```
In[•]:= (*  F[1, {0}] = electron neutrino,
F[1, {1}] = muon neutrino, F[1, {2}] = tau neutrino,
    F[2, {0}] = electron, F[2, {1}] = muon, F[2, {2}] = tau,
    F[3, {0}] = up, F[3, {1}] = charm, F[3, {2}] = top,
    F[4, {0}] = down, F[4, {1}] = strange, F[4, {2}] = bottom,
    V[1] = photon, V[2] = Z, V[3] = W-, S[1] = H *)
$LoadAddOns = {"FeynArts"};
<< FeynCalc`
$FAVerbose = 0;

MakeBoxes[p1, TraditionalForm] := "\!\(\*SubscriptBox[\(p\), \(1\)]\)";
MakeBoxes[p2, TraditionalForm] := "\!\(\*SubscriptBox[\(p\), \(2\)]\)";
topology = CreateTopologies[0, 1 → 2];
```

**FeynCalc** 10.0.0 (dev version). For help, use the online documentation, visit the forum and have a look at the supplied examples. The PDF-version of the manual can be downloaded here.

If you use FeynCalc in your research, please evaluate FeynCalcHowToCite[] to learn how to cite this software.

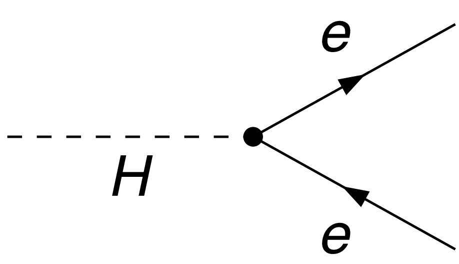
*Please keep in mind that the proper academic attribution of our work is crucial to ensure the future development of this package*!

**FeynArts** 3.12 (24 May 2024) 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[∘]:=
```
(* SM: H → lept lept *)
feynman = InsertFields[topology,
   {S[1]} → {F[2, {1}], -F[2, {1}]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_H"] ^ 2;
SP[p1, p1] = SMP["m_e"] ^ 2;
SP[p2, p2] = SMP["m_e"] ^ 2;
SP[p1, p2] = (SMP["m_H"] ^ 2 - 2 SMP["m_e"] ^ 2) / 2;
squareamplitude[0] = (amplitude[0] (ComplexConjugate[amplitude[0]])) //
     FeynAmpDenominatorExplicit //
    FermionSpinSum[#] & // DiracSimplify // Simplify
v
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```




Out[∘]=

$$i\,(\varphi(\overline{p_1}, m_e)).\left(-\frac{i\,\mathrm{e}\,m_e}{2\,m_W\,(\sin(\theta_W))}\right).(\varphi(-\overline{p_2}, m_e))$$

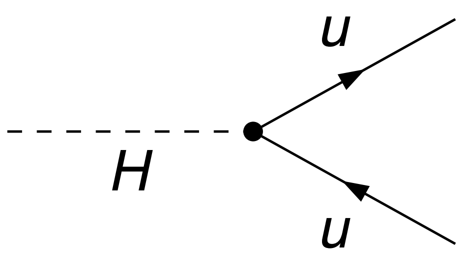
Out[∘]=

$$-\frac{\mathrm{e}^2\left(4\,m_e^4 - m_e^2\,m_H^2\right)}{2\,m_W^2\,(\sin(\theta_W))^2}$$

Out[∘]=

$$v$$

In[ ]:=
```
(* SM: H → quark quark *)
feynman = InsertFields[topology,
   {S[1]} → {F[3, {1}], -F[3, {1}]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_H"]^2;
SP[p1, p1] = SMP["m_u"]^2;
SP[p2, p2] = SMP["m_u"]^2;
SP[p1, p2] = (SMP["m_H"]^2 - 2 SMP["m_u"]^2) / 2;
squareamplitude2[0] = (amplitude[0] (ComplexConjugate[amplitude[0]])) //
      FeynAmpDenominatorExplicit // FermionSpinSum[#] & //
    DiracSimplify // Simplify // SUNSimplify
masslesssquareamplitude[0] =
 squareamplitude[0] // ReplaceAll[#, {SMP["m_u"] → 0}] & // Simplify
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```




Out[ ]=

$$i\,(\varphi(\overline{p_1}, m_u)).\left(-\frac{i\,\mathrm{e}\, m_u\, \delta_{\mathrm{Col2\,Col3}}}{2\, m_W\, (\sin(\theta_W))}\right).(\varphi(-\overline{p_2}, m_u))$$

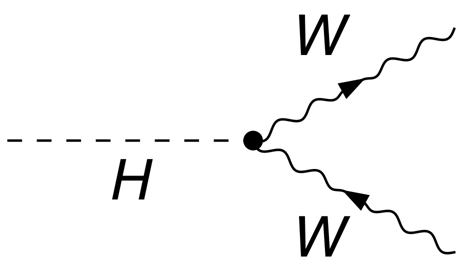
Out[ ]=

$$\frac{\mathrm{e}^2\, C_A\, m_u^2\, (m_H^2 - 4\, m_u^2)}{2\, m_W^2\, (\sin(\theta_W))^2}$$

Out[ ]=

$$-\frac{\mathrm{e}^2\, (4\, m_e^4 - m_e^2\, m_H^2)}{2\, m_W^2\, (\sin(\theta_W))^2}$$

In[ ]:=
```
(* SM: H → W- W+ *)
feynman =
  InsertFields[topology, {S[1]} → {V[3], -V[3]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_H"]^2;
SP[p1, p1] = SMP["m_W"]^2;
SP[p2, p2] = SMP["m_W"]^2;
SP[p1, p2] = (SMP["m_H"]^2 - 2 SMP["m_W"]^2) / 2;
squareamplitude[0] = (amplitude3[0] (ComplexConjugate[amplitude[0]])) //
     FeynAmpDenominatorExplicit // DoPolarizationSums[#, p1] & //
   DoPolarizationSums[#, p2] & // Simplify
(* output = feynman diagrams, amplitude, squared amplitude *)
```




Out[ ]=

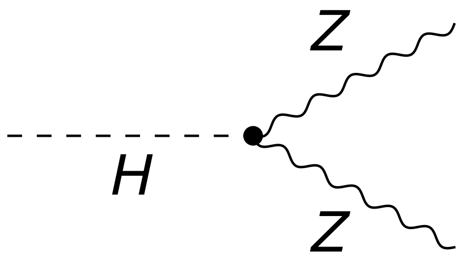
$$\frac{e\, m_W\, (\overline{\varepsilon}^*(p_1) \cdot \overline{\varepsilon}^*(p_2))}{\sin(\theta_W)}$$

DoPolarizationSums : Error ! DoPolarizationSums has encountered a fatal problem and must abort the computation. The problem reads: Polarization vectors do not seem to appear in a proper way in the expression.

Out[ ]=

$Aborted

In[ ]:=
```
(* SM: H → Z Z *)
feynman =
  InsertFields[topology, {S[1]} → {V[2], V[2]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_H"] ^ 2;
SP[p1, p1] = SMP["m_Z"] ^ 2;
SP[p2, p2] = SMP["m_Z"] ^ 2;
SP[p1, p2] = (SMP["m_H"] ^ 2 - 2 SMP["m_Z"] ^ 2) / 2;
squareamplitude[0] = (amplitude[0] (ComplexConjugate[amplitude[0]])) //
     FeynAmpDenominatorExplicit // DoPolarizationSums[#, p1] & //
   DoPolarizationSums[#, p2] & // Simplify
(* output = feynman diagrams, amplitude, squared amplitude *)
```



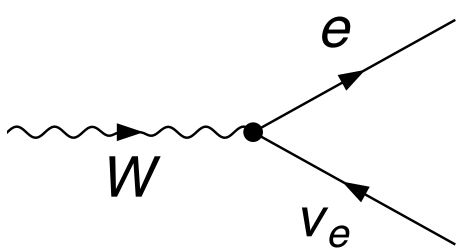

Out[ ]=

$$\frac{\mathrm{e}\, m_W\, (\overline{\varepsilon}^*(p_1)\cdot\overline{\varepsilon}^*(p_2))}{(\cos(\theta_W))^2\,(\sin(\theta_W))}$$

Out[ ]=

$$\frac{\mathrm{e}^2\, m_W^2 \left(-4\, m_H^2\, m_Z^2 + m_H^4 + 12\, m_Z^4\right)}{4\, m_Z^4\,(\cos(\theta_W))^4\,(\sin(\theta_W))^2}$$

In[ ]:=
```
(* SM: W- → e- nu *)
feynman = InsertFields[topology,
   {V[3]} → {F[2, {1}], -F[1, {1}]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_W"] ^ 2;
SP[p1, p1] = SMP["m_e"] ^ 2;
SP[p2, p2] = 0;
SP[p1, p2] = (SMP["m_W"] ^ 2 - SMP["m_e"] ^ 2) / 2;
SP[p, p1] = SP[p1, p1] + SP[p2, p1];
SP[p, p2] = SP[p1, p2] + SP[p2, p2];
squareamplitude[0] = (amplitude[0] (ComplexConjugate[amplitude[0]])) //
      FeynAmpDenominatorExplicit // FermionSpinSum[#] & // DiracSimplify //
   DoPolarizationSums[#, p, ExtraFactor → 1 / 3] & // Simplify
masslesssquareamplitude[0] =
 squareamplitude[0] // ReplaceAll[#, {SMP["m_e"] → 0}] & // Simplify
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```




Out[ ]=

$$-\frac{\mathrm{e}\,(\varphi(\overline{p_1}, m_e)).(\overline{\gamma}\cdot\overline{\varepsilon}(p)).\overline{\gamma}^7.(\varphi(-\overline{p_2}))}{\sqrt{2}\,(\sin(\theta_W))}$$

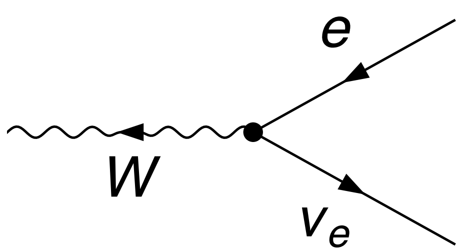
Out[ ]=

$$-\frac{\mathrm{e}^2\left(m_e^2\, m_W^2 + m_e^4 - 2\, m_W^4\right)}{6\, m_W^2\,(\sin(\theta_W))^2}$$

Out[ ]=

$$\frac{\mathrm{e}^2\, m_W^2}{3\,(\sin(\theta_W))^2}$$

In[∘]:=
```
(* SM: W+ → e+ nu *)
feynman = InsertFields[topology,
   {-V[3]} → {-F[2, {1}], F[1, {1}]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_W"] ^ 2;
SP[p1, p1] = SMP["m_e"] ^ 2;
SP[p2, p2] = 0;
SP[p1, p2] = (SMP["m_W"] ^ 2 - SMP["m_e"] ^ 2) / 2;
SP[p, p1] = SP[p1, p1] + SP[p2, p1];
SP[p, p2] = SP[p1, p2] + SP[p2, p2];
squareamplitude[0] = (amplitude[0] (ComplexConjugate[amplitude[0]])) //
      FeynAmpDenominatorExplicit // FermionSpinSum[#] & // DiracSimplify //
   DoPolarizationSums[#, p, ExtraFactor → 1 / 3] & // Simplify
masslesssquareamplitude[0] =
 squareamplitude[0] // ReplaceAll[#, {SMP["m_e"] → 0}] & // Simplify
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```




Out[∘]=

$$\frac{\mathrm{e}\,(\varphi(\overline{p_2})).(\overline{\gamma}\cdot\overline{\varepsilon}(p)).\overline{\gamma}^7.(\varphi(-\overline{p_1}, m_e))}{\sqrt{2}\,(\sin(\theta_W))}$$

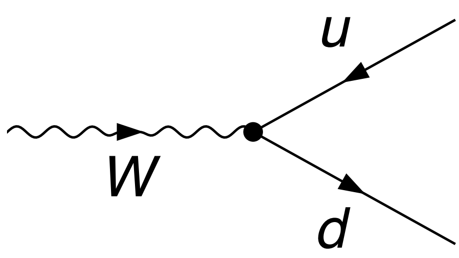
Out[∘]=

$$-\frac{\mathrm{e}^2\left(m_e^2\,m_W^2+m_e^4-2\,m_W^4\right)}{6\,m_W^2\,(\sin(\theta_W))^2}$$

Out[∘]=

$$\frac{\mathrm{e}^2\,m_W^2}{3\,(\sin(\theta_W))^2}$$

In[ ]:=
```
(* SM: W- → d antiu *)
feynman = InsertFields[topology,
   {V[3]} → {-F[3, {1}], F[4, {1}]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_W"] ^ 2;
SP[p1, p1] = SMP["m_u"] ^ 2;
SP[p2, p2] = SMP["m_d"] ^ 2;
SP[p1, p2] = (SMP["m_W"] ^ 2 - SMP["m_u"] ^ 2 - SMP["m_d"] ^ 2) / 2;
SP[p, p1] = SP[p1, p1] + SP[p2, p1];
SP[p, p2] = SP[p1, p2] + SP[p2, p2];
squareamplitude[0] =
 (amplitude[0] (ComplexConjugate[amplitude[0]])) // SUNSimplify //
    FermionSpinSum // DiracSimplify //
   DoPolarizationSums[#, p, ExtraFactor → 1 / 3] & // Simplify
masslesssquareamplitude[0] = squareamplitude[0] //
   ReplaceAll[#, {SMP["m_u"] → 0, SMP["m_d"] → 0}] & // Simplify
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```




Out[ ]=

$$\frac{\mathrm{e}\,\delta_{\mathrm{Col2\,Col3}}\,(\varphi(\overline{p_2}, m_d)).(\overline{\gamma}\cdot\overline{\varepsilon}(p)).\overline{\gamma}^7.(\varphi(-\overline{p_1}, m_u))}{\sqrt{2}\,(\sin(\theta_W))}$$

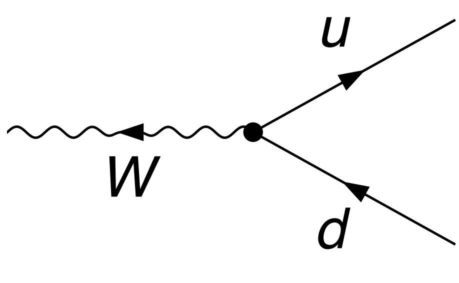
Out[ ]=

$$-\frac{\mathrm{e}^2\, C_A \left(m_d^2 \left(m_W^2 - 2\, m_u^2\right) + m_d^4 + m_u^2\, m_W^2 + m_u^4 - 2\, m_W^4\right)}{6\, m_W^2\, (\sin(\theta_W))^2}$$

Out[ ]=

$$\frac{\mathrm{e}^2\, C_A\, m_W^2}{3\,(\sin(\theta_W))^2}$$

In[ ]:=
```
(* SM: W+ → u antid *)
feynman = InsertFields[topology,
   {-V[3]} → {F[3, {1}], -F[4, {1}]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_W"] ^ 2;
SP[p1, p1] = SMP["m_u"] ^ 2;
SP[p2, p2] = SMP["m_d"] ^ 2;
SP[p1, p2] = (SMP["m_W"] ^ 2 - SMP["m_u"] ^ 2 - SMP["m_d"] ^ 2) / 2;
SP[p, p1] = SP[p1, p1] + SP[p2, p1];
SP[p, p2] = SP[p1, p2] + SP[p2, p2];
squareamplitude[0] =
 (amplitude[0] (ComplexConjugate[amplitude[0]])) // SUNSimplify //
     FermionSpinSum // DiracSimplify //
   DoPolarizationSums[#, p, ExtraFactor → 1 / 3] & // Simplify
masslesssquareamplitude[0] = squareamplitude[0] //
   ReplaceAll[#, {SMP["m_u"] → 0, SMP["m_d"] → 0}] & // Simplify
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```




Out[ ]=

$$-\frac{\mathrm{e}\,\delta_{\mathrm{Col2\,Col3}}\,(\varphi(\overline{p_1}, m_u)).(\overline{\gamma}\cdot\overline{\varepsilon}(p)).\overline{\gamma}^7.(\varphi(-\overline{p_2}, m_d))}{\sqrt{2}\,(\sin(\theta_W))}$$

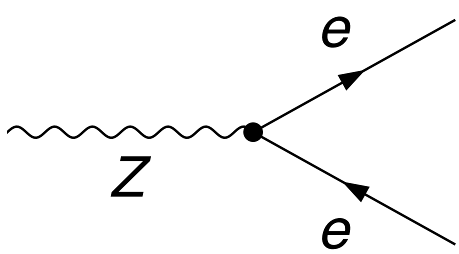
Out[ ]=

$$-\frac{\mathrm{e}^2\,C_A\left(m_d^2\left(m_W^2-2\,m_u^2\right)+m_d^4+m_u^2\,m_W^2+m_u^4-2\,m_W^4\right)}{6\,m_W^2\,(\sin(\theta_W))^2}$$

Out[ ]=

$$\frac{\mathrm{e}^2\,C_A\,m_W^2}{3\,(\sin(\theta_W))^2}$$

In[ ]:=
```
(* SM: Z → e- e+ *)
feynman = InsertFields[topology,
   {V[2]} → {F[2, {1}], -F[2, {1}]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_Z"] ^ 2;
SP[p1, p1] = SMP["m_e"] ^ 2;
SP[p2, p2] = SMP["m_e"] ^ 2;
SP[p1, p2] = (SMP["m_Z"] ^ 2 - 2 SMP["m_e"] ^ 2) / 2;
SP[p, p1] = SP[p1, p1] + SP[p2, p1];
SP[p, p2] = SP[p1, p2] + SP[p2, p2];
squareamplitude[0] = (amplitude[0] (ComplexConjugate[amplitude[0]])) //
      FeynAmpDenominatorExplicit // FermionSpinSum[#] & // DiracSimplify //
   DoPolarizationSums[#, p, ExtraFactor → 1 / 3] & // Simplify
masslesssquareamplitude[0] =
 squareamplitude[0] // ReplaceAll[#, {SMP["m_e"] → 0}] & // Simplify
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```




Out[ ]=

$$i\,(\varphi(\overline{p_1}, m_e)).\left(\frac{i\,\mathrm{e}\,(\sin(\theta_W))\,(\overline{\gamma}\cdot\overline{\varepsilon}(p)).\overline{\gamma}^6}{\cos(\theta_W)} + \frac{i\,\mathrm{e}\left((\sin(\theta_W))^2 - \frac{1}{2}\right)(\overline{\gamma}\cdot\overline{\varepsilon}(p)).\overline{\gamma}^7}{(\cos(\theta_W))\,(\sin(\theta_W))}\right).(\varphi(-\overline{p_2}, m_e))$$

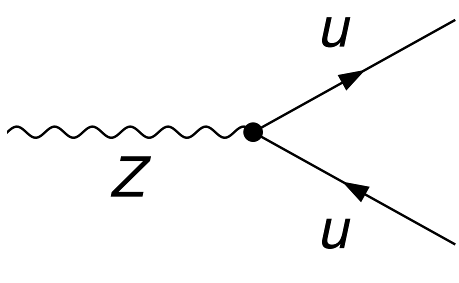
Out[ ]=

$$\frac{\mathrm{e}^2\left(m_e^2\left(16\,(\sin(\theta_W))^4 - 8\,(\sin(\theta_W))^2 - 1\right) + m_Z^2\left(8\,(\sin(\theta_W))^4 - 4\,(\sin(\theta_W))^2 + 1\right)\right)}{6\,(\cos(\theta_W))^2\,(\sin(\theta_W))^2}$$

Out[ ]=

$$\frac{\mathrm{e}^2\, m_Z^2\left(8\,(\sin(\theta_W))^4 - 4\,(\sin(\theta_W))^2 + 1\right)}{6\,(\cos(\theta_W))^2\,(\sin(\theta_W))^2}$$

In[ ]:=
```
(* SM: Z → u antiu *)
feynman = InsertFields[topology,
   {V[2]} → {F[3, {1}], -F[3, {1}]}, InsertionLevel → {Classes}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] = FCFAConvert[CreateFeynAmp[feynman], IncomingMomenta → {p},
  OutgoingMomenta → {p1, p2}, UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True, Contract → True]
FCClearScalarProducts[];
SP[p, p] = SMP["m_Z"] ^ 2;
SP[p1, p1] = SMP["m_u"] ^ 2;
SP[p2, p2] = SMP["m_u"] ^ 2;
SP[p1, p2] = (SMP["m_Z"] ^ 2 - 2 SMP["m_u"] ^ 2) / 2;
SP[p, p1] = SP[p1, p1] + SP[p2, p1];
SP[p, p2] = SP[p1, p2] + SP[p2, p2];
squareamplitude[0] =
 (amplitude[0] (ComplexConjugate[amplitude[0]])) // SUNSimplify //
    FermionSpinSum // DiracSimplify //
   DoPolarizationSums[#, p, ExtraFactor → 1 / 3] & // Simplify
masslesssquareamplitude[0] =
 squareamplitude[0] // ReplaceAll[#, {SMP["m_u"] → 0}] & // Simplify
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```




Out[ ]=

$$i\,(\varphi(\overline{p_1}, m_u)).\left(\frac{i\,\mathrm{e}\,\delta_{\mathrm{Col2\,Col3}}\left(\frac{1}{2}-\frac{2}{3}\,(\sin(\theta_W))^2\right)(\overline{\gamma}\cdot\overline{\varepsilon}(p)).\overline{\gamma}^7}{(\cos(\theta_W))\,(\sin(\theta_W))}-\frac{2\,i\,\mathrm{e}\,\delta_{\mathrm{Col2\,Col3}}\,(\sin(\theta_W))\,(\overline{\gamma}\cdot\overline{\varepsilon}(p)).\overline{\gamma}^6}{3\,(\cos(\theta_W))}\right).(\varphi(-\overline{p_2}, m_u))$$

Out[ ]=

$$\frac{\mathrm{e}^2\,C_A\left(m_u^2\left(64\,(\sin(\theta_W))^4-48\,(\sin(\theta_W))^2-9\right)+m_Z^2\left(32\,(\sin(\theta_W))^4-24\,(\sin(\theta_W))^2+9\right)\right)}{54\,(\cos(\theta_W))^2\,(\sin(\theta_W))^2}$$

Out[ ]=

$$\frac{\mathrm{e}^2\,C_A\,m_Z^2\left(32\,(\sin(\theta_W))^4-24\,(\sin(\theta_W))^2+9\right)}{54\,(\cos(\theta_W))^2\,(\sin(\theta_W))^2}$$

In[ ]:=
```
Print["\tCPU Time used: ", Round[N[TimeUsed[], 4], 0.001], " s."];
```

CPU Time used: 4.122 s.

In[ ]:=
```
FeynCalcHowToCite[]
```


- V. Shtabovenko, R. Mertig and F. Orellana, arXiv:2312.14089.
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