V. SHTABOVENKO, R. MERTIG, AND F. ORELLANA, NEW DEVEL- OPMENTS IN FEYNCALC 9.0, COMPUTER PHYSICS COMMUNI- CATIONS 207, 432 (2016).

EWET.FR (V 1.0)

```
(**********************************************************)
(*                                                        *)
(*        Model for Electroweak Effective Theory          *)
(*                                                        *)
(**********************************************************)

M$ModelName = "EWET";

M$Information = {Authors -> {"Javier Martínez","Juan José Sanz Cillero"},
   Date->"24/05/2022",
   Institutions -> {"Universidad Complutense de Madrid"},
   Emails -> {"javmar21@ucm.es","jusanz02@ucm.es"},
   Version -> "1"
};

FeynmanGauge = True;

(* ************************* *)
(* *****  Gauge groups  ***** *)
(* ************************* *)

M$GaugeGroups = {
  U1Y  == {
    Abelian          -> True,
    CouplingConstant -> g1,
    GaugeBoson       -> B,
    Charge           -> Y
  },
  SU2L == {
    Abelian           -> False,
    CouplingConstant  -> gw,
    GaugeBoson        -> Wi,
    StructureConstant -> Eps,
    Representations   -> {Ta,SU2D},
    Definitions       -> {Ta[a_,b_,c_]->PauliSigma[a,b,c]/2, FSU2L[i_,j_,k_]:> I Eps[i,j,k]}
  }
};
```

```
(* ************************** *)
(* **** Particle classes **** *)
(* ************************** *)

M$ClassesDescription = {

(* Gauge bosons: physical vector fields *)
  V[1] == {
    ClassName       -> A,
    SelfConjugate   -> True,
    Mass            -> 0,
    Width           -> 0,
    ParticleName    -> "a",
    PDG             -> 22,
    PropagatorLabel -> "\[Gamma]",
    PropagatorType  -> W,
    PropagatorArrow -> None,
    FullName        -> "Photon"
  },
  V[2] == {
    ClassName       -> Z,
    SelfConjugate   -> True,
    Mass            -> {MZ, 91.1876},
    Width           -> {WZ, 2.4952},
    ParticleName    -> "Z",
    PDG             -> 23,
    PropagatorLabel -> "Z",
    PropagatorType  -> Sine,
    PropagatorArrow -> None,
    FullName        -> "Z"
  },
  V[3] == {
    ClassName        -> W,
    SelfConjugate    -> False,
    Mass             -> {MW, Internal},
    Width            -> {WW, 2.085},
    ParticleName     -> "W+",
    AntiParticleName -> "W-",
    QuantumNumbers   -> {Q -> 1},
    PDG              -> 24,
    PropagatorLabel  -> "W",
    PropagatorType   -> Sine,
    PropagatorArrow  -> Forward,
    FullName         -> "W"
  },
```

```
(* ************************** *)
(* *****    Indices     ***** *)
(* ************************** *)

IndexRange[Index[SU2W      ]] = Unfold[Range[3]];
IndexRange[Index[SU2D      ]] = Unfold[Range[2]];

IndexStyle[SU2W,       j];
IndexStyle[SU2D,       k];

(* ************************** *)
(* *** Interaction orders *** *)
(* ***  (as used by mg5)  *** *)
(* ************************** *)

M$InteractionOrderHierarchy = {
  {QED, 2}
};
```

```
(* Higgs: physical scalars  *)
  S[1] == {
    ClassName       -> H,
    SelfConjugate   -> True,
    Mass            -> {MH,125},
    Width           -> {WH,0.00407},
    PropagatorLabel -> "H",
    PropagatorType  -> Straight,
    PropagatorArrow -> None,
    PDG             -> 25,
    ParticleName    -> "H",
    FullName        -> "H"
  },

(* Pions: Goldstones  *)
  S[2] == {
    ClassName       -> pi0,
    SelfConjugate   -> True,
    Mass            -> {MPI0, 0},
    Width           -> {WPI0, 0},
    PropagatorLabel -> ComposedChar["\\pi",Null,0],
    PropagatorType  -> D,
    PropagatorArrow -> None,
    ParticleName    -> "Pi0",
    FullName        -> "Pi0"
  },

  S[3] == {
    ClassName        -> piC,
    SelfConjugate    -> False,
    Mass             -> {MPIC, 0},
    QuantumNumbers   -> {Q -> 1},
    Width            -> {WPIC, 0},
    PropagatorLabel  -> "\[Pi]",
    PropagatorType   -> D,
    PropagatorArrow  -> Forward,
    ParticleName     -> "Pi+",
    AntiParticleName -> "Pi-",
    FullName         -> "Pi"
  }
};
```

THE LAGRANGIAN [1,2]

$$\mathcal{L}^{(\hat{d})} = \mathcal{L}^{(\hat{d})}_{\text{Scalar}} + \mathcal{L}^{(\hat{d})}_{\text{FS}}$$

- Work in progress:
  - Fermions
  - Color operators
  - Ghosts
  - GF terms
  - Heavy BSM resonances
- Other applications:
  - ChPT
  - ChPT + Resonances

[1] C. KRAUSE, A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ- CILLERO, COLORFUL IMPRINTS OF HEAVY STATES IN THE ELEC- TROWEAK EFFECTIVE THEORY, JOURNAL OF HIGH ENERGY PHYSICS 2019, 10.1007/JHEP05(2019)092 (2019).
[2] A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ-CILLERO, FINGERPRINTS OF HEAVY SCALES IN ELECTROWEAK EFFECTIVE LAGRANGIANS, JOURNAL OF HIGH ENERGY PHYSICS 2017, 10.1007/JHEP04(2017)012 (2017).

THE FIELDS

THEORY[1,2]

- $$M(\pi) = \sigma^a \pi^a = \begin{pmatrix} \pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0 \end{pmatrix}$$

- $$U(\pi) = \exp\{i\, M(\pi)/v\}$$

- $$u(\pi) = [U(\pi)]^{1/2}$$

[1] C. KRAUSE, A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ- CILLERO, COLORFUL IMPRINTS OF HEAVY STATES IN THE ELEC- TROWEAK EFFECTIVE THEORY, JOURNAL OF HIGH ENERGY PHYSICS 2019, 10.1007/JHEP05(2019)092 (2019).
[2] A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ-CILLERO, FINGERPRINTS OF HEAVY SCALES IN ELECTROWEAK EFFECTIVE LAGRANGIANS, JOURNAL OF HIGH ENERGY PHYSICS 2017, 10.1007/JHEP04(2017)012 (2017).

EWET FEYNRULES.NB (V 1.0)

```
M = epsf.{{ pi0, Sqrt[2] piC } , {Sqrt[2] piCbar, -pi0}};
                 raíz cuadrada     raíz cuadrada
UU = MatrixExp[I M / vev] // Simplify;
     exponencial··· número i  simplifica
uu = MatrixPower[UU, 1 / 2] // Simplify;
     potencia matricial        simplifica
UTayl = Series[UU, {vev, Infinity, 5}] // Normal ;
        serie           infinito         normal
UdagTayl =
  FullSimplify[ConjugateTranspose[UTayl]] /.
  simplifica comple··· transpuesto conjugado
    {Conjugate[pi0] → pi0, Conjugate[piC] → piCbar, Conjugate[piCbar] → piC} //
     conjugado             conjugado                 conjugado
   Expand;
   expande factores
uTayl = Series[uu, {vev, Infinity, 5}] // Normal;
        serie           infinito         normal
udagTayl =
  FullSimplify[ConjugateTranspose[uTayl]] /.
  simplifica comple··· transpuesto conjugado
    {Conjugate[pi0] → pi0, Conjugate[piC] → piCbar, Conjugate[piCbar] → piC} //
     conjugado             conjugado                 conjugado
   Expand;
   expande factores
```

THE FIELDS

THEORY[1,2]

- $$W^{\pm,\mu} = \frac{W^{1,\mu} \mp iW^{2,\mu}}{\sqrt{2}},$$
  $$Z^\mu = c_W W^{3,\mu} - s_W B^\mu$$
  $$A^\mu = s_W W^{3,\mu} + c_W B^\mu$$

- $$\hat{W}^\mu = -g_W \frac{\sigma^a}{2} W^{a,\mu}, \quad \hat{B}^\mu = -g_1 \frac{\sigma^3}{2} B^\mu$$

EWET.FR (V 1.0)

```
(* Gauge bosons: unphysical vector fields *)
  V[11] == {
    ClassName     -> B,
    Unphysical    -> True,
    SelfConjugate -> True,
    Definitions   -> { B[mu_] -> -sw Z[mu]+cw A[mu]}
  },
  V[12] == {
    ClassName     -> Wi,
    Unphysical    -> True,
    SelfConjugate -> True,
    Indices       -> {Index[SU2W]},
    FlavorIndex   -> SU2W,
    Definitions   -> { Wi[mu_,1] -> (Wbar[mu]+W[mu])/Sqrt[2], Wi[mu_,2] -> (Wbar[mu]-W[mu])/(I*Sqrt[2]),
Wi[mu_,3] -> cw Z[mu] + sw A[mu]}
  },
```

EWET FEYNRULES.NB (V 1.0)

```
What[mu_] = -epsf*gw/2*Sum[PauliMatrix[i]*Wi[mu, i], {i, 1, 3}];
                        |s···  |matriz Pauli

Bhat[mu_] = -epsf*g1/2*PauliMatrix[3]*B[mu];
                        |matriz Pauli
```

[1] C. KRAUSE, A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ- CILLERO, COLORFUL IMPRINTS OF HEAVY STATES IN THE ELEC- TROWEAK EFFECTIVE THEORY, JOURNAL OF HIGH ENERGY PHYSICS 2019, 10.1007/JHEP05(2019)092 (2019).
[2] A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ-CILLERO, FINGERPRINTS OF HEAVY SCALES IN ELECTROWEAK EFFECTIVE LAGRANGIANS, JOURNAL OF HIGH ENERGY PHYSICS 2017, 10.1007/JHEP04(2017)012 (2017).

THE FIELDS

THEORY[1,2]

- $$D_\mu U = \partial_\mu U - i\hat{W}_\mu U + iU\hat{B}_\mu$$

- $$\hat{W}_{\mu\nu} = \partial_\mu \hat{W}_\nu - \partial_\nu \hat{W}_\mu - i[\hat{W}_\mu, \hat{W}_\nu]$$
  $$\hat{B}_{\mu\nu} = \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu - i[\hat{B}_\mu, \hat{B}_\nu]$$

- $$u_\mu = iu(D_\mu U)^\dagger u = -iu^\dagger D_\mu U u^\dagger = u_\mu^\dagger ,$$
  $$f_\pm^{\mu\nu} = u^\dagger \hat{W}^{\mu\nu} u \pm u\hat{B}^{\mu\nu} u^\dagger ,$$
  $$\hat{X}^{\mu\nu} = \partial_\mu \hat{X}_\nu - \partial_\nu \hat{X}_\mu , \quad \hat{X}_\mu = -g_1 B_\mu ,$$
  $$\mathcal{T} = u\mathcal{T}_R u^\dagger , \quad \mathcal{T}_R = -g_1 \frac{\sigma^3}{2} .$$

[1] C. KRAUSE, A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ- CILLERO, COLORFUL IMPRINTS OF HEAVY STATES IN THE ELEC- TROWEAK EFFECTIVE THEORY, JOURNAL OF HIGH ENERGY PHYSICS 2019, 10.1007/JHEP05(2019)092 (2019).
[2] A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ-CILLERO, FINGERPRINTS OF HEAVY SCALES IN ELECTROWEAK EFFECTIVE LAGRANGIANS, JOURNAL OF HIGH ENERGY PHYSICS 2017, 10.1007/JHEP04(2017)012 (2017).

EWET FEYNRULES.NB (V 1.0)

```
DU[mu_] := del[UTayl, mu] - I*What[mu].UTayl + I*UTayl.Bhat[mu];
                            número i             número i

DUdag[mu_] := del[UdagTayl, mu] + I*UdagTayl.What[mu] - I*Bhat[mu].UdagTayl;
                                  número i              número i
```

```
u[mu_] := Normal[Series[-I*udagTayl.DU[mu].udagTayl, {epsf, 0, 5}]]
          normal  serie   número i
```

```
BBhat[mu_, nu_] = del[Bhat[nu], mu] - del[Bhat[mu], nu] -
   I (Bhat[mu].Bhat[nu] - Bhat[nu].Bhat[mu]);
   número i

WWhat[mu_, nu_] = FS[What, mu, nu] - I*(What[mu].What[nu] - What[nu].What[mu]);
                                     número i
```

```
fplus[mu_, nu_] =
  Normal[Series[udagTayl.WWhat[mu, nu].uTayl + uTayl.BBhat[mu, nu].udagTayl,
  normal  serie
    {epsf, 0, 6}]];

fminus[mu_, nu_] =
  Normal[Series[ udagTayl.WWhat[mu, nu].uTayl - uTayl.BBhat[mu, nu].udagTayl,
  normal  serie
    {epsf, 0, 6}]];
TT = -g1/2*uTayl.PauliMatrix[3].udagTayl;
                 matriz Pauli

X[mu_] = -g1*epsf*B[mu];

XX[mu_, nu_] = FS[X, mu, nu];
```

THE OPERATORS: $\mathcal{L}^{(2)}$

THEORY[1,2]

- $$\mathcal{L}^{(2)}_{\rm FS} = -\frac{1}{2g_W^2}\left\langle \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right\rangle - \frac{1}{2g_1^2}\left\langle \hat{B}_{\mu\nu}\,,\hat{B}^{\mu\nu}\right\rangle$$

- $$\mathcal{L}^{(2)}_{\rm Scalar} = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - V\left(h/v\right) + \frac{v^2}{4}\mathcal{F}_u\left(h/v\right)\langle u_\mu u^\mu\rangle\,,$$

- $$V\left(h/v\right) = \frac{1}{2}m_h^2 v^2 \left[\sum_{n\geq 3} b_n \left(\frac{h}{v}\right)^n\right]$$
  $$\mathcal{F}_u\left(h/v\right) = 1 + \sum_{n=1} c_n^{(u)} \left(\frac{h}{v}\right)^n .$$

EWET FEYNRULES.NB (V 1.0)

```
Lagr2FS =
  Normal[Series[-1/(2*gw^2) Tr[WWhat[mu, nu].WWhat[mu, nu]] -
  ⌊normal   ⌊serie                ⌊traza
      1/(2*g1^2) Tr[BBhat[mu, nu].BBhat[mu, nu]], {epsf, 0, 6}]] // Expand;
                ⌊traza                                        ⌊expande factores

L2tr = Tr[u[mu].u[mu]] // Expand;
         ⌊traza             ⌊expande fa

Lagr2Scalar =
  Normal[Series[1/2*del[epsf*H, mu] *del[epsf*H, mu] -
  ⌊normal   ⌊serie
      1/2*MH^2*epsf^2*H^2 -
      1/2*MH^2*vev^2*
       (b3*epsf^3*H^3/vev^3 + b4*epsf^4*H^4/vev^4 +
         b5*epsf^5*H^5/vev^5 + b6*epsf^6*H^6/vev^6) + vev^2/4*L2tr +
      vev*epsf*H/2*a*L2tr + epsf^2*H^2/4*b*L2tr +
      epsf^3*H^3/4*c3u*L2tr + epsf^4*H^4/4*c4u*L2tr, {epsf, 0, 6}]];
```


[1] C. KRAUSE, A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ- CILLERO, COLORFUL IMPRINTS OF HEAVY STATES IN THE ELEC- TROWEAK EFFECTIVE THEORY, JOURNAL OF HIGH ENERGY PHYSICS 2019, 10.1007/JHEP05(2019)092 (2019).
[2] A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ-CILLERO, FINGERPRINTS OF HEAVY SCALES IN ELECTROWEAK EFFECTIVE LAGRANGIANS, JOURNAL OF HIGH ENERGY PHYSICS 2017, 10.1007/JHEP04(2017)012 (2017).

THE OPERATORS: $\mathcal{L}^{(4)}$

THEORY[1,2]

- $$\mathcal{L}_{\rm FS}^{(4)} = \sum_{i=1}^{3} \left[\mathcal{F}_i\,(h/v)\,\mathcal{O}_i + \tilde{\mathcal{F}}_i\,(h/v)\,\tilde{\mathcal{O}}_i \right] + + \mathcal{F}_9\,(h/v)\,\mathcal{O}_9 + \mathcal{F}_{11}\,(h/v)\,\mathcal{O}_{11}\,,$$
- $$\mathcal{L}_{\rm Scalar}^{(4)} = \sum_{i=4}^{8} \mathcal{F}_i\,(h/v)\,\mathcal{O}_i + \mathcal{F}_{10}\,(h/v)\,\mathcal{O}_{10}$$
- $$\mathcal{F}_i\,(h/v) = \sum_{n=0} \mathcal{F}_{i,n} \left(\frac{h}{v}\right)^n$$
  $$\tilde{\mathcal{F}}_i\,(h/v) = \sum_{n=0} \tilde{\mathcal{F}}_{i,n} \left(\frac{h}{v}\right)^n$$

EWET FEYNRULES.NB (V 1.0)

```
Lagr4Scalar =
  Normal[Series[F4n0 * O4 + F5n0 * O5 + F6n0 * O6 + F7n0 * O7 + F8n0 * O8 + F10n0 * O10 +
  |normal   |serie
     (F4n1 * O4 + F5n1 * O5 + F6n1 * O6 + F7n1 * O7 + F8n1 * O8 + F10n1 * O10) * epsf * H / vev +
     (F4n2 * O4 + F5n2 * O5 + F6n2 * O6 + F7n2 * O7 + F8n2 * O8 + F10n2 * O10) * epsf ^ 2 * H ^ 2 / vev ^ 2 +
     F10n3 * O10 * epsf ^ 3 * H ^ 3 / vev ^ 3 + F10n4 * O10 * epsf ^ 4 * H ^ 4 / vev ^ 4, {epsf, 0, 6}]];
```

```
Lagr4FS =
  Normal[Series[F1n0 * O1 + F2n0 * O2 + F3n0 * O3 + F9n0 * O9 + F11n0 * O11 + FF1n0 * OO1 +
  |normal   |serie
     FF2n0 * OO2 + FF3n0 * OO3 +
     (F1n1 * O1 + F2n1 * O2 + F3n1 * O3 + F9n1 * O9 + F11n1 * O11 + FF1n1 * OO1 + FF2n1 * OO2 +
        FF3n1 * OO3) * epsf * H / vev +
     (F1n2 * O1 + F2n2 * O2 + F3n2 * O3 + F9n2 * O9 + F11n2 * O11 + FF1n2 * OO1 + FF2n2 * OO2 +
        FF3n2 * OO3) * epsf ^ 2 * H ^ 2 / vev ^ 2 +
     (F1n3 * O1 + F2n3 * O2 + F3n3 * O3 + F9n3 * O9 + F11n3 * O11 + FF1n3 * OO1 + FF2n3 * OO2 +
        FF3n3 * OO3) * epsf ^ 3 * H ^ 3 / vev ^ 3 +
     (F1n4 * O1 + F2n4 * O2 + F11n4 * O11 + FF2n4 * OO2) * epsf ^ 4 * H ^ 4 / vev ^ 4, {epsf, 0, 6}]];
```


[1] C. KRAUSE, A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ- CILLERO, COLORFUL IMPRINTS OF HEAVY STATES IN THE ELEC- TROWEAK EFFECTIVE THEORY, JOURNAL OF HIGH ENERGY PHYSICS 2019, 10.1007/JHEP05(2019)092 (2019).
[2] A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ-CILLERO, FINGERPRINTS OF HEAVY SCALES IN ELECTROWEAK EFFECTIVE LAGRANGIANS, JOURNAL OF HIGH ENERGY PHYSICS 2017, 10.1007/JHEP04(2017)012 (2017).

THE OPERATORS: $\mathcal{L}_{FS}{}^{(4)}$

THEORY[1,2]

i	$\mathcal{O}_i$	$\tilde{\mathcal{O}}_i$
1	$\frac{1}{4}\langle f_+^{\mu\nu} f_{+\mu\nu} - f_-^{\mu\nu} f_{-\mu\nu}\rangle$	$\frac{i}{2}\langle f_-^{\mu\nu}[u_\mu, u_\nu]\rangle$
2	$\frac{1}{2}\langle f_+^{\mu\nu} f_{+\mu\nu} + f_-^{\mu\nu} f_{-\mu\nu}\rangle$	$\langle f_+^{\mu\nu} f_{-\mu\nu}\rangle$
3	$\frac{i}{2}\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle$	$\frac{(\partial_\mu h)}{v}\langle f_+^{\mu\nu} u_\nu\rangle$
4	$\langle u_\mu u_\nu\rangle\langle u^\mu u^\nu\rangle$	—
5	$\langle u_\mu u^\mu\rangle^2$	—
6	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle u_\nu u^\nu\rangle$	—
7	$\frac{(\partial_\mu h)(\partial_\nu h)}{v^2}\langle u^\mu u^\nu\rangle$	—
8	$\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4}$	—
9	$\frac{(\partial_\mu h)}{v}\langle f_-^{\mu\nu} u_\nu\rangle$	—
10	$\langle \mathcal{T} u_\mu\rangle^2$	—
11	$\hat{X}_{\mu\nu}\hat{X}^{\mu\nu}$	—

TABLE I. CP-invariant operators of the $\mathcal{O}(p^4)$ EWET Lagrangian. P-even (P-odd) operators are shown in the left (right) column.

EWET FEYNRULES.NB (V 1.0)

```
O1 =
  Normal[Series[1/4*Tr[fplus[mu, nu].fplus[mu, nu] - fminus[mu, nu].fminus[mu, nu]],
  normal   serie          traza
     {epsf, 0, 6}]] // Expand;
                        expande factores

O2 =
  Normal[Series[1/2*Tr[fplus[mu, nu].fplus[mu, nu] + fminus[mu, nu].fminus[mu, nu]],
  normal   serie          traza
     {epsf, 0, 6}]] // Expand;
                        expande factores

O3 = Normal[Series[ I/2*Tr[fplus[mu, nu].(u[mu].u[nu] - u[nu].u[mu])], {epsf, 0, 6}]] //
     normal   serie    núm··· traza
  Expand;
  expande factores

O9 = Normal[Series[1/vev*del[epsf*H, mu]*Tr[fminus[mu, nu].u[nu]], {epsf, 0, 6}]] //
     normal   serie                      traza
  Expand;
  expande factores

O11 = Normal[Series[XX[mu, nu]*XX[mu, nu], {epsf, 0, 6}]] // Expand;
      normal   serie                                       expande fa
```

```
OO1 = Normal[Series[I/2*Tr[fminus[mu, nu].(u[mu].u[nu] - u[nu].u[mu])], {epsf, 0, 6}]] //
      normal   serie   núm··· traza
  Expand;
  expande factores

OO2 = Normal[Series[ Tr[fplus[mu, nu].fminus[mu, nu]], {epsf, 0, 6}]] // Expand;
      normal   serie   traza                                        expande fa

OO3 = Normal[Series[1/vev*del[epsf*H, mu]*Tr[fplus[mu, nu].u[nu]], {epsf, 0, 6}]] //
      normal   serie                      traza
  Expand;
  expande factores
```


[1] C. KRAUSE, A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ- CILLERO, COLORFUL IMPRINTS OF HEAVY STATES IN THE ELEC- TROWEAK EFFECTIVE THEORY, JOURNAL OF HIGH ENERGY PHYSICS 2019, 10.1007/JHEP05(2019)092 (2019).
[2] A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ-CILLERO, FINGERPRINTS OF HEAVY SCALES IN ELECTROWEAK EFFECTIVE LAGRANGIANS, JOURNAL OF HIGH ENERGY PHYSICS 2017, 10.1007/JHEP04(2017)012 (2017).

THE OPERATORS: $\mathcal{L}_{Scalar}^{(4)}$

THEORY[1,2]

i	$\mathcal{O}_i$	$\tilde{\mathcal{O}}_i$
1	$\frac{1}{4}\langle f_+^{\mu\nu} f_{+\mu\nu} - f_-^{\mu\nu} f_{-\mu\nu}\rangle$	$\frac{i}{2}\langle f_-^{\mu\nu}[u_\mu, u_\nu]\rangle$
2	$\frac{1}{2}\langle f_+^{\mu\nu} f_{+\mu\nu} + f_-^{\mu\nu} f_{-\mu\nu}\rangle$	$\langle f_+^{\mu\nu} f_{-\mu\nu}\rangle$
3	$\frac{i}{2}\langle f_+^{\mu\nu}[u_\mu, u_\nu]\rangle$	$\frac{(\partial_\mu h)}{v}\langle f_+^{\mu\nu} u_\nu\rangle$
4	$\langle u_\mu u_\nu\rangle\langle u^\mu u^\nu\rangle$	—
5	$\langle u_\mu u^\mu\rangle^2$	—
6	$\frac{(\partial_\mu h)(\partial^\mu h)}{v^2}\langle u_\nu u^\nu\rangle$	—
7	$\frac{(\partial_\mu h)(\partial_\nu h)}{v^2}\langle u^\mu u^\nu\rangle$	—
8	$\frac{(\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)}{v^4}$	—
9	$\frac{(\partial_\mu h)}{v}\langle f_-^{\mu\nu} u_\nu\rangle$	—
10	$\langle \mathcal{T} u_\mu\rangle^2$	—
11	$\hat{X}_{\mu\nu}\hat{X}^{\mu\nu}$	—

TABLE I. CP-invariant operators of the $\mathcal{O}(p^4)$ EWET Lagrangian. P-even (P-odd) operators are shown in the left (right) column.

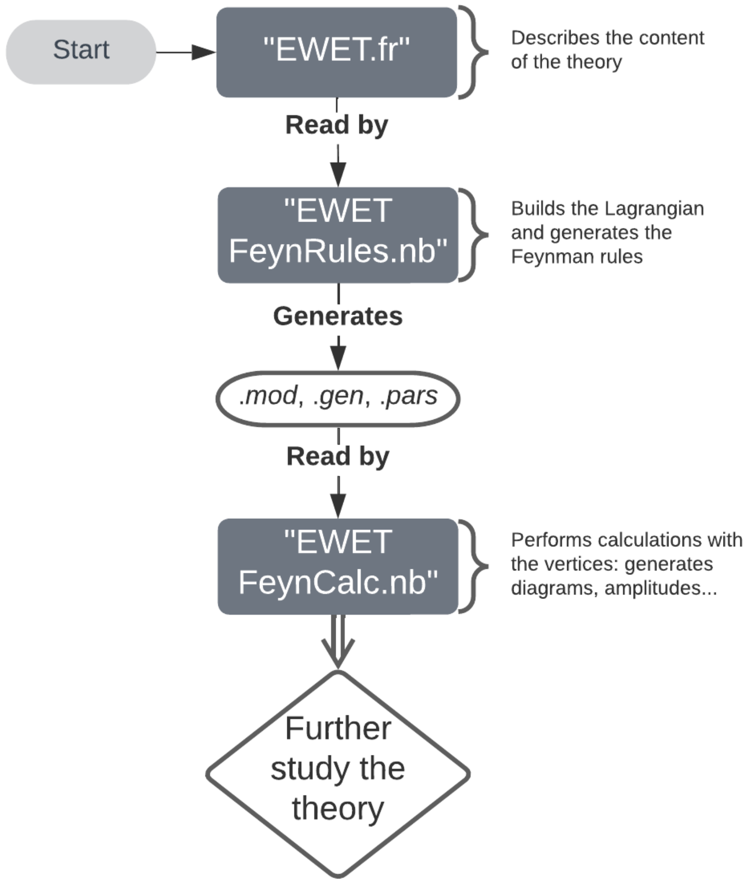
EWET FEYNRULES.NB (V 1.0)

```
O4 = Normal[Series[Tr[u[mu].u[nu]] * Tr[u[mu].u[nu]], {epsf, 0, 6}]] // Expand;

O5 = Normal[Series[Tr[u[mu].u[mu]] * Tr[u[nu].u[nu]], {epsf, 0, 6}]] // Expand;

O6 =
  Normal[Series[1 / vev ^ 2 * del[epsf * H, mu] * del[epsf * H, mu] * Tr[u[nu].u[nu]],
     {epsf, 0, 6}]] // Expand;

O7 =
  Normal[Series[1 / vev ^ 2 * del[epsf * H, mu] * del[epsf * H, nu] * Tr[u[mu].u[nu]],
     {epsf, 0, 6}]] // Expand;

O8 =
  Normal[Series[1 / vev ^ 2 * del[epsf * H, mu] * del[epsf * H, mu] * 1 / vev ^ 2 *
      del[epsf * H, nu] ^ 2, {epsf, 0, 6}]] // Expand;

O10 = Normal[Series[Tr[TT.u[mu]] * Tr[TT.u[mu]], {epsf, 0, 6}]] // Expand;
```


[1] C. KRAUSE, A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ- CILLERO, COLORFUL IMPRINTS OF HEAVY STATES IN THE ELEC- TROWEAK EFFECTIVE THEORY, JOURNAL OF HIGH ENERGY PHYSICS 2019, 10.1007/JHEP05(2019)092 (2019).
[2] A. PICH, I. ROSELL, J. SANTOS, AND J. J. SANZ-CILLERO, FINGERPRINTS OF HEAVY SCALES IN ELECTROWEAK EFFECTIVE LAGRANGIANS, JOURNAL OF HIGH ENERGY PHYSICS 2017, 10.1007/JHEP04(2017)012 (2017).

FEYNRULES

EWET FEYNRULES.NB (V 1.0)



```
In[]:= SetOptions[$FrontEnd, "ClearEvaluationQueueOnKernelQuit" → False];
        asigna opciones interfaz                                     falso
        Quit[];
        detén núcleo del sistema
```

EWET FeynRules

```
In[]:= $FeynRulesPath =
         SetDirectory["/Applications/Mathematica.app/Contents/AddOns/feynrules"];
         establece directorio

In[]:= << FeynRules`;
 – FeynRules –

Version: 2.3.49 (29 September 2021).

Authors: A. Alloul, N. Christensen, C. Degrande, C. Duhr, B. Fuks


Please cite:

    – Comput.Phys.Commun.185:2250–2300,2014 (arXiv:1310.1921);

    – Comput.Phys.Commun.180:1614–1641,2009 (arXiv:0806.4194).


http://feynrules.phys.ucl.ac.be


The FeynRules palette can be opened using the command FRPalette[].

In[]:= SetDirectory[NotebookDirectory[]];
       establece directorio directorio de cuaderno
       LoadModel["EWET.fr"];
Durante la evaluación de In[3]:=
       This model implementation was created by
Durante la evaluación de In[3]:=
       Javier Martínez
Durante la evaluación de In[3]:=
       Juan José Sanz Cillero
Durante la evaluación de In[3]:=
       Model Version: 1
Durante la evaluación de In[3]:=
       For more information, type ModelInformation[].
Durante la evaluación de In[3]:=

Durante la evaluación de In[3]:=
         – Loading particle classes.
Durante la evaluación de In[3]:=
         – Loading gauge group classes.
Durante la evaluación de In[3]:=
         – Loading parameter classes.
Durante la evaluación de In[3]:=

       Model EWET loaded.
```

Fields and Operators

```
In[•]:= M = epsf * {{ pi0, Sqrt[2] piC } , {Sqrt[2] piCbar, -pi0}};
        UU = MatrixExp[I M / vev] // Simplify;
        uu = MatrixPower[UU, 1 / 2] // Simplify;

In[•]:= UTayl = Series[UU, {vev, Infinity, 5}] // Normal ;

In[•]:= UdagTayl = FullSimplify[ConjugateTranspose[UTayl]] /. {Conjugate[pi0] → pi0,
            Conjugate[piC] → piCbar, Conjugate[piCbar] → piC} // Expand;

In[•]:= uTayl  = Series[uu, {vev, Infinity, 5}] // Normal;

In[•]:= udagTayl  = FullSimplify[ConjugateTranspose[uTayl]] /. {Conjugate[pi0] → pi0,
            Conjugate[piC] → piCbar, Conjugate[piCbar] → piC} // Expand;

In[•]:= What[mu_] = -epsf * gw / 2 * Sum[PauliMatrix[i] * Wi[mu, i], {i, 1, 3}];

In[•]:= Bhat[mu_] = -epsf * g1 / 2 * PauliMatrix[3] * B[mu];

In[•]:= DU[mu_] := del[UTayl, mu] - I * What[mu].UTayl + I * UTayl.Bhat[mu];

In[•]:= DUdag[mu_] := del[UdagTayl, mu] + I * UdagTayl.What[mu] - I * Bhat[mu].UdagTayl;

In[•]:= u[mu_] := Normal[Series[ -I * udagTayl.DU[mu].udagTayl, {epsf, 0, 5}]]

In[•]:= BBhat[mu_, nu_] =
          del[Bhat[nu], mu] - del[Bhat[mu], nu] - I (Bhat[mu].Bhat[nu] - Bhat[nu].Bhat[mu]);

In[•]:= WWhat[mu_, nu_] = FS[What, mu, nu] - I * (What[mu].What[nu] - What[nu].What[mu]);

In[•]:= fplus[mu_, nu_] = Normal[Series[
            udagTayl.WWhat[mu, nu].uTayl + uTayl.BBhat[mu, nu].udagTayl, {epsf, 0, 6}]] ;

In[•]:= fminus[mu_, nu_] = Normal[Series[
            udagTayl.WWhat[mu, nu].uTayl - uTayl.BBhat[mu, nu].udagTayl, {epsf, 0, 6}]];
        TT  = -g1 / 2 * uTayl.PauliMatrix[3].udagTayl;

In[•]:= X[mu_] = -g1 * epsf * B[mu];
```

```
In[]:= XX[mu_, nu_] = FS[X, mu, nu];
```

L2

L2 Scalar

```
In[]:= L2tr = Tr[u[mu].u[mu]] // Expand;
```

```
In[]:= Lagr2Scalar = Normal[
         Series[1 / 2 * del[epsf * H, mu] * del[epsf * H, mu] - 1 / 2 * MH^2 * epsf^2 * H^2 -
           1 / 2 * MH^2 * vev^2 * (b3 * epsf^3 * H^3 / vev^3 + b4 * epsf^4 * H^4 / vev^4 +
              b5 * epsf^5 * H^5 / vev^5 + b6 * epsf^6 * H^6 / vev^6) +
           vev^2 / 4 * L2tr + vev * epsf * H / 2 * a * L2tr + epsf^2 * H^2 / 4 * b * L2tr +
           epsf^3 * H^3 / 4 * c3u * L2tr + epsf^4 * H^4 / 4 * c4u * L2tr, {epsf, 0, 6}]];
```

L2 FS

```
In[]:= Lagr2FS = Normal[Series[-1 / (2 * gw^2) Tr[WWhat[mu, nu].WWhat[mu, nu]] -
           1 / (2 * g1^2) Tr[BBhat[mu, nu].BBhat[mu, nu]], {epsf, 0, 6}]] // Expand;
```

L4

L4 Scalar

```
In[]:= O4 = Normal[Series[Tr[u[mu].u[nu]] * Tr[u[mu].u[nu]], {epsf, 0, 6}]] // Expand;
```

```
In[]:= O5 = Normal[Series[Tr[u[mu].u[mu]] * Tr[u[nu].u[nu]], {epsf, 0, 6}]] // Expand;
```

```
In[]:= O6 = Normal[Series[1 / vev^2 * del[epsf * H, mu] *
           del[epsf * H, mu] * Tr[u[nu].u[nu]], {epsf, 0, 6}]] // Expand;
```

```
In[]:= O7 = Normal[Series[1 / vev^2 * del[epsf * H, mu] *
           del[epsf * H, nu] * Tr[u[mu].u[nu]], {epsf, 0, 6}]] // Expand;
```

```
In[]:= O8 = Normal[Series[1 / vev^2 * del[epsf * H, mu] * del[epsf * H, mu] *
           1 / vev^2 * del[epsf * H, nu]^2, {epsf, 0, 6}]] // Expand;
```

Lagrangian

L4 Lagrangian with up to 6 particles vertices

```
In[•]:= SixPartVertsLagr =
          Normal[Series[Lagr2Scalar + Lagr2FS + Lagr4Scalar + Lagr4FS, {epsf, 0, 6}]] /.
          ⌊normal  ⌊serie
           {epsf → 1};

In[•]:= WriteFeynArtsOutput[SixPartVertsLagr,
          Output → "SixPartVertsLagr", CouplingRename → False, MaxParticles → 6];
                                                       ⌊falso
```

```
 - - - FeynRules interface to FeynArts - - -
      C. Degrande C. Duhr, 2013
      Counterterms: B. Fuks, 2012
Calculating Feynman rules for L1
```

Starting Feynman rules calculation for L1.

```
Expanding the Lagrangian...
Expanding the indices over 6 cores
Neglecting all terms with more than 6 particles.
Collecting the different structures that enter the vertex.
384
  possible non-zero vertices have been found -> starting the computation:  / 384.
384 vertices obtained.
mytimecheck,after LGC
Writing FeynArts model file into directory SixPartVertsLagr
Writing FeynArts generic file on SixPartVertsLagr.gen.
```

L4 Lagrangian with up to 4 particles vertices

```
In[•]:= FourPartVertsLagr =
          Normal[Series[Lagr2Scalar + Lagr2FS + Lagr4Scalar + Lagr4FS, {epsf, 0, 4}]] /.
          ⌊normal   ⌊serie
           {epsf → 1};

In[•]:= WriteFeynArtsOutput[FourPartVertsLagr,
          Output → "FourPartVertsLagr", CouplingRename → False, MaxParticles → 4];
                                                         ⌊falso
```

```
 - - - FeynRules interface to FeynArts - - -
       C. Degrande C. Duhr, 2013
       Counterterms: B. Fuks, 2012
Calculating Feynman rules for L1
Starting Feynman rules calculation for L1.
Expanding the Lagrangian...
Expanding the indices over 6 cores
Collecting the different structures that enter the vertex.
84 possible non-zero vertices have been found -> starting the computation:  / 84.
84 vertices obtained.
mytimecheck,after LGC
Writing FeynArts model file into directory FourPartVertsLagr
Writing FeynArts generic file on FourPartVertsLagr.gen.
```

L2 Lagrangian

```
In[•]:= LOLagr = Normal[Series[Lagr2Scalar + Lagr2FS, {epsf, 0, 6}]] /. {epsf → 1};
                 ⌊normal   ⌊serie

In[•]:= WriteFeynArtsOutput[LOLagr, Output → "LOLagr",
          CouplingRename → False, MaxParticles → 6];
                           ⌊falso
```

```
- - - FeynRules interface to FeynArts - - -
      C. Degrande C. Duhr, 2013
      Counterterms: B. Fuks, 2012
Creating output directory: LOLagr
Calculating Feynman rules for L1
Starting Feynman rules calculation for L1.
Expanding the Lagrangian...
Expanding the indices over 6 cores
Collecting the different structures that enter the vertex.
169
  possible non-zero vertices have been found -> starting the computation:  / 169.
169 vertices obtained.
mytimecheck,after LGC
Writing FeynArts model file into directory LOLagr
Writing FeynArts generic file on LOLagr.gen.
```

Vertices

3 particles vertices

```
In[-]:= ThreePartVerts =
         FeynmanRules[FourPartVertsLagr, MaxParticles → 3, MinParticles → 3]
Starting Feynman rule calculation.
Expanding the Lagrangian...
Expanding the indices over 6 cores
Neglecting all terms with less than 3 particles.
Collecting the different structures that enter the vertex.
23 possible non-zero vertices have been found -> starting the computation:  / 23.
23 vertices obtained.
```

Out[-]= $\Big\{\Big\{\{\{H,1\},\{H,2\},\{H,3\}\},-\frac{3\,i\,b3\,MH^2}{vev}\Big\},$

$\Big\{\{\{H,1\},\{pi0,2\},\{pi0,3\}\},-\frac{2\,i\,e^2\,F10n1\,p_2.p_3}{c_w^2\,vev^3}-\frac{2\,i\,a\,p_2.p_3}{vev}\Big\},$

$\Big\{\{\{A,1\},\{piC,2\},\{piC^\dagger,3\}\},$

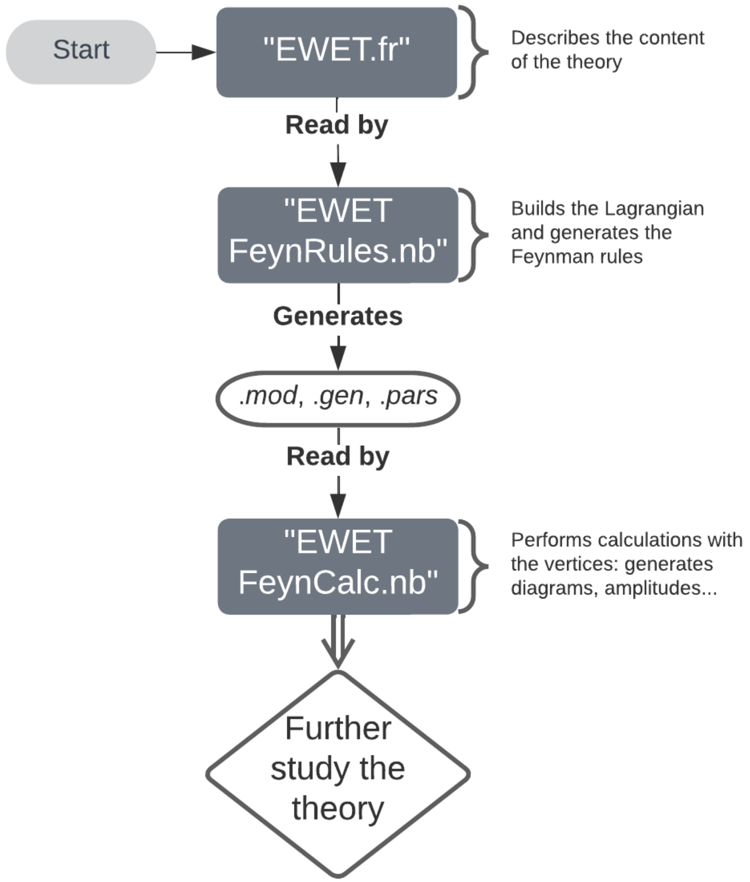
$-i\,e\,p_2^{\mu_1}+i\,e\,p_3^{\mu_1}+\frac{4\,i\,e\,F3n0\,p_3^{\mu_1}\,p_1.p_2}{vev^2}-\frac{4\,i\,e\,F3n0\,p_2^{\mu_1}\,p_1.p_3}{vev^2}\Big\},$

$\Big\{\{\{pi0,1\},\{piC,2\},\{piC^\dagger,3\}\},\frac{2\,e^2\,F10n0\,p_1.p_2}{c_w^2\,vev^3}-\frac{2\,e^2\,F10n0\,p_1.p_3}{c_w^2\,vev^3}\Big\},$

+ . . .

FEYNCALC

EWET FEYNCALC.NB (V 1.0)



```
In[•]:= SetOptions[$FrontEnd, "ClearEvaluationQueueOnKernelQuit" → False];
        asigna opciones interfaz                                   falso
        Quit[];
        detén núcleo del sistema
```

EWET FEYNCALC

```
In[•]:= $LoadAddOns = {"FeynArts"};
        Get["FeynCalc`"]
        recibe
        $FAVerbose = 0;
```

FeynCalc 9.3.1 (stable version). For help, use the documentation center, check out the wiki or visit the forum.

To save your and our time, please check our FAQ for answers to some common FeynCalc questions.

See also the supplied examples. If you use FeynCalc in your research, please cite

- V. Shtabovenko, R. Mertig and F. Orellana, Comput.Phys.Commun. 256 (2020) 107478, arXiv:2001.04407.
- V. Shtabovenko, R. Mertig and F. Orellana, Comput.Phys.Commun. 207 (2016) 432–444, arXiv:1601.01167.
- R. Mertig, M. Böhm, and A. Denner, Comput. Phys. Commun. 64 (1991) 345–359.

FeynArts 3.11 (25 Mar 2022) patched for use with FeynCalc, for documentation see the manual or visit www.feynarts.de.

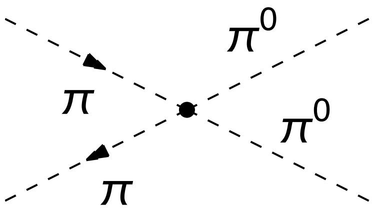
If you use FeynArts in your research, please cite

- T. Hahn, Comput. Phys. Commun., 140, 418–431, 2001, arXiv:hep–ph/0012260

```
In[•]:= SetDirectory[NotebookDirectory[]];
        establece directorio directorio de cuaderno

In[•]:= FAPatch[PatchModelsOnly → True,
                                     verdadero
          FAModelsDirectory → FileNameJoin[{NotebookDirectory[], "SixPartVertsLagr"}]];
                              une nombre de arc··· directorio de cuaderno

        Successfully patched FeynArts.

In[•]:= SetOptions[FourVector, FeynCalcInternal → False];
        asigna opciones                              falso

In[•]:= Model["EWET.fr"];
```

PiPi->Pi0Pi0 Vertex

```
In[∘]:= diags = InsertFields[CreateTopologies[0, 2 → 2,
          ExcludeTopologies → {Tadpoles, WFCorrections(*,Internal, Reducible*)},
          Adjacencies → {4}], {S[3], -S[3]} → {S[2], S[2]}, Model → FileNameJoin[
                                                                  ⌊une nombre de archivo
           {NotebookDirectory[], "SixPartVertsLagr/SixPartVertsLagr"}], GenericModel →
           ⌊directorio de cuaderno
          FileNameJoin[{NotebookDirectory[], "SixPartVertsLagr/SixPartVertsLagr"}],
          ⌊une nombre de arc··· ⌊directorio de cuaderno
         InsertionLevel → {Classes} , ExcludeParticles → {V[3]}];

In[∘]:= Paint[diags, ColumnsXRows → {1, 1}, Numbering → None,
                                                         ⌊ninguno
          SheetHeader → None];
                        ⌊ninguno
```




```
In[∘]:= M = ExpandScalarProduct[FCFAConvert[CreateFeynAmp[diags],
         IncomingMomenta → {p1, p2}, OutgoingMomenta → {k1, k2}, List → False,
                                                                  ⌊lista  ⌊falso
         ChangeDimension → 4, DropSumOver → True, SMP → True, Contract → True]]
                                           ⌊verdadero  ⌊verdadero       ⌊verdadero
```

Out[∘]=

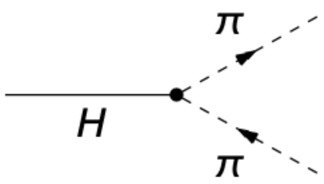
$$-i\left(\frac{2\,i\,(\overline{k1}\cdot\overline{k2})\,(cw^2\,vev^2+8\,e^2\,F10n0)}{3\,cw^2\,vev^4}+\frac{i\,(\overline{k1}\cdot\overline{p1})\,(cw^2\,vev^2+4\,e^2\,F10n0)}{3\,cw^2\,vev^4}+\frac{i\,(\overline{k1}\cdot\overline{p2})\,(cw^2\,vev^2+4\,e^2\,F10n0)}{3\,cw^2\,vev^4}+\frac{i\,(\overline{k2}\cdot\overline{p1})\,(cw^2\,vev^2+4\,e^2\,F10n0)}{3\,cw^2\,vev^4}+\frac{i\,(\overline{k2}\cdot\overline{p2})\,(cw^2\,vev^2+4\,e^2\,F10n0)}{3\,cw^2\,vev^4}+\frac{16\,i\,F4n0\,(\overline{k1}\cdot\overline{p2})\,(\overline{k2}\cdot\overline{p1})}{vev^4}+\frac{16\,i\,F4n0\,(\overline{k1}\cdot\overline{p1})\,(\overline{k2}\cdot\overline{p2})}{vev^4}+\frac{32\,i\,F5n0\,(\overline{k1}\cdot\overline{k2})\,(\overline{p1}\cdot\overline{p2})}{vev^4}+\frac{2\,i\,(\overline{p1}\cdot\overline{p2})}{3\,vev^2}\right)$$

CHECKS: VERTICES

FEYNCALC

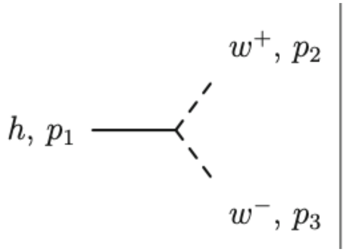
```
M = ExpandScalarProduct[FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1},
    OutgoingMomenta → {k1, k2}, List → False, ChangeDimension → 4, DropSumOver → True, SMP → True, Contract → True]]
                                   |lista    |falso                                   |verdadero      |verdadero                 |verdadero
```

$$-\frac{2\,a\,(\overline{k1}\cdot\overline{k2})}{vev}$$



$$= -i\frac{2a}{v}(k_1 k_2)$$

Ref. [11]



$$-\frac{2ia}{v}(p_2 p_3)$$

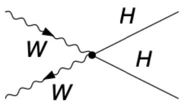
[11] R. DELGADO LÓPEZ, STUDY OF THE ELECTROWEAK SYMMETRY BREAKING SECTOR FOR THE LHC, 1ST ED., SPRINGER THESES (SPRINGER CHAM, 2017). HTTPS://DOI.ORG/10.1007/978-3-319-60498-5

CHECKS:VERTICES

FEYNCALC

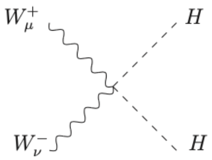
```
M = ExpandScalarProduct[FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1, p2}, OutgoingMomenta → {k1, k2}, List → False, ChangeDimension → 4,
    DropSumOver → True, SMP → True, Contract → True]]
```

$$-i\left(\frac{i\,b\,e^2\,(\bar\varepsilon(p1)\cdot\bar\varepsilon(p2))}{2\,sw^2}+\frac{4\,i\,e^2\,(F2n2+FF2n2)\,(\overline{p1}\cdot\bar\varepsilon(p2))\,(\overline{p2}\cdot\bar\varepsilon(p1))}{sw^2\,vev^2}-\frac{4\,i\,e^2\,(F2n2+FF2n2)\,(\overline{p1}\cdot\overline{p2})\,(\bar\varepsilon(p1)\cdot\bar\varepsilon(p2))}{sw^2\,vev^2}-\frac{2\,i\,e^2\,F6n0\,(\overline{k1}\cdot\overline{k2})\,(\bar\varepsilon(p1)\cdot\bar\varepsilon(p2))}{sw^2\,vev^2}-\frac{i\,e^2\,F7n0\,(\overline{k1}\cdot\bar\varepsilon(p2))\,(\overline{k2}\cdot\bar\varepsilon(p1))}{sw^2\,vev^2}-\frac{i\,e^2\,F7n0\,(\overline{k1}\cdot\bar\varepsilon(p1))\,(\overline{k2}\cdot\bar\varepsilon(p2))}{sw^2\,vev^2}+\frac{i\,e^2\,(F9n1+FF3n1)\,(\overline{p1}\cdot\bar\varepsilon(p2))\,(\overline{k1}\cdot\bar\varepsilon(p1)+\overline{k2}\cdot\bar\varepsilon(p1))}{2\,sw^2\,vev^2}+\frac{i\,e^2\,(F9n1+FF3n1)\,(\overline{p2}\cdot\bar\varepsilon(p1))\,(\overline{k1}\cdot\bar\varepsilon(p2)+\overline{k2}\cdot\bar\varepsilon(p2))}{2\,sw^2\,vev^2}-\frac{i\,e^2\,(F9n1+FF3n1)\,(\bar\varepsilon(p1)\cdot\bar\varepsilon(p2))\,(\overline{k1}\cdot\overline{p1}+\overline{k1}\cdot\overline{p2}+\overline{k2}\cdot\overline{p1}+\overline{k2}\cdot\overline{p2})}{2\,sw^2\,vev^2}\right)$$

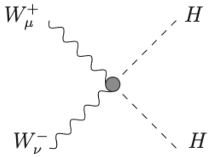


$$= i\frac{bg_W^2}{2}g_{\mu\nu}+$$
$$-i\frac{2g_W^2\mathcal{F}_{6,0}}{v^2}(k_1k_2)g_{\mu\nu}+$$
$$-i\frac{g_W^2\mathcal{F}_{7,0}}{v^2}(k_{1\nu}k_{2\mu}+k_{1\mu}k_{2\nu})+$$
$$+i\frac{g_W^2(\mathcal{F}_{9,1}+\tilde{\mathcal{F}}_{3,1})}{2v^2}[p_{1\nu}(k_1+k_2)_\mu+$$
$$+p_{2\mu}(k_1+k_2)_\nu-(p_1+p_2)^2g_{\mu\nu}]+$$
$$+i\frac{4g_W^2(\mathcal{F}_{2,2}+\tilde{\mathcal{F}}_{2,2})}{v^2}[p_{1\nu}p_{2\mu}-(p_1p_2)g_{\mu\nu}]$$

Ref. [12]



$$V^{\rm SM}_{W_\mu^+W_\nu^-HH}=\frac{ig^2}{2}g_{\mu\nu}$$



$$V^{\rm EChL\ (\sout{SM})}_{W_\mu^+W_\nu^-HH}=V^{\rm SM}_{W_\mu^+W_\nu^-HH}+\frac{ig^2}{2}(b-1)g_{\mu\nu}$$

[12] C. GARCIA-GARCIA, NEW PHYSICS SIGNALS OF THE ELECTROWEAK CHIRAL LAGRANGIAN IN VECTOR BOSON SCATTERING AT THE LHC (2020). 2001.08965 [HEP-PH]

Amplitudes Checks

PiPi->Pi0Pi0 Amplitude

In[•]:=
```
diags = InsertFields[CreateTopologies[0, 2 → 2,
     ExcludeTopologies → {Tadpoles, WFCorrections(*,Internal, Reducible*)},
     Adjacencies → {3, 4}], {S[3], -S[3]} → {S[2], S[2]}, Model →
     FileNameJoin[{NotebookDirectory[], "SixPartVertsLagr/SixPartVertsLagr"}],
     ⌊une nombre de arc⋯ ⌊directorio de cuaderno
    GenericModel → FileNameJoin[{NotebookDirectory[],
                   ⌊une nombre de arc⋯ ⌊directorio de cuaderno
       "SixPartVertsLagr/SixPartVertsLagr"}], InsertionLevel → {Classes}];
```

In[•]:=
```
M = ExpandScalarProduct[
   FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1, p2},
     OutgoingMomenta → {k1, k2}, List → False, ChangeDimension → 4,
                                 ⌊lista  ⌊falso
     DropSumOver → True, SMP → True, Contract → True] // FeynAmpDenominatorExplicit]
                 ⌊verdadero    ⌊verdadero          ⌊verdadero
```

Out[•]=

$$-\frac{a\left(a\,\mathrm{cw}^2\,\mathrm{vev}^2+\mathrm{F10n1}\,\mathrm{e}^2\right)s^2}{\mathrm{cw}^2\,\mathrm{vev}^4\left(s-m_H^2\right)}-\frac{2\,\mathrm{F10n0}\,\mathrm{e}^2\left(\frac{\mathrm{F10n0}\,t\,\mathrm{e}^2}{\mathrm{cw}^2\,\mathrm{vev}^3}+\frac{2\,\mathrm{F10n0}\left(-\frac{s}{2}-\frac{u}{2}\right)\mathrm{e}^2}{\mathrm{cw}^2\,\mathrm{vev}^3}\right)}{\mathrm{cw}^2\,\mathrm{vev}^3}-$$

$$\frac{2\,\mathrm{F10n0}\,\mathrm{e}^2\left(\frac{2\,\mathrm{F10n0}\left(-\frac{s}{2}-\frac{t}{2}\right)\mathrm{e}^2}{\mathrm{cw}^2\,\mathrm{vev}^3}+\frac{\mathrm{F10n0}\,u\,\mathrm{e}^2}{\mathrm{cw}^2\,\mathrm{vev}^3}\right)}{\mathrm{cw}^2\,\mathrm{vev}^3}-i\left(\frac{8\,i\,\mathrm{F5n0}\,s^2}{\mathrm{vev}^4}+\frac{i\left(\mathrm{cw}^2\,\mathrm{vev}^2+8\,\mathrm{F10n0}\,\mathrm{e}^2\right)s}{3\,\mathrm{cw}^2\,\mathrm{vev}^4}+\frac{i\,s}{3\,\mathrm{vev}^2}-\right.$$

$$\left.\frac{i\,t\left(\mathrm{cw}^2\,\mathrm{vev}^2+4\,\mathrm{F10n0}\,\mathrm{e}^2\right)}{3\,\mathrm{cw}^2\,\mathrm{vev}^4}-\frac{i\,u\left(\mathrm{cw}^2\,\mathrm{vev}^2+4\,\mathrm{F10n0}\,\mathrm{e}^2\right)}{3\,\mathrm{cw}^2\,\mathrm{vev}^4}+\frac{4\,i\,\mathrm{F4n0}\,t^2}{\mathrm{vev}^4}+\frac{4\,i\,\mathrm{F4n0}\,u^2}{\mathrm{vev}^4}\right)-$$

$$\frac{1}{t-m_W^2}\left(\frac{1}{2\,\mathrm{cw}^2\,\mathrm{sw}\,\mathrm{vev}^2}i\,\mathrm{e}\left(-\mathrm{vev}^2\,\mathrm{cw}^2+2\,\mathrm{F3n0}\,t\,\mathrm{cw}^2+2\,\mathrm{FF1n0}\,t\,\mathrm{cw}^2-4\,\mathrm{F10n0}\,\mathrm{e}^2\right)\right.$$

$$\left(-\frac{i\,u\,\mathrm{e}}{4\,\mathrm{sw}}+\frac{i\,s\left(\mathrm{cw}^2\,\mathrm{vev}^2+4\,\mathrm{F10n0}\,\mathrm{e}^2\right)\mathrm{e}}{4\,\mathrm{cw}^2\,\mathrm{sw}\,\mathrm{vev}^2}+\frac{i\left(\mathrm{F3n0}+\mathrm{FF1n0}\right)s\left(\frac{s}{2}+\frac{u}{2}\right)\mathrm{e}}{\mathrm{sw}\,\mathrm{vev}^2}+\frac{i\left(\mathrm{F3n0}+\mathrm{FF1n0}\right)\left(-\frac{s}{2}-\frac{u}{2}\right)u\,\mathrm{e}}{\mathrm{sw}\,\mathrm{vev}^2}\right)+$$

$$\left.\frac{i\left(-\mathrm{vev}^2+2\,\mathrm{F3n0}\,t+2\,\mathrm{FF1n0}\,t\right)\mathrm{e}\left(-\frac{i\,u\left(\mathrm{cw}^2\,\mathrm{vev}^2+4\,\mathrm{F10n0}\,\mathrm{e}^2\right)\mathrm{e}}{4\,\mathrm{cw}^2\,\mathrm{sw}\,\mathrm{vev}^2}+\frac{i\,s\,\mathrm{e}}{4\,\mathrm{sw}}-\frac{i\left(\mathrm{F3n0}+\mathrm{FF1n0}\right)s\left(-\frac{s}{2}-\frac{u}{2}\right)\mathrm{e}}{\mathrm{sw}\,\mathrm{vev}^2}-\frac{i\left(\mathrm{F3n0}+\mathrm{FF1n0}\right)\left(\frac{s}{2}+\frac{u}{2}\right)u\,\mathrm{e}}{\mathrm{sw}\,\mathrm{vev}^2}\right)}{2\,\mathrm{sw}\,\mathrm{vev}^2}\right)-$$

$$\frac{1}{u-m_W^2}\left(\frac{1}{2\,\mathrm{cw}^2\,\mathrm{sw}\,\mathrm{vev}^2}i\,\mathrm{e}\left(-\mathrm{vev}^2\,\mathrm{cw}^2+2\,\mathrm{F3n0}\,u\,\mathrm{cw}^2+2\,\mathrm{FF1n0}\,u\,\mathrm{cw}^2-4\,\mathrm{F10n0}\,\mathrm{e}^2\right)\right.$$

$$\left(-\frac{i\,t\,\mathrm{e}}{4\,\mathrm{sw}}+\frac{i\,s\left(\mathrm{cw}^2\,\mathrm{vev}^2+4\,\mathrm{F10n0}\,\mathrm{e}^2\right)\mathrm{e}}{4\,\mathrm{cw}^2\,\mathrm{sw}\,\mathrm{vev}^2}+\frac{i\left(\mathrm{F3n0}+\mathrm{FF1n0}\right)s\left(\frac{s}{2}+\frac{t}{2}\right)\mathrm{e}}{\mathrm{sw}\,\mathrm{vev}^2}+\frac{i\left(\mathrm{F3n0}+\mathrm{FF1n0}\right)\left(-\frac{s}{2}-\frac{t}{2}\right)t\,\mathrm{e}}{\mathrm{sw}\,\mathrm{vev}^2}\right)+$$

$$\left.\frac{i\left(-\mathrm{vev}^2+2\,\mathrm{F3n0}\,u+2\,\mathrm{FF1n0}\,u\right)\mathrm{e}\left(-\frac{i\,t\left(\mathrm{cw}^2\,\mathrm{vev}^2+4\,\mathrm{F10n0}\,\mathrm{e}^2\right)\mathrm{e}}{4\,\mathrm{cw}^2\,\mathrm{sw}\,\mathrm{vev}^2}+\frac{i\,s\,\mathrm{e}}{4\,\mathrm{sw}}-\frac{i\left(\mathrm{F3n0}+\mathrm{FF1n0}\right)s\left(-\frac{s}{2}-\frac{t}{2}\right)\mathrm{e}}{\mathrm{sw}\,\mathrm{vev}^2}-\frac{i\left(\mathrm{F3n0}+\mathrm{FF1n0}\right)\left(\frac{s}{2}+\frac{t}{2}\right)t\,\mathrm{e}}{\mathrm{sw}\,\mathrm{vev}^2}\right)}{2\,\mathrm{sw}\,\mathrm{vev}^2}\right)$$

In[∘]:= `simp = Simplify[M]`
simplifica

Out[∘]=
$$\frac{1}{24\,\mathrm{cw}^4\,\mathrm{vev}^6}\Bigg(-\frac{24\,a\,\mathrm{cw}^2\,s^2\,\mathrm{vev}^2\left(a\,\mathrm{cw}^2\,\mathrm{vev}^2+\mathrm{e}^2\,\mathrm{F10n1}\right)}{s-m_H^2}+$$
$$8\,\mathrm{cw}^2\,\mathrm{vev}^2\left(\mathrm{cw}^2\left(12\,\mathrm{F4n0}\left(t^2+u^2\right)+24\,\mathrm{F5n0}\,s^2+\mathrm{vev}^2\,(2\,s-t-u)\right)+4\,\mathrm{e}^2\,\mathrm{F10n0}\,(2\,s-t-u)\right)-\frac{1}{\mathrm{sw}^2\left(t-m_W^2\right)}$$
$$6\,\mathrm{e}^2\,\mathrm{vev}^2\Big(-\left(\mathrm{cw}^4\,(s-u)\left(2\,\mathrm{F3n0}\,t+2\,\mathrm{FF1n0}\,t-\mathrm{vev}^2\right)\times\left(2\,\mathrm{F3n0}\,(s+u)+2\,\mathrm{FF1n0}\,(s+u)+\mathrm{vev}^2\right)\right)+$$
$$4\,\mathrm{cw}^2\,\mathrm{e}^2\,\mathrm{F10n0}\,(s-u)\left(\mathrm{F3n0}\,(s-t+u)+\mathrm{FF1n0}\,(s-t+u)+\mathrm{vev}^2\right)+8\,\mathrm{e}^4\,\mathrm{F10n0}^2\,s\Big)-\frac{1}{\mathrm{sw}^2\left(u-m_W^2\right)}$$
$$6\,\mathrm{e}^2\,\mathrm{vev}^2\Big(-\left(\mathrm{cw}^4\,(s-t)\left(2\,\mathrm{F3n0}\,u+2\,\mathrm{FF1n0}\,u-\mathrm{vev}^2\right)\times\left(2\,\mathrm{F3n0}\,(s+t)+2\,\mathrm{FF1n0}\,(s+t)+\mathrm{vev}^2\right)\right)+$$
$$4\,\mathrm{cw}^2\,\mathrm{e}^2\,\mathrm{F10n0}\,(s-t)\left(\mathrm{F3n0}\,(s+t-u)+\mathrm{FF1n0}\,(s+t-u)+\mathrm{vev}^2\right)+8\,\mathrm{e}^4\,\mathrm{F10n0}^2\,s\Big)+$$
$$48\,\mathrm{e}^4\,\mathrm{F10n0}^2\,(s+t-u)+48\,\mathrm{e}^4\,\mathrm{F10n0}^2\,(s-t+u)\Bigg)$$

CHECKS: AMPLITUDES

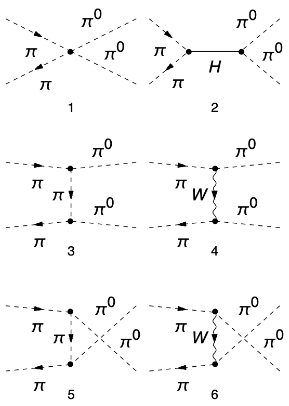
FEYNCALC

```
simp = Simplify[M]
```

simplifica

$$\frac{1}{24\,\mathrm{cw}^4\,\mathrm{vev}^6}\left(-\frac{24\,a\,\mathrm{cw}^2\,s^2\,\mathrm{vev}^2\left(a\,\mathrm{cw}^2\,\mathrm{vev}^2+\mathrm{e}^2\,\mathrm{F10n1}\right)}{s-m_H^2}+8\,\mathrm{cw}^2\,\mathrm{vev}^2\left(\mathrm{cw}^2\left(12\,\mathrm{F4n0}\left(t^2+u^2\right)+24\,\mathrm{F5n0}\,s^2+\mathrm{vev}^2\,(2\,s-t-u)\right)+4\,\mathrm{e}^2\,\mathrm{F10n0}\,(2\,s-t-u)\right)-\frac{6\,\mathrm{e}^2\,\mathrm{vev}^2\left(-\left(\mathrm{cw}^4\,(s-u)\left(2\,\mathrm{F3n0}\,t+2\,\mathrm{FF1n0}\,t-\mathrm{vev}^2\right)\times\left(2\,\mathrm{F3n0}\,(s+u)+2\,\mathrm{FF1n0}\,(s+u)+\mathrm{vev}^2\right)\right)+4\,\mathrm{cw}^2\,\mathrm{e}^2\,\mathrm{F10n0}\,(s-u)\left(\mathrm{F3n0}\,(s-t+u)+\mathrm{FF1n0}\,(s-t+u)+\mathrm{vev}^2\right)+8\,\mathrm{e}^4\,\mathrm{F10n0}^2\,s\right)}{\mathrm{sw}^2\left(t-m_W^2\right)}-\frac{6\,\mathrm{e}^2\,\mathrm{vev}^2\left(-\left(\mathrm{cw}^4\,(s-t)\left(2\,\mathrm{F3n0}\,u+2\,\mathrm{FF1n0}\,u-\mathrm{vev}^2\right)\times\left(2\,\mathrm{F3n0}\,(s+t)+2\,\mathrm{FF1n0}\,(s+t)+\mathrm{vev}^2\right)\right)+4\,\mathrm{cw}^2\,\mathrm{e}^2\,\mathrm{F10n0}\,(s-t)\left(\mathrm{F3n0}\,(s+t-u)+\mathrm{FF1n0}\,(s+t-u)+\mathrm{vev}^2\right)+8\,\mathrm{e}^4\,\mathrm{F10n0}^2\,s\right)}{\mathrm{sw}^2\left(u-m_W^2\right)}+48\,\mathrm{e}^4\,\mathrm{F10n0}^2\,(s+t-u)+48\,\mathrm{e}^4\,\mathrm{F10n0}^2\,(s-t+u)\right)$$

$\pi\ \pi \to \pi^0\ \pi^0$



$$\begin{aligned}\mathcal{M}(\pi^+\pi^-\to\pi^0\pi^0) = {} & \frac{s}{v^2}\left(1+\frac{a^2 s}{m_h^2-s}\right)+\\ & +\frac{g_W^2}{4}\left(\frac{s-u}{m_W^2-t}+\frac{s-t}{m_W^2-u}\right)+\frac{4\mathcal{F}_{4,0}}{v^4}(t^2+u^2)+\\ & +\frac{8\mathcal{F}_{5,0}}{v^4}s^2+\frac{g_W^2(\mathcal{F}_{3,0}+\tilde{\mathcal{F}}_{1,0})}{2v^2}\left(\frac{s^2-u^2}{m_W^2-t}+\frac{s^2-t^2}{m_W^2-u}\right)+\\ & +\frac{g_W^2(\mathcal{F}_{3,0}+\tilde{\mathcal{F}}_{1,0})^2}{v^4}\left[\frac{t(u^2-s^2)}{m_W^2-t}+\frac{u(t^2-s^2)}{m_W^2-u}\right]+\\ & +\frac{e^2\mathcal{F}_{10,0}}{c_W^2 v^2}\left[g_W^2\left(\frac{s-u}{m_W^2-t}+\frac{s-t}{m_W^2-u}\right)+\frac{4s}{v^2}\right]+\\ & +\frac{a\,\mathcal{F}_{10,1}\,e^2 s^2}{c_W^2 v^4(m_h^2-s)},\end{aligned}$$

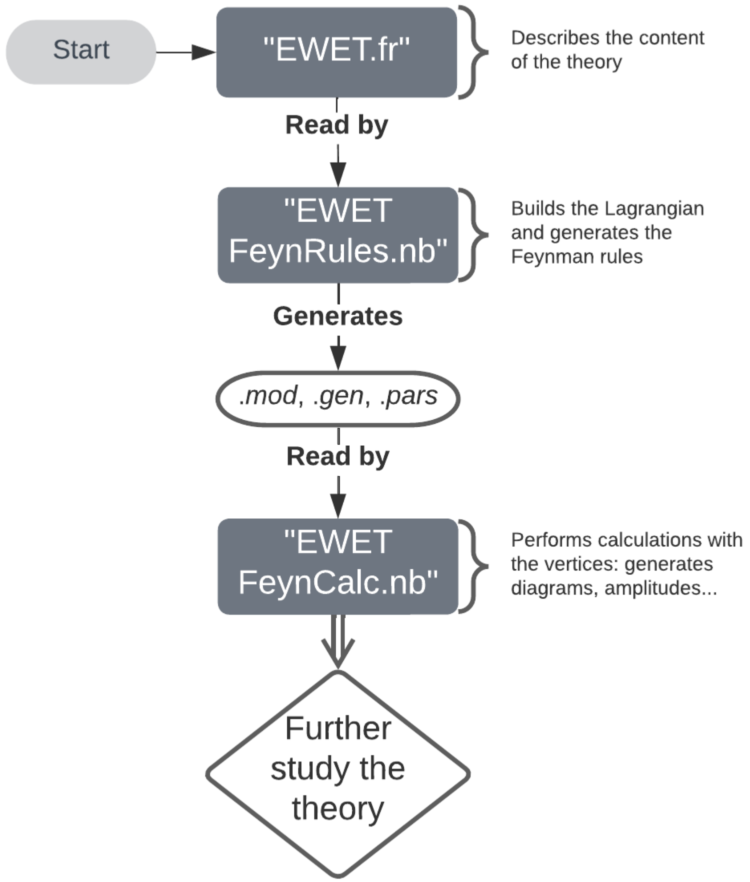
Ref. [11]

$$A^{2\omega 2\omega}(s,t,u)=\frac{s}{v^2}\left(1+\frac{a^2 s}{M_h^2-s}\right)$$

[11] R. DELGADO LÓPEZ, STUDY OF THE ELECTROWEAK SYMMETRY BREAKING SECTOR FOR THE LHC, 1ST ED., SPRINGER THESES (SPRINGER CHAM, 2017).

PREDICTIONS: A FIRST EXAMPLE

$H \rightarrow \gamma\, \pi^0$ *

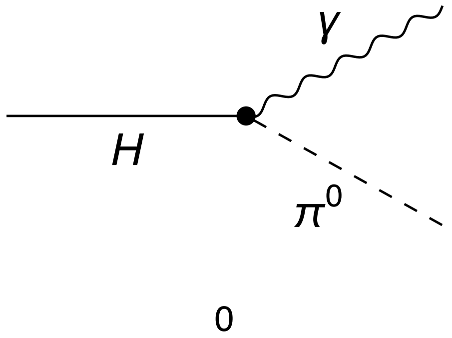


*Related with $H \rightarrow \gamma\, Z_L$ (Equivalence theorem)

H->APi0 New Amplitude

Tree level

```
In[]:= diags = InsertFields[CreateTopologies[0, 1 → 2, Adjacencies → {3, 4, 5, 6}(*,
        ExcludeTopologies→{Tadpoles, WFCorrections,Internal, Reducible}*)],
       {S[1]} → {V[1], S[2]}, Model → FileNameJoin[
                                        une nombre de archivo
         {NotebookDirectory[], "SixPartVertsLagr/SixPartVertsLagr"}], GenericModel →
          directorio de cuaderno
        FileNameJoin[{NotebookDirectory[], "SixPartVertsLagr/SixPartVertsLagr"}],
        une nombre de arc··· directorio de cuaderno
       InsertionLevel → {Classes}];
```

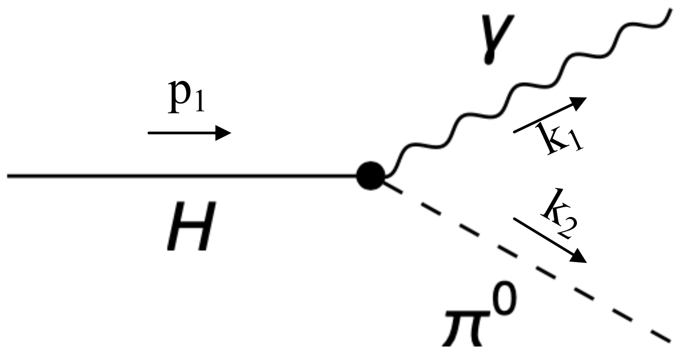


Out[]= FeynArtsGraphics()(([1]))

```
In[]:= M = ExpandScalarProduct[
       FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1    },
         OutgoingMomenta → {k1, k2}, List → False, ChangeDimension → 4,
                                      lista     falso
         DropSumOver → True, SMP → True, Contract → True] //
                      verdadero   verdadero            verdadero
        FeynAmpDenominatorExplicit]
```

Out[]= $-i\left(\frac{2\,\mathrm{e}\,\mathrm{FF3n0}\,(m_H^2 - \frac{t}{2})\,(\overline{\mathrm{k2}}\cdot\bar{\varepsilon}^*(\mathrm{k1}))}{\mathrm{vev}^2} - \frac{2\,\mathrm{e}\,\mathrm{FF3n0}\,(\frac{s}{2} - m_H^2)\,(\overline{\mathrm{p1}}\cdot\bar{\varepsilon}^*(\mathrm{k1}))}{\mathrm{vev}^2}\right)$

$H \to \gamma\, \pi^0$

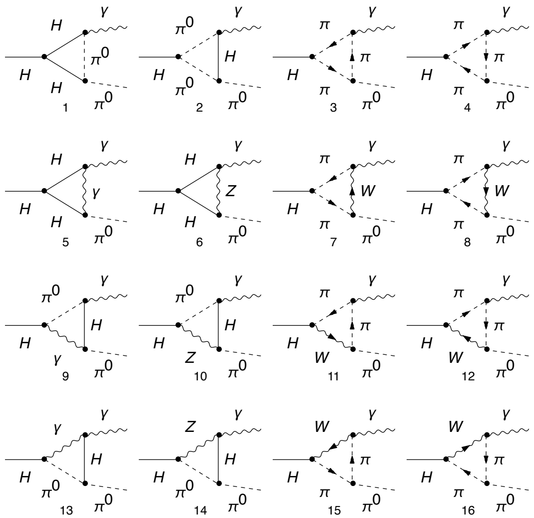


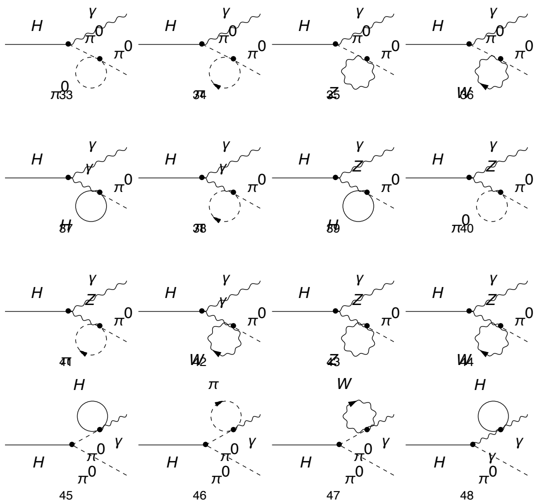
$$\mathcal{M}_0 = \frac{e\tilde{\mathcal{F}}_{3,0}}{v^2}\left[(s - m_h^2)(p_1 \varepsilon^*_{k_1}) + (t - m_h^2)(k_2 \varepsilon^*_{k_1})\right]$$

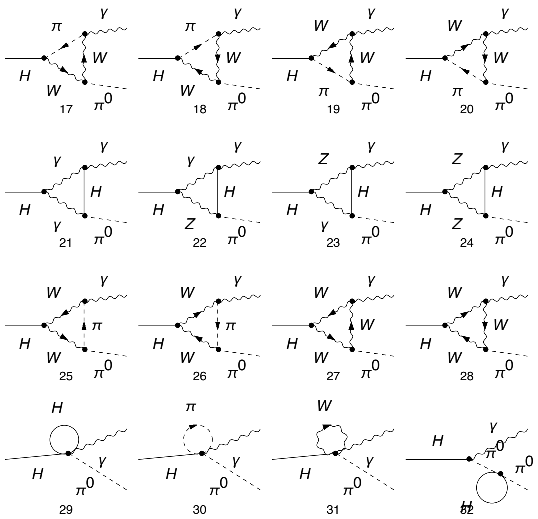
$$s = (k_1 + k_2)^2$$
$$t = (p_1 - k_1)^2$$

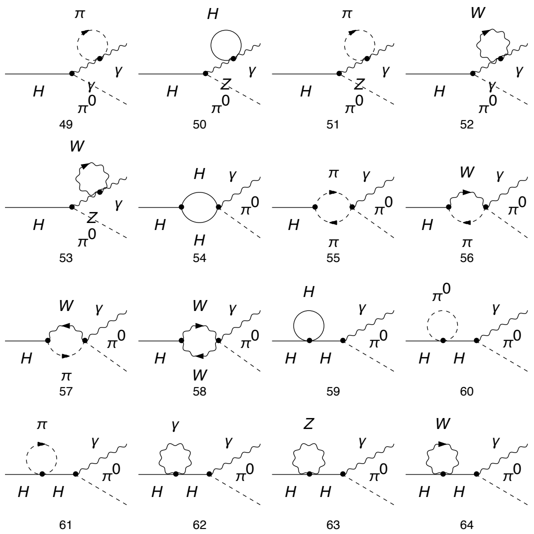
One loop

```
In[•]:= diags = InsertFields[CreateTopologies[1, 1 → 2, Adjacencies → {3, 4, 5, 6}(*,
          ExcludeTopologies→{Tadpoles, WFCorrections,Internal, Reducible}*)],
        {S[1]} → {V[1], S[2]}, Model → FileNameJoin[
                                       une nombre de archivo
          {NotebookDirectory[], "SixPartVertsLagr/SixPartVertsLagr"}], GenericModel →
           directorio de cuaderno
         FileNameJoin[{NotebookDirectory[], "SixPartVertsLagr/SixPartVertsLagr"}],
         une nombre de arc··· directorio de cuaderno
        InsertionLevel → {Classes} ];

In[•]:= Paint[diags, ColumnsXRows → {4, 4}, Numbering → Simple,
         SheetHeader → None]
                       ninguno
```

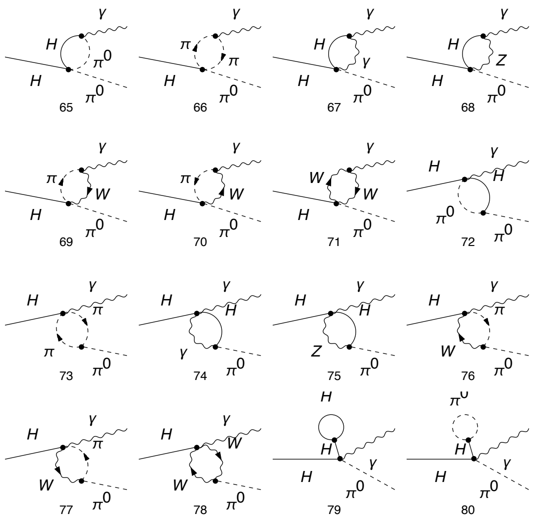


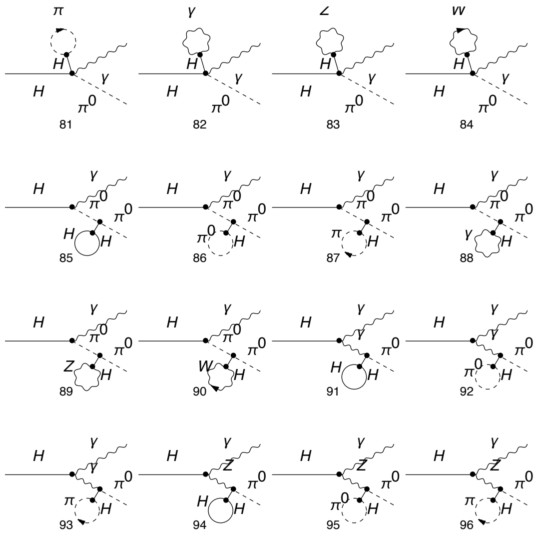


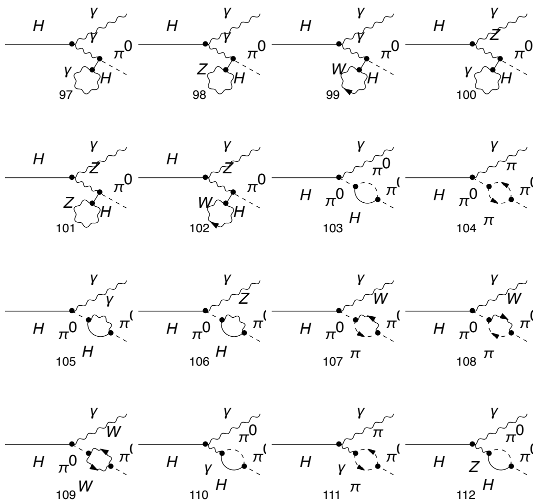


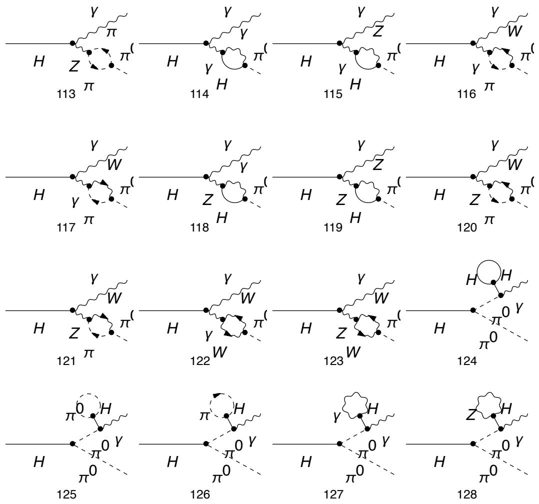


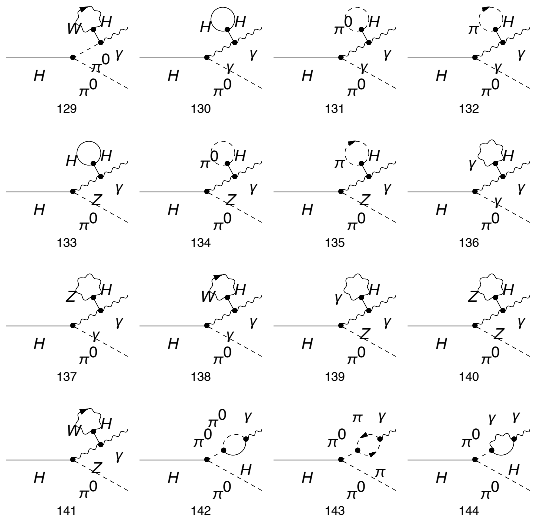
AUTOMATICLY GENERATED BY FEYNARTS

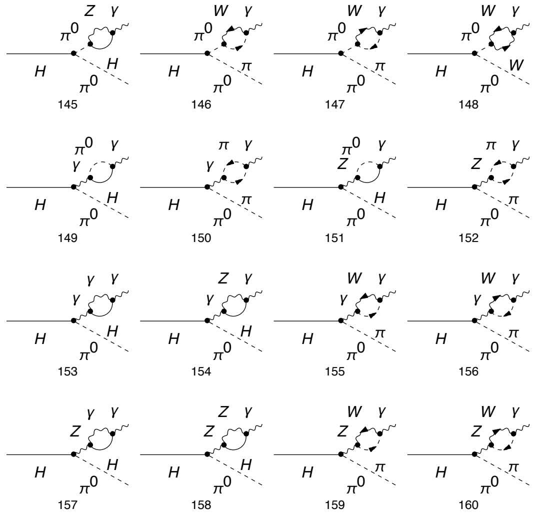


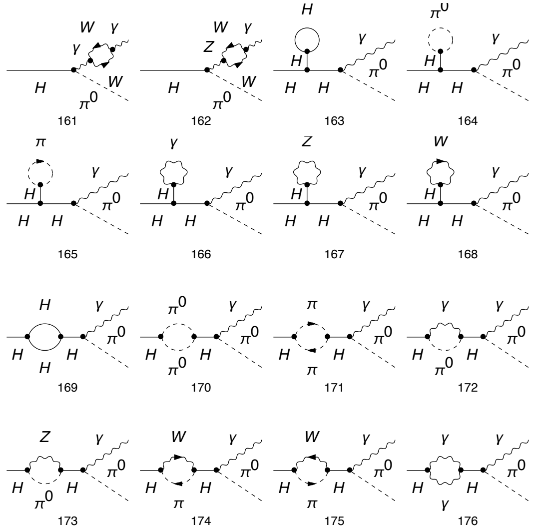


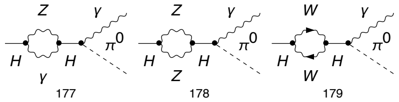


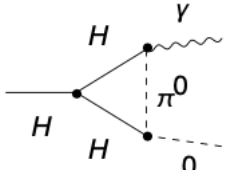



129 130 131 132
133 134 135 136
137 138 139 140
141 142 143 144


145 146 147 148
149 150 151 152
153 154 155 156
157 158 159 160

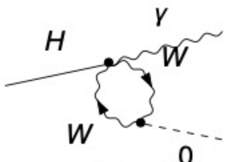

161 162 163 164
165 166 167 168
169 170 171 172
173 174 175 176


177 178 179



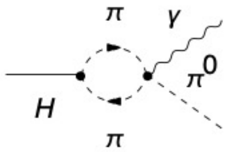
1

$$\mathcal{M}_1 = \int \frac{d^d q}{(2\pi)^d} \frac{3e\tilde{\mathcal{F}}_{3,0}\left(a c_W{}^2 v^2 + e^2 \mathcal{F}_{10,1}\right)\left(b_3 v^2 m_H^2 - 2\mathcal{F}_{10,3}\right)}{4\pi^4 c_W{}^2 v^8 \left(q^2 - m_H^2\right)} \cdot \left[\frac{-\left(k_1 \varepsilon^*_{k_1}\right)\left(k_1 q\right)}{-2\left(k_1 q\right) + q^2}\right] \cdot \left[\frac{(k_1 k_2) - (k_2 q)}{2(k_1 k_2) - 2\left(k_1 q\right) - 2\left(k_2 q\right) + q^2 - m_H^2}\right],$$



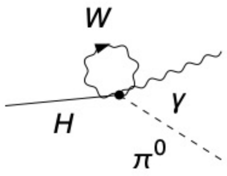
47

$$\mathcal{M}_{47} = -\int \frac{d^d q}{(2\pi)^d} \frac{e\, g_W^4 (\mathcal{F}_{2,1} + \tilde{\mathcal{F}}_{2,1})(\mathcal{F}_{3,0} + \tilde{\mathcal{F}}_{1,0})}{8\pi^4 v^2 \left(q^2 - m_W^2\right)\left[2\left(k_2 q\right) + q^2 - m_W^2\right]} \cdot \left\{2q^2\left(k_2 \varepsilon^*_{k_1}\right) + \left(k_2 q\right)\left[7\left(k_2 \varepsilon^*_{k_1}\right) + 10\left(q \varepsilon^*_{k_1}\right)\right]\right\},$$



30

$$\mathcal{M}_{30} = \int \frac{d^d q}{(2\pi)^d} \frac{a\, e\left(k_1 q + k_2 q - q^2\right)}{2\pi^4 c_W{}^2 v^4 q^2 \left[2(k_1 k_2) - 2\left(k_1 q\right) - 2\left(k_2 q\right) + q^2\right]} \cdot \left[e^2 \mathcal{F}_{10,0}\left(k_2 \varepsilon^*_{k_1}\right) + c_W{}^2 \tilde{\mathcal{F}}_{1,0}\left(k_1 \varepsilon^*_{k_1}\right)\left(k_1 k_2\right)\right],$$

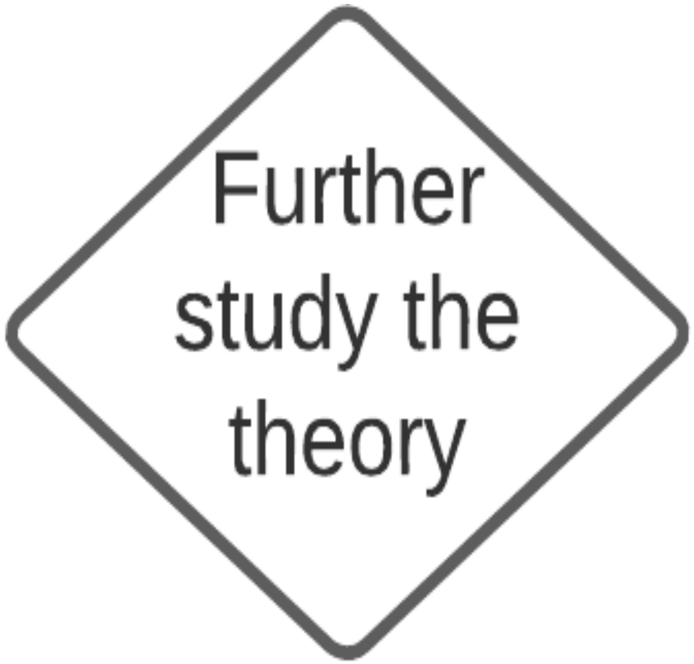


50

$$\mathcal{M}_{50} = -\int \frac{d^d q}{(2\pi)^d} \frac{3\, e\, g_W^2 (\mathcal{F}_{3,1} + \tilde{\mathcal{F}}_{1,1})\left(k_2 \varepsilon^*_{k_1}\right)}{8\pi^4 v^2 \left(q^2 - m_W^2\right)}$$

CONCLUSIONS

- Simple code for studying the EWET (HEFT) theory.
- Four external legs vertices generated for direct study of the theory up to one loop precision.
- Fast and versatile (UFO for MG5, CalcHep, …).
- Next steps: fermions, color, resonances, ChPT…



THE END

BACKUP. FeynRules.nb Extra code

```
In[ ]:= SetOptions[$FrontEnd, "ClearEvaluationQueueOnKernelQuit" → False];
        asigna opciones  interfaz                                  falso
        Quit[];
        detén núcleo del sistema
```

EWET FeynRules

```
In[ ]:= $FeynRulesPath =
          SetDirectory["/Applications/Mathematica.app/Contents/AddOns/feynrules"];
          establece directorio

In[ ]:= << FeynRules`;
         – FeynRules –

        Version: 2.3.49 ( 29 September 2021).

        Authors: A. Alloul, N. Christensen, C. Degrande, C. Duhr, B. Fuks


        Please cite:

            – Comput.Phys.Commun.185:2250–2300,2014 (arXiv:1310.1921);

            – Comput.Phys.Commun.180:1614–1641,2009 (arXiv:0806.4194).


        http://feynrules.phys.ucl.ac.be


        The FeynRules palette can be opened using the command FRPalette[].

In[ ]:= SetDirectory[NotebookDirectory[]];
        establece directoric directorio de cuaderno
        LoadModel["EWET.fr"];
Durante la evaluación de In[3]:=
        This model implementation was created by
Durante la evaluación de In[3]:=
        Javier Martínez
Durante la evaluación de In[3]:=
        Juan José Sanz Cillero
Durante la evaluación de In[3]:=
        Model Version: 1
Durante la evaluación de In[3]:=
        For more information, type ModelInformation[].
Durante la evaluación de In[3]:=

Durante la evaluación de In[3]:=
           – Loading particle classes.
Durante la evaluación de In[3]:=
           – Loading gauge group classes.
Durante la evaluación de In[3]:=
           – Loading parameter classes.
Durante la evaluación de In[3]:=

        Model EWET loaded.
```

Fields and Operators

```
In[•]:= M = epsf * {{ pi0, Sqrt[2] piC } , {Sqrt[2] piCbar, -pi0}};
UU = MatrixExp[I M / vev] // Simplify;
uu = MatrixPower[UU, 1 / 2] // Simplify;

In[•]:= UTayl = Series[UU, {vev, Infinity, 5}] // Normal ;

In[•]:= UdagTayl = FullSimplify[ConjugateTranspose[UTayl]] /. {Conjugate[pi0] → pi0,
        Conjugate[piC] → piCbar, Conjugate[piCbar] → piC} // Expand;

In[•]:= uTayl = Series[uu, {vev, Infinity, 5}] // Normal;

In[•]:= udagTayl = FullSimplify[ConjugateTranspose[uTayl]] /. {Conjugate[pi0] → pi0,
        Conjugate[piC] → piCbar, Conjugate[piCbar] → piC} // Expand;

In[•]:= What[mu_] = -epsf * gw / 2 * Sum[PauliMatrix[i] * Wi[mu, i], {i, 1, 3}];

In[•]:= Bhat[mu_] = -epsf * g1 / 2 * PauliMatrix[3] * B[mu];

In[•]:= DU[mu_] := del[UTayl, mu] - I * What[mu].UTayl + I * UTayl.Bhat[mu];

In[•]:= DUdag[mu_] := del[UdagTayl, mu] + I * UdagTayl.What[mu] - I * Bhat[mu].UdagTayl;

In[•]:= u[mu_] := Normal[Series[ -I * udagTayl.DU[mu].udagTayl, {epsf, 0, 5}]]

In[•]:= BBhat[mu_, nu_] =
      del[Bhat[nu], mu] - del[Bhat[mu], nu] - I (Bhat[mu].Bhat[nu] - Bhat[nu].Bhat[mu]);

In[•]:= WWhat[mu_, nu_] = FS[What, mu, nu] - I * (What[mu].What[nu] - What[nu].What[mu]);

In[•]:= fplus[mu_, nu_] = Normal[Series[
        udagTayl.WWhat[mu, nu].uTayl + uTayl.BBhat[mu, nu].udagTayl, {epsf, 0, 6}]] ;

In[•]:= fminus[mu_, nu_] = Normal[Series[
        udagTayl.WWhat[mu, nu].uTayl - uTayl.BBhat[mu, nu].udagTayl, {epsf, 0, 6}]];
TT = -g1 / 2 * uTayl.PauliMatrix[3].udagTayl;

In[•]:= X[mu_] = -g1 * epsf * B[mu];
```

```
In[]:= XX[mu_, nu_] = FS[X, mu, nu];
```

L2

L2 Scalar

```
In[]:= L2tr = Tr[u[mu].u[mu]] // Expand;
          traza              expande fa

In[]:= Lagr2Scalar = Normal[
                     normal
    Series[ 1 / 2 * del[epsf * H, mu] * del[epsf * H, mu] - 1 / 2 * MH^2 * epsf^2 * H^2 -
    serie
      1 / 2 * MH^2 * vev^2 * (b3 * epsf^3 * H^3 / vev^3 + b4 * epsf^4 * H^4 / vev^4 +
         b5 * epsf^5 * H^5 / vev^5 + b6 * epsf^6 * H^6 / vev^6) +
      vev^2 / 4 * L2tr + vev * epsf * H / 2 * a * L2tr + epsf^2 * H^2 / 4 * b * L2tr +
      epsf^3 * H^3 / 4 * c3u * L2tr + epsf^4 * H^4 / 4 * c4u * L2tr, {epsf, 0, 6}]];
```

L2 FS

```
In[]:= Lagr2FS = Normal[Series[ -1 / (2 * gw^2) Tr[WWhat[mu, nu].WWhat[mu, nu]] -
                 normal serie                 traza
        1 / (2 * g1^2) Tr[BBhat[mu, nu].BBhat[mu, nu]], {epsf, 0, 6}]] // Expand;
                       traza                                          expande factores
```

L4

L4 Scalar

```
In[]:= O4 = Normal[Series[Tr[u[mu].u[nu]] * Tr[u[mu].u[nu]], {epsf, 0, 6}]] // Expand;
            normal serie  traza            traza                             expande fa

In[]:= O5 = Normal[Series[Tr[u[mu].u[mu]] * Tr[u[nu].u[nu]], {epsf, 0, 6}]] // Expand;
            normal serie  traza            traza                             expande fa

In[]:= O6 = Normal[Series[1 / vev^2 * del[epsf * H, mu] *
            normal serie
        del[epsf * H, mu] * Tr[u[nu].u[nu]], {epsf, 0, 6}]] // Expand;
                            traza                         expande factores

In[]:= O7 = Normal[Series[1 / vev^2 * del[epsf * H, mu] *
            normal serie
        del[epsf * H, nu] * Tr[u[mu].u[nu]], {epsf, 0, 6}]] // Expand;
                            traza                         expande factores

In[]:= O8 = Normal[Series[1 / vev^2 * del[epsf * H, mu] * del[epsf * H, mu] *
            normal serie
        1 / vev^2 * del[epsf * H, nu]^2, {epsf, 0, 6}]] // Expand;
                                                     expande factores
```

```
In[]:= O10 = Normal[Series[Tr[TT.u[mu]] * Tr[TT.u[mu]], {epsf, 0, 6}]] // Expand;

In[]:= Lagr4Scalar =
        Normal[Series[F4n0 * O4 + F5n0 * O5 + F6n0 * O6 + F7n0 * O7 + F8n0 * O8 + F10n0 * O10 +
            (F4n1 * O4 + F5n1 * O5 + F6n1 * O6 + F7n1 * O7 + F8n1 * O8 + F10n1 * O10) * epsf * H / vev +
            (F4n2 * O4 + F5n2 * O5 + F6n2 * O6 + F7n2 * O7 + F8n2 * O8 + F10n2 * O10) *
             epsf^2 * H^2 / vev^2 + F10n3 * O10 * epsf^3 * H^3 / vev^3 +
            F10n4 * O10 * epsf^4 * H^4 / vev^4, {epsf, 0, 6}]];
```

L4 FS

P-even

```
In[]:= O1 = Normal[
          Series[1 / 4 * Tr[fplus[mu, nu].fplus[mu, nu] - fminus[mu, nu].fminus[mu, nu]],
           {epsf, 0, 6}]] // Expand;

In[]:= O2  =  Normal[
          Series[1 / 2 * Tr[fplus[mu, nu].fplus[mu, nu] + fminus[mu, nu].fminus[mu, nu]],
           {epsf, 0, 6}]] // Expand;

In[]:= O3  = Normal[Series[
           I / 2 * Tr[fplus[mu, nu].(u[mu].u[nu] - u[nu].u[mu])], {epsf, 0, 6}]] // Expand;

In[]:= O9 = Normal[Series[
           1 / vev * del[epsf * H, mu] * Tr[fminus[mu, nu].u[nu]], {epsf, 0, 6}]] // Expand;

In[]:= O11 = Normal[Series[XX[mu, nu] * XX[mu, nu], {epsf, 0, 6}]] // Expand;
```

P-odd

```
In[]:= OO1 = Normal[Series[I / 2 * Tr[fminus[mu, nu].(u[mu].u[nu] - u[nu].u[mu])],
           {epsf, 0, 6}]] // Expand;

In[]:= OO2  = Normal[Series[ Tr[fplus[mu, nu].fminus[mu, nu]], {epsf, 0, 6}]] // Expand;
```

```
In[•]:= OO3 = Normal[Series[
          1 / vev * del[epsf * H, mu] * Tr[fplus[mu, nu].u[nu]], {epsf, 0, 6}]] // Expand;

In[•]:= Lagr4FS =
        Normal[Series[F1n0 * O1 + F2n0 * O2 + F3n0 * O3 + F9n0 * O9 + F11n0 * O11 + FF1n0 * OO1 +
            FF2n0 * OO2 + FF3n0 * OO3 + (F1n1 * O1 + F2n1 * O2 + F3n1 * O3 + F9n1 * O9 + F11n1 * O11 +
               FF1n1 * OO1 + FF2n1 * OO2 + FF3n1 * OO3) * epsf * H / vev +
            (F1n2 * O1 + F2n2 * O2 + F3n2 * O3 + F9n2 * O9 + F11n2 * O11 + FF1n2 * OO1 +
               FF2n2 * OO2 + FF3n2 * OO3) * epsf ^ 2 * H ^ 2 / vev ^ 2 +
            (F1n3 * O1 + F2n3 * O2 + F3n3 * O3 + F9n3 * O9 + F11n3 * O11 + FF1n3 * OO1 +
               FF2n3 * OO2 + FF3n3 * OO3) * epsf ^ 3 * H ^ 3 / vev ^ 3 +
            (F1n4 * O1 + F2n4 * O2 + F11n4 * O11 + FF2n4 * OO2) * epsf ^ 4 *
             H ^ 4 / vev ^ 4, {epsf, 0, 6}]];
```

Lagrangian

L4 Lagrangian with up to 6 particles vertices

```
In[•]:= SixPartVertsLagr =
        Normal[Series[Lagr2Scalar + Lagr2FS + Lagr4Scalar + Lagr4FS, {epsf, 0, 6}]] /.
          {epsf → 1};

In[•]:= WriteFeynArtsOutput[SixPartVertsLagr,
        Output → "SixPartVertsLagr", CouplingRename → False, MaxParticles → 6];
```

```
 - - - FeynRules interface to FeynArts - - -
      C. Degrande C. Duhr, 2013
      Counterterms: B. Fuks, 2012
Calculating Feynman rules for L1
Starting Feynman rules calculation for L1.
Expanding the Lagrangian...
Expanding the indices over 6 cores
Neglecting all terms with more than 6 particles.
Collecting the different structures that enter the vertex.
384
  possible non-zero vertices have been found -> starting the computation:  / 384.
384 vertices obtained.
mytimecheck,after LGC
Writing FeynArts model file into directory SixPartVertsLagr
Writing FeynArts generic file on SixPartVertsLagr.gen.
```

L4 Lagrangian with up to 4 particles vertices

```
In[•]:= FourPartVertsLagr =
          Normal[Series[Lagr2Scalar + Lagr2FS + Lagr4Scalar + Lagr4FS, {epsf, 0, 4}]] /.
          ⌊normal    ⌊serie
           {epsf → 1};

In[•]:= WriteFeynArtsOutput[FourPartVertsLagr,
          Output → "FourPartVertsLagr", CouplingRename → False, MaxParticles → 4];
                                                         ⌊falso
```

```
 – – – FeynRules interface to FeynArts – – –
      C. Degrande C. Duhr, 2013
      Counterterms: B. Fuks, 2012
Calculating Feynman rules for L1
Starting Feynman rules calculation for L1.
Expanding the Lagrangian...
Expanding the indices over 6 cores
Collecting the different structures that enter the vertex.
84 possible non-zero vertices have been found -> starting the computation:  / 84.
84 vertices obtained.
mytimecheck,after LGC
Writing FeynArts model file into directory FourPartVertsLagr
Writing FeynArts generic file on FourPartVertsLagr.gen.
```

L2 Lagrangian

```
In[•]:= LOLagr = Normal[Series[Lagr2Scalar + Lagr2FS, {epsf, 0, 6}]] /. {epsf → 1};
                 ⌊normal   ⌊serie

In[•]:= WriteFeynArtsOutput[LOLagr, Output → "LOLagr",
          CouplingRename → False, MaxParticles → 6];
                           ⌊falso
```

```
- - - FeynRules interface to FeynArts - - -
      C. Degrande C. Duhr, 2013
      Counterterms: B. Fuks, 2012
Creating output directory: LOLagr
Calculating Feynman rules for L1
Starting Feynman rules calculation for L1.
Expanding the Lagrangian...
Expanding the indices over 6 cores
Collecting the different structures that enter the vertex.
169
  possible non-zero vertices have been found -> starting the computation:  / 169.
169 vertices obtained.
mytimecheck,after LGC
Writing FeynArts model file into directory LOLagr
Writing FeynArts generic file on LOLagr.gen.
```

Vertices

3 particles vertices

In[•]:=
```
ThreePartVerts =
  FeynmanRules[FourPartVertsLagr, MaxParticles → 3, MinParticles → 3]
```

```
Starting Feynman rule calculation.
Expanding the Lagrangian...
Expanding the indices over 6 cores
Neglecting all terms with less than 3 particles.
Collecting the different structures that enter the vertex.
23 possible non-zero vertices have been found -> starting the computation:  / 23.
23 vertices obtained.
```

Out[•]=

$$\Big\{\Big\{\{\{H, 1\}, \{H, 2\}, \{H, 3\}\}, -\frac{3\,i\,b3\,MH^2}{vev}\Big\},$$

$$\Big\{\{\{H, 1\}, \{pi0, 2\}, \{pi0, 3\}\}, -\frac{2\,i\,e^2\,F10n1\,p_2.p_3}{c_w^2\,vev^3} - \frac{2\,i\,a\,p_2.p_3}{vev}\Big\},$$

$$\Big\{\Big\{\{A, 1\}, \{piC, 2\}, \{piC^\dagger, 3\}\Big\},$$

$$-i\,e\,p_2^{\mu_1} + i\,e\,p_3^{\mu_1} + \frac{4\,i\,e\,F3n0\,p_3^{\mu_1}\,p_1.p_2}{vev^2} - \frac{4\,i\,e\,F3n0\,p_2^{\mu_1}\,p_1.p_3}{vev^2}\Big\},$$

$$\Big\{\Big\{\{pi0, 1\}, \{piC, 2\}, \{piC^\dagger, 3\}\Big\}, \frac{2\,e^2\,F10n0\,p_1.p_2}{c_w^2\,vev^3} - \frac{2\,e^2\,F10n0\,p_1.p_3}{c_w^2\,vev^3}\Big\},$$

4 particles vertices

```
In[•]:= ThreePartVerts =
  FeynmanRules[FourPartVertsLagr, MaxParticles → 4, MinParticles → 4]

Starting Feynman rule calculation.

Expanding the Lagrangian...

Expanding the indices over 6 cores

Collecting the different structures that enter the vertex.

61 possible non-zero vertices have been found -> starting the computation:  / 61.

61 vertices obtained.
```

Out[•]=

$$\Big\{\Big\{\{\{H,1\},\{H,2\},\{H,3\},\{H,4\}\},\; -\frac{12\,i\,b4\,MH^2}{vev^2}+\frac{8\,i\,F8n0\,p_1.p_4\,p_2.p_3}{vev^4}+\frac{8\,i\,F8n0\,p_1.p_3\,p_2.p_4}{vev^4}+\frac{8\,i\,F8n0\,p_1.p_2\,p_3.p_4}{vev^4}\Big\},$$

$$\Big\{\{\{A,1\},\{A,2\},\{piC,3\},\{piC^\dagger,4\}\},\; -\frac{8\,i\,e^2\,F1n0\,p_1^{\mu_2}\,p_2^{\mu_1}}{vev^2}-\frac{4\,i\,e^2\,F3n0\,p_1^{\mu_2}\,p_3^{\mu_1}}{vev^2}-\frac{4\,i\,e^2\,F3n0\,p_2^{\mu_1}\,p_3^{\mu_2}}{vev^2}-\frac{4\,i\,e^2\,F3n0\,p_1^{\mu_2}\,p_4^{\mu_1}}{vev^2}-$$

$$\frac{4\,i\,e^2\,F3n0\,p_2^{\mu_1}\,p_4^{\mu_2}}{vev^2}+2\,i\,e^2\,\eta_{\mu_1,\mu_2}+\frac{8\,i\,e^2\,F1n0\,\eta_{\mu_1,\mu_2}\,p_1.p_2}{vev^2}+\frac{4\,i\,e^2\,F3n0\,\eta_{\mu_1,\mu_2}\,p_1.p_3}{vev^2}+$$

$$\frac{4\,i\,e^2\,F3n0\,\eta_{\mu_1,\mu_2}\,p_1.p_4}{vev^2}+\frac{4\,i\,e^2\,F3n0\,\eta_{\mu_1,\mu_2}\,p_2.p_3}{vev^2}+\frac{4\,i\,e^2\,F3n0\,\eta_{\mu_1,\mu_2}\,p_2.p_4}{vev^2}\Big\},$$

$$\Big\{\{\{A,1\},\{pi0,2\},\{piC,3\},\{piC^\dagger,4\}\},\; -\frac{4\,e^3\,F10n0\,p_2^{\mu_1}}{c_w^2\,vev^3}+\frac{4\,e\,FF1n0\,p_3^{\mu_1}\,p_1.p_2}{vev^3}+$$

$$\frac{4\,e\,FF1n0\,p_4^{\mu_1}\,p_1.p_2}{vev^3}-\frac{4\,e\,FF1n0\,p_2^{\mu_1}\,p_1.p_3}{vev^3}-\frac{4\,e\,FF1n0\,p_2^{\mu_1}\,p_1.p_4}{vev^3}\Big\},$$

5 particles vertices

In[•]:=
```
ThreePartVerts =
  FeynmanRules[SixPartVertsLagr, MaxParticles → 5, MinParticles → 5]
```

Starting Feynman rule calculation.

Expanding the Lagrangian...

Expanding the indices over 6 cores

Collecting the different structures that enter the vertex.

110

possible non-zero vertices have been found -> starting the computation: / 110.

110 vertices obtained.

Out[•]=

$$\Big\{\Big\{\{\{H,1\},\{H,2\},\{H,3\},\{H,4\},\{H,5\}\},$$

$$-\frac{60\, i\, b5\, MH^2}{vev^3}+\frac{8\, i\, F8n1\, p_1.p_4\, p_2.p_3}{vev^5}+\frac{8\, i\, F8n1\, p_1.p_5\, p_2.p_3}{vev^5}+\frac{8\, i\, F8n1\, p_1.p_3\, p_2.p_4}{vev^5}+$$

$$\frac{8\, i\, F8n1\, p_1.p_5\, p_2.p_4}{vev^5}+\frac{8\, i\, F8n1\, p_1.p_3\, p_2.p_5}{vev^5}+\frac{8\, i\, F8n1\, p_1.p_4\, p_2.p_5}{vev^5}+$$

$$\frac{8\, i\, F8n1\, p_1.p_2\, p_3.p_4}{vev^5}+\frac{8\, i\, F8n1\, p_1.p_5\, p_3.p_4}{vev^5}+\frac{8\, i\, F8n1\, p_2.p_5\, p_3.p_4}{vev^5}+$$

$$\frac{8\, i\, F8n1\, p_1.p_2\, p_3.p_5}{vev^5}+\frac{8\, i\, F8n1\, p_1.p_4\, p_3.p_5}{vev^5}+\frac{8\, i\, F8n1\, p_2.p_4\, p_3.p_5}{vev^5}+$$

$$\frac{8\, i\, F8n1\, p_1.p_2\, p_4.p_5}{vev^5}+\frac{8\, i\, F8n1\, p_1.p_3\, p_4.p_5}{vev^5}+\frac{8\, i\, F8n1\, p_2.p_3\, p_4.p_5}{vev^5}\Big\},$$

$$\Big\{\{\{A,1\},\{A,2\},\{H,3\},\{piC,4\},\{piC^{\dagger},5\}\},-\frac{8\, i\, e^2\, F1n1\, p_1^{\mu_2}\, p_2^{\mu_1}}{vev^3}-$$

$$\frac{4\, i\, e^2\, F9n0\, p_1^{\mu_2}\, p_3^{\mu_1}}{vev^3}-\frac{4\, i\, e^2\, F9n0\, p_2^{\mu_1}\, p_3^{\mu_2}}{vev^3}-\frac{4\, i\, e^2\, F3n1\, p_1^{\mu_2}\, p_4^{\mu_1}}{vev^3}-\frac{4\, i\, e^2\, F3n1\, p_2^{\mu_1}\, p_4^{\mu_2}}{vev^3}-$$

$$\frac{4\, i\, e^2\, F3n1\, p_1^{\mu_2}\, p_5^{\mu_1}}{vev^3}-\frac{4\, i\, e^2\, F3n1\, p_2^{\mu_1}\, p_5^{\mu_2}}{vev^3}+\frac{4\, i\, a\, e^2\, \eta_{\mu_1,\mu_2}}{vev}+\frac{8\, i\, e^2\, F1n1\, \eta_{\mu_1,\mu_2}\, p_1.p_2}{vev^3}+$$

$$\frac{4\, i\, e^2\, F9n0\, \eta_{\mu_1,\mu_2}\, p_1.p_3}{vev^3}+\frac{4\, i\, e^2\, F3n1\, \eta_{\mu_1,\mu_2}\, p_1.p_4}{vev^3}+\frac{4\, i\, e^2\, F3n1\, \eta_{\mu_1,\mu_2}\, p_1.p_5}{vev^3}+$$

$$\frac{4\, i\, e^2\, F9n0\, \eta_{\mu_1,\mu_2}\, p_2.p_3}{vev^3}+\frac{4\, i\, e^2\, F3n1\, \eta_{\mu_1,\mu_2}\, p_2.p_4}{vev^3}+\frac{4\, i\, e^2\, F3n1\, \eta_{\mu_1,\mu_2}\, p_2.p_5}{vev^3}\Big\},$$

6 particles vertices

```
In[•]:= ThreePartVerts =
  FeynmanRules[SixPartVertsLagr, MaxParticles → 6, MinParticles → 6]
```

Starting Feynman rule calculation.

Expanding the Lagrangian...

Expanding the indices over 6 cores

Collecting the different structures that enter the vertex.

190
possible non-zero vertices have been found -> starting the computation: / 190.

190 vertices obtained.

Out[•]= {{{{H, 1}, {H, 2}, {H, 3}, {H, 4}, {H, 5}, {H, 6}},

$$-\frac{360\, i\, b6\, MH^2}{vev^4}+\frac{16\, i\, F8n2\, p_1.p_4\, p_2.p_3}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_5\, p_2.p_3}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_6\, p_2.p_3}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_1.p_3\, p_2.p_4}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_5\, p_2.p_4}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_6\, p_2.p_4}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_1.p_3\, p_2.p_5}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_4\, p_2.p_5}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_6\, p_2.p_5}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_1.p_3\, p_2.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_4\, p_2.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_5\, p_2.p_6}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_1.p_2\, p_3.p_4}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_5\, p_3.p_4}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_6\, p_3.p_4}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_2.p_5\, p_3.p_4}{vev^6}+\frac{16\, i\, F8n2\, p_2.p_6\, p_3.p_4}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_2\, p_3.p_5}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_1.p_4\, p_3.p_5}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_6\, p_3.p_5}{vev^6}+\frac{16\, i\, F8n2\, p_2.p_4\, p_3.p_5}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_2.p_6\, p_3.p_5}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_2\, p_3.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_4\, p_3.p_6}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_1.p_5\, p_3.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_2.p_4\, p_3.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_2.p_5\, p_3.p_6}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_1.p_2\, p_4.p_5}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_3\, p_4.p_5}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_6\, p_4.p_5}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_2.p_3\, p_4.p_5}{vev^6}+\frac{16\, i\, F8n2\, p_2.p_6\, p_4.p_5}{vev^6}+\frac{16\, i\, F8n2\, p_3.p_6\, p_4.p_5}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_1.p_2\, p_4.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_3\, p_4.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_5\, p_4.p_6}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_2.p_3\, p_4.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_2.p_5\, p_4.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_3.p_5\, p_4.p_6}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_1.p_2\, p_5.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_3\, p_5.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_1.p_4\, p_5.p_6}{vev^6}+$$
$$\frac{16\, i\, F8n2\, p_2.p_3\, p_5.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_2.p_4\, p_5.p_6}{vev^6}+\frac{16\, i\, F8n2\, p_3.p_4\, p_5.p_6}{vev^6}\Big\},$$

Hermiticity

```
In[•]:= CheckHermiticity[SixPartVertsLagr]
Checking for hermiticity by calculating the Feynman rules contained in L-HC[L].
If the lagrangian is hermitian, then the number of vertices should be zero.
Starting Feynman rule calculation.
Expanding the Lagrangian...
No vertices found.
0 vertices obtained.
The lagrangian is hermitian.
```

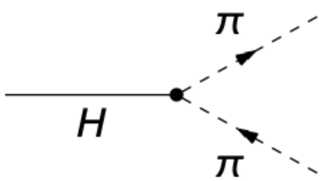
BACKUP. Extra vertices Checks

CHECKS: VERTICES

FEYNCALC

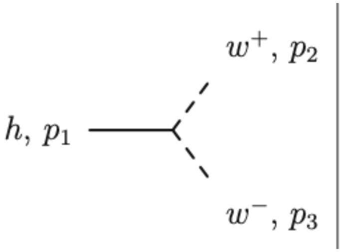
```
M = ExpandScalarProduct[FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1},
    OutgoingMomenta → {k1, k2}, List → False, ChangeDimension → 4, DropSumOver → True, SMP → True, Contract → True]]
                                   lista    falso                                   verdadero     verdadero          verdadero
```

$$-\frac{2\,a\,(\overline{k1}\cdot\overline{k2})}{vev}$$



$$= -i\frac{2a}{v}(k_1 k_2)$$

Ref. [6]



$$-\frac{2ia}{v}(p_2 p_3)$$

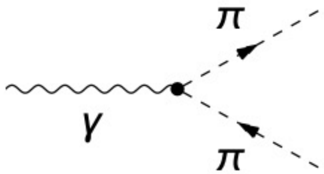
[6] R. DELGADO LÓPEZ, STUDY OF THE ELECTROWEAK SYMMETRY BREAKING SECTOR FOR THE LHC, 1ST ED., SPRINGER THESES (SPRINGER CHAM, 2017).

CHECKS: VERTICES

FEYNCALC

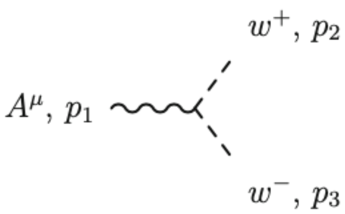
```
M = ExpandScalarProduct[FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1},
    OutgoingMomenta → {k1, k2}, List → False, ChangeDimension → 4, DropSumOver → True, SMP → True, Contract → True]]
                          |lista   |falso                                   |verdadero     |verdadero            |verdadero
```

$$-i\left(\frac{4\,i\,e\,\mathrm{F3n0}\,(\overline{k2}\cdot\overline{p1})\,(\overline{k1}\cdot\bar{\varepsilon}(p1))}{\mathrm{vev}^2}-\frac{4\,i\,e\,\mathrm{F3n0}\,(\overline{k1}\cdot\overline{p1})\,(\overline{k2}\cdot\bar{\varepsilon}(p1))}{\mathrm{vev}^2}-i\,e\,(\overline{k1}\cdot\bar{\varepsilon}(p1))+i\,e\,(\overline{k2}\cdot\bar{\varepsilon}(p1))\right)$$

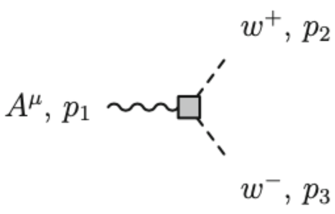


$$= ie(k_2 - k_1)_\mu + $$
$$+ i\frac{4e\mathcal{F}_{3,0}}{v^2}\left[(p_1 k_2)k_{1\mu} - (p_1 k_1)k_{2\mu}\right]$$

Ref. [6]



$$ie(p_{2\mu} - p_{3\mu})$$



$$-\frac{4ie(a_3-a_2)}{v^2}\left[(p_1p_3)p_{2\,\mu} - (p_1p_2)p_{3\,\mu}\right]$$

$$a_2 = \frac{\mathcal{F}_{3,0} - \tilde{\mathcal{F}}_{1,0}}{2},$$
$$a_3 = -\frac{\mathcal{F}_{3,0} + \tilde{\mathcal{F}}_{1,0}}{2}$$

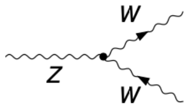
[6] R. DELGADO LÓPEZ, STUDY OF THE ELECTROWEAK SYMMETRY BREAKING SECTOR FOR THE LHC, 1ST ED., SPRINGER THESES (SPRINGER CHAM, 2017).

CHECKS: VERTICES

FEYNCALC

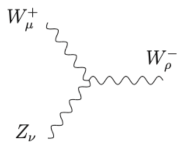
```
M = ExpandScalarProduct[FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1},
    OutgoingMomenta → {k1, k2}, List → False, ChangeDimension → 4, DropSumOver → True, SMP → True, Contract → True]] /. {SMP["e"] → g * sw}
                                 lista     falso                                 verdadero       verdadero          verdadero
```

$$-i\left(-\frac{1}{2\,\mathrm{cw}\,\mathrm{sw}^2} i\,g\,(\bar\varepsilon^*(\mathrm{k1})\cdot\bar\varepsilon(\mathrm{p1}))\,(\overline{\mathrm{p1}}\cdot\bar\varepsilon^*(\mathrm{k2}))\left(\mathrm{cw}^2\left(g^2\,\mathrm{sw}^2\,(-4\,\mathrm{F2n0}+\mathrm{F3n0}+\mathrm{FF1n0}-4\,\mathrm{FF2n0})+2\,\mathrm{sw}^2\right)+g^2\,\mathrm{sw}^4\,(2\,\mathrm{F1n0}-\mathrm{F3n0}+\mathrm{FF1n0})\right)+\right.$$
$$\frac{1}{2\,\mathrm{cw}\,\mathrm{sw}^2} i\,g\,(\overline{\mathrm{p1}}\cdot\bar\varepsilon^*(\mathrm{k1}))\,(\bar\varepsilon^*(\mathrm{k2})\cdot\bar\varepsilon(\mathrm{p1}))\left(\mathrm{cw}^2\left(g^2\,\mathrm{sw}^2\,(-4\,\mathrm{F2n0}+\mathrm{F3n0}+\mathrm{FF1n0}-4\,\mathrm{FF2n0})+2\,\mathrm{sw}^2\right)+g^2\,\mathrm{sw}^4\,(2\,\mathrm{F1n0}-\mathrm{F3n0}+\mathrm{FF1n0})\right)+$$
$$\frac{i\,g\,(\bar\varepsilon^*(\mathrm{k1})\cdot\bar\varepsilon^*(\mathrm{k2}))\,(\overline{\mathrm{k1}}\cdot\bar\varepsilon(\mathrm{p1}))\left(\mathrm{cw}^2\left(g^2\,\mathrm{sw}^2\,(-4\,\mathrm{F2n0}+\mathrm{F3n0}+\mathrm{FF1n0}-4\,\mathrm{FF2n0})+2\,\mathrm{sw}^2\right)+g^2\,\mathrm{sw}^4\,(\mathrm{F3n0}+\mathrm{FF1n0})\right)}{2\,\mathrm{cw}\,\mathrm{sw}^2}-\frac{i\,g\,(\bar\varepsilon^*(\mathrm{k1})\cdot\bar\varepsilon^*(\mathrm{k2}))\,(\overline{\mathrm{k2}}\cdot\bar\varepsilon(\mathrm{p1}))\left(\mathrm{cw}^2\left(g^2\,\mathrm{sw}^2\,(-4\,\mathrm{F2n0}+\mathrm{F3n0}+\mathrm{FF1n0}-4\,\mathrm{FF2n0})+2\,\mathrm{sw}^2\right)+g^2\,\mathrm{sw}^4\,(\mathrm{F3n0}+\mathrm{FF1n0})\right)}{2\,\mathrm{cw}\,\mathrm{sw}^2}-$$
$$\left.\frac{i\,g\,(\overline{\mathrm{k1}}\cdot\bar\varepsilon^*(\mathrm{k2}))\,(\bar\varepsilon^*(\mathrm{k1})\cdot\bar\varepsilon(\mathrm{p1}))\left(\mathrm{cw}^2\left(g^2\,\mathrm{sw}^2\,(-4\,\mathrm{F2n0}+\mathrm{F3n0}+\mathrm{FF1n0}-4\,\mathrm{FF2n0})+2\,\mathrm{sw}^2\right)+g^2\,\mathrm{sw}^4\,(\mathrm{F3n0}+\mathrm{FF1n0})\right)}{2\,\mathrm{cw}\,\mathrm{sw}^2}+\frac{i\,g\,(\overline{\mathrm{k2}}\cdot\bar\varepsilon^*(\mathrm{k1}))\,(\bar\varepsilon^*(\mathrm{k2})\cdot\bar\varepsilon(\mathrm{p1}))\left(\mathrm{cw}^2\left(g^2\,\mathrm{sw}^2\,(-4\,\mathrm{F2n0}+\mathrm{F3n0}+\mathrm{FF1n0}-4\,\mathrm{FF2n0})+2\,\mathrm{sw}^2\right)+g^2\,\mathrm{sw}^4\,(\mathrm{F3n0}+\mathrm{FF1n0})\right)}{2\,\mathrm{cw}\,\mathrm{sw}^2}\right)$$

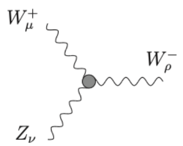


$$= -ig_W c_W\,[g_{\mu\nu}(p_1+k_1)_\rho +$$
$$-g_{\rho\nu}(p_1+k_2)_\mu - g_{\mu\rho}(k_1-k_2)_\nu] +$$
$$+i\frac{g_W^3}{c_W}\{-\frac{\mathcal{F}_{3,0}+\tilde{\mathcal{F}}_{1,0}}{2}[g_{\mu\rho}(k_2-k_1)_\nu +$$
$$+g_{\mu\nu}(c_W^2 p_1 + k_1)_\rho + g_{\nu\rho}(-k_2 - c_W^2 p_1)_\mu] +$$
$$+s_W^2\left[\mathcal{F}_{1,0}-\frac{\mathcal{F}_{3,0}-\tilde{\mathcal{F}}_{1,0}}{2}\right](g_{\nu\rho}p_{1\mu}-g_{\mu\nu}p_{1\rho})+$$
$$+2c_W^2(\mathcal{F}_{2,0}-\tilde{\mathcal{F}}_{2,0})\,[g_{\mu\rho}(k_2-k_1)_\nu$$
$$+g_{\mu\nu}(p_1+k_1)_\rho - g_{\nu\rho}(p_1+k_2)_\mu]\}$$

Ref. [7]



$$V^{\mathrm{SM}}_{W_\mu^+ W_\rho^- Z_\nu} = igc_{\mathrm{w}}\left[g_{\mu\nu}(p_0-p_+)_\rho + g_{\nu\rho}(p_- - p_0)_\mu + g_{\mu\rho}(p_+ - p_-)_\nu\right]$$



$$V^{\mathrm{EChL}}_{W_\mu^+ W_\rho^- Z_\nu} = V^{\mathrm{SM}}_{W_\mu^+ W_\rho^- Z_\nu} - \frac{ig^3}{c_{\mathrm{w}}}\Big\{a_3\left[g_{\mu\rho}(p_+-p_-)_\nu + g_{\mu\nu}(c_{\mathrm{w}}^2 p_0 - p_+)_\rho\right.$$
$$\left.+g_{\nu\rho}(p_- - c_{\mathrm{w}}^2 p_0)_\mu\right] + s_{\mathrm{w}}^2\,(a_1-a_2)\left[p_{0\mu}g_{\nu\rho} - p_{0\rho}g_{\mu\nu}\right]\Big\}$$

$$a_i = \mathcal{F}_{i,0} \quad \text{for} \quad i = 1,4,5$$
$$a_2 = \frac{\mathcal{F}_{3,0}-\tilde{\mathcal{F}}_{1,0}}{2},$$
$$a_3 = -\frac{\mathcal{F}_{3,0}+\tilde{\mathcal{F}}_{1,0}}{2}$$

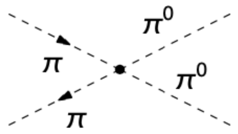
[7] C. GARCIA-GARCIA, NEW PHYSICS SIGNALS OF THE ELECTROWEAK CHIRAL LAGRANGIAN IN VECTOR BOSON SCATTERING AT THE LHC (2020).

CHECKS: VERTICES

FEYNCALC

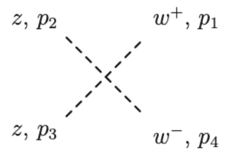
```
M = ExpandScalarProduct[FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1, p2}, OutgoingMomenta → {k1, k2}, List → False, ChangeDimension → 4,
                                                                                                                   lista    falso
    DropSumOver → True, SMP → True, Contract → True]]
                 verdadero    verdadero         verdadero
```

$$-i\left(\frac{2\,i\,(\overline{k1}\cdot\overline{k2})\,(\text{cw}^2\,\text{vev}^2+8\,e^2\,\text{F10n0})}{3\,\text{cw}^2\,\text{vev}^4}+\frac{i\,(\overline{k1}\cdot\overline{p1})\,(\text{cw}^2\,\text{vev}^2+4\,e^2\,\text{F10n0})}{3\,\text{cw}^2\,\text{vev}^4}+\frac{i\,(\overline{k1}\cdot\overline{p2})\,(\text{cw}^2\,\text{vev}^2+4\,e^2\,\text{F10n0})}{3\,\text{cw}^2\,\text{vev}^4}+\frac{i\,(\overline{k2}\cdot\overline{p1})\,(\text{cw}^2\,\text{vev}^2+4\,e^2\,\text{F10n0})}{3\,\text{cw}^2\,\text{vev}^4}+\frac{i\,(\overline{k2}\cdot\overline{p2})\,(\text{cw}^2\,\text{vev}^2+4\,e^2\,\text{F10n0})}{3\,\text{cw}^2\,\text{vev}^4}+\frac{16\,i\,\text{F4n0}\,(\overline{k1}\cdot\overline{p2})\,(\overline{k2}\cdot\overline{p1})}{\text{vev}^4}+\frac{16\,i\,\text{F4n0}\,(\overline{k1}\cdot\overline{p1})\,(\overline{k2}\cdot\overline{p2})}{\text{vev}^4}+\frac{32\,i\,\text{F5n0}\,(\overline{k1}\cdot\overline{k2})\,(\overline{p1}\cdot\overline{p2})}{\text{vev}^4}+\frac{2\,i\,(\overline{p1}\cdot\overline{p2})}{3\,\text{vev}^2}\right)$$

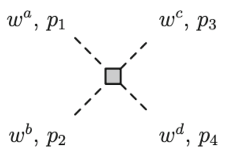


$$= \frac{i}{3v^2}\{2[(k_1k_2)+(p_1p_2)]+(p_1+p_2)^2\}+$$
$$+i\frac{16}{v^2}\{\mathcal{F}_{4,0}[(k_1p_2)(k_2p_1)+(k_1p_1)(k_2p_2)]+$$
$$+2\mathcal{F}_{5,0}(k_1k_2)(p_1p_2)\}+$$
$$+i\frac{4e^2\mathcal{F}_{10,0}}{3v^4}[4(k_1k_2)+(p_1+p_2)^2]$$

Ref. [7]



$$\frac{i}{3v^2}[2(p_1p_4+p_2p_3)+(p_1+p_4)^2]$$



$$\frac{16ia_4}{v^4}\{[(p_1p_3)(p_2p_4)+(p_1p_4)(p_2p_3)]\delta_{a,b}\delta_{c,d} +[(p_1p_2)(p_3p_4)+(p_1p_4)(p_2p_3)]\delta_{a,c}\delta_{b,d} +[(p_1p_2)(p_3p_4)+(p_1p_3)(p_2p_4)]\delta_{a,d}\delta_{b,c}\}$$
$$+\frac{32ia_5}{v^4}\{[(p_1p_2)(p_3p_4)]\delta_{a,b}\delta_{c,d} +[(p_1p_3)(p_2p_4)]\delta_{a,c}\delta_{b,d}+[(p_1p_4)(p_2p_3)]\delta_{a,d}\delta_{b,c}\}$$

$a_i = \mathcal{F}_{i,0}$ for $i = 1, 4, 5$

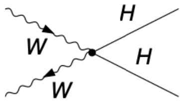
[6] R. DELGADO LÓPEZ, STUDY OF THE ELECTROWEAK SYMMETRY BREAKING SECTOR FOR THE LHC, 1ST ED., SPRINGER THESES (SPRINGER CHAM, 2017).

CHECKS: VERTICES

FEYNCALC

```
M = ExpandScalarProduct[FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1, p2}, OutgoingMomenta → {k1, k2}, List → False, ChangeDimension → 4,
    DropSumOver → True, SMP → True, Contract → True]]
```

$$-i\left(\frac{i\,b\,e^2\,(\bar\varepsilon(p1)\cdot\bar\varepsilon(p2))}{2\,sw^2}+\frac{4\,i\,e^2\,(F2n2+FF2n2)\,(\overline{p1}\cdot\bar\varepsilon(p2))\,(\overline{p2}\cdot\bar\varepsilon(p1))}{sw^2\,vev^2}-\frac{4\,i\,e^2\,(F2n2+FF2n2)\,(\overline{p1}\cdot\overline{p2})\,(\bar\varepsilon(p1)\cdot\bar\varepsilon(p2))}{sw^2\,vev^2}-\frac{2\,i\,e^2\,F6n0\,(\overline{k1}\cdot\overline{k2})\,(\bar\varepsilon(p1)\cdot\bar\varepsilon(p2))}{sw^2\,vev^2}-\frac{i\,e^2\,F7n0\,(\overline{k1}\cdot\bar\varepsilon(p2))\,(\overline{k2}\cdot\bar\varepsilon(p1))}{sw^2\,vev^2}-\frac{i\,e^2\,F7n0\,(\overline{k1}\cdot\bar\varepsilon(p1))\,(\overline{k2}\cdot\bar\varepsilon(p2))}{sw^2\,vev^2}+\frac{i\,e^2\,(F9n1+FF3n1)\,(\overline{p1}\cdot\bar\varepsilon(p2))\,(\overline{k1}\cdot\bar\varepsilon(p1)+\overline{k2}\cdot\bar\varepsilon(p1))}{2\,sw^2\,vev^2}+\frac{i\,e^2\,(F9n1+FF3n1)\,(\overline{p2}\cdot\bar\varepsilon(p1))\,(\overline{k1}\cdot\bar\varepsilon(p2)+\overline{k2}\cdot\bar\varepsilon(p2))}{2\,sw^2\,vev^2}-\frac{i\,e^2\,(F9n1+FF3n1)\,(\bar\varepsilon(p1)\cdot\bar\varepsilon(p2))\,(\overline{k1}\cdot\overline{p1}+\overline{k1}\cdot\overline{p2}+\overline{k2}\cdot\overline{p1}+\overline{k2}\cdot\overline{p2})}{2\,sw^2\,vev^2}\right)$$



$$= i\frac{b g_W^2}{2} g_{\mu\nu} +$$

$$-i\frac{2 g_W^2 \mathcal{F}_{6,0}}{v^2}(k_1 k_2) g_{\mu\nu} +$$

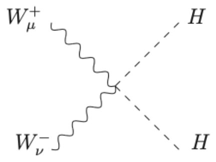
$$-i\frac{g_W^2 \mathcal{F}_{7,0}}{v^2}(k_{1\nu} k_{2\mu} + k_{1\mu} k_{2\nu}) +$$

$$+i\frac{g_W^2(\mathcal{F}_{9,1} + \tilde{\mathcal{F}}_{3,1})}{2v^2}[p_{1\nu}(k_1 + k_2)_\mu +$$

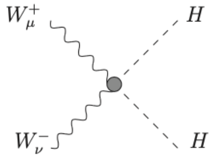
$$+p_{2\mu}(k_1 + k_2)_\nu - (p_1 + p_2)^2 g_{\mu\nu}] +$$

$$+i\frac{4 g_W^2(\mathcal{F}_{2,2} + \tilde{\mathcal{F}}_{2,2})}{v^2}[p_{1\nu} p_{2\mu} - (p_1 p_2) g_{\mu\nu}]$$

Ref. [7]



$$V^{\rm SM}_{W^+_\mu W^-_\nu HH} = \frac{ig^2}{2} g_{\mu\nu}$$



$$V^{\rm SM}_{W^+_\mu W^-_\nu HH} = V^{\rm SM}_{W^+_\mu W^-_\nu HH} + \frac{ig^2}{2}(b-1) g_{\mu\nu}$$

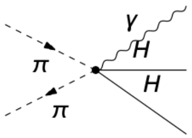
[7] C. GARCIA-GARCIA, NEW PHYSICS SIGNALS OF THE ELECTROWEAK CHIRAL LAGRANGIAN IN VECTOR BOSON SCATTERING AT THE LHC (2020).

CHECKS:VERTICES

FEYNCALC

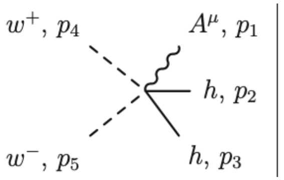
```
M = ExpandScalarProduct[FCFAConvert[CreateFeynAmp[diags], IncomingMomenta → {p1, p2},
    OutgoingMomenta → {k1, k2, k3}, List → False, ChangeDimension → 4, DropSumOver → True, SMP → True, Contract → True]] /. {b → 0, F6n0 → 0, F7n0 → 0, F9n1 → 0}
                                     lista    falso                                          verdadero        verdadero        verdadero
```

$$-i\left(\frac{8\, i\, e\, \text{F3n2}\,(\overline{\text{k1}}\cdot\overline{\text{p2}})\,(\overline{\text{p1}}\cdot\bar{\varepsilon}^{*}(\text{k1}))}{\text{vev}^4}-\frac{8\, i\, e\, \text{F3n2}\,(\overline{\text{k1}}\cdot\overline{\text{p1}})\,(\overline{\text{p2}}\cdot\bar{\varepsilon}^{*}(\text{k1}))}{\text{vev}^4}\right)$$



$$
\begin{aligned}
&= i\frac{2be}{v^2}(p_2-p_1)_\mu +\\
&+i\frac{8e\mathcal{F}_{6,0}}{v^4}(k_2k_3)(p_1-p_2)_\mu +\\
&+i\frac{4e\mathcal{F}_{7,0}}{v^4}[k_3(p_1-p_2)k_{2\mu} +\\
&+k_2(p_1-p_2)k_{3\mu}]+\\
&+i\frac{2e\mathcal{F}_{9,1}}{v^4}[k_1(p_1-p_2)(k_2+k_3)_\mu +\\
&-k_1(k_2+k_3)(p_1-p_2)_\mu]+\\
&+i\frac{8e\mathcal{F}_{3,2}}{v^4}[(k_1p_2)p_{1\mu}-(k_1p_1)p_{2\mu}]
\end{aligned}
$$

Ref. [7]



$$\frac{2ibe}{v^2}(p_{4\mu}-p_{5\mu})$$

[6] R. DELGADO LÓPEZ, STUDY OF THE ELECTROWEAK SYMMETRY BREAKING SECTOR FOR THE LHC, 1ST ED., SPRINGER THESES (SPRINGER CHAM, 2017).