In[ ]:=
```
(*  F[1, {1}] = electron neutrino,
F[1, {2}] = muon neutrino, F[1, {3}] = tau neutrino,
    F[2, {1}] = electron, F[2, {2}] = muon, F[2, {3}] = tau,
    F[3, {1}] = up, F[3, {2}] = charm, F[3, {3}] = top,
    F[4, {1}] = down, F[4, {2}] = strange, F[4, {3}] = 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[\(p\), \(2\)]\)";
MakeBoxes[p3, TraditionalForm] := "\!\(\*SubscriptBox[\(p\), \(3\)]\)";
topology = CreateTopologies[0, 1 → 3];
```

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.

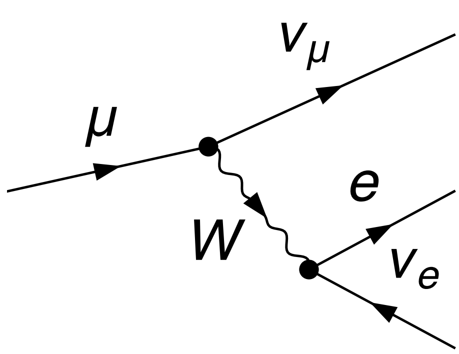
Please keep in mind that the proper academic attribution of our work is crucial to ensure the future development of this package!

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: mu → nu_mu e- antinu_e *)
feynman = InsertFields[topology,
   {F[2, {2}]} → {F[1, {2}], F[2, {1}], -F[1, {1}]}, InsertionLevel → {Classes},
   Model → {SM, UnitarySM}, GenericModel → {Lorentz, UnitaryLorentz}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] =
 FCFAConvert[CreateFeynAmp[feynman, GaugeRules → {FAGaugeXi[W | Z] → Infinity}],
  IncomingMomenta → {p}, OutgoingMomenta → {p1, p2, p3},
  UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True,
  Contract → True, DropSumOver → True, FinalSubstitutions →
   {SMP["e"] → Sqrt[8 / Sqrt[2] * SMP["G_F"] * SMP["m_W"] ^ 2 × SMP["sin_W"] ^ 2]}]
FCClearScalarProducts[];
SP[p, p] = SMP["m_mu"] ^ 2;
SP[p1, p1] = 0;
SP[p2, p2] = SMP["m_e"] ^ 2;
SP[p3, p3] = 0;
squareamplitude[0] = (amplitude[0] (ComplexConjugate[amplitude[0]])) //
    FermionSpinSum[#, ExtraFactor → 1 / 2] & // DiracSimplify // Factor
squareamplitude[1] = squareamplitude[0] // FCE // ReplaceAll[#, {p2 + p3 → 0}] & //
    FeynAmpDenominatorExplicit //
   Series[#, {SMP["m_W"], Infinity, 0}] & // Normal
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```



Out[ ]=

$$-\frac{2\sqrt{2}\,G_F\,m_W^2\,(\varphi(\overline{p_2},m_e)).\bar{\gamma}^{\text{Lor2}}.\bar{\gamma}^7.(\varphi(-\overline{p_3}))\,(\varphi(\overline{p_1})).\bar{\gamma}^{\text{Lor2}}.\bar{\gamma}^7.(\varphi(\overline{p},m_\mu))}{(\overline{p_2}+\overline{p_3})^2-m_W^2}-$$

$$\frac{2\sqrt{2}\,G_F\,(\varphi(\overline{p_2},m_e)).(\bar{\gamma}\cdot(\overline{p_2}+\overline{p_3})).\bar{\gamma}^7.(\varphi(-\overline{p_3}))\,(\varphi(\overline{p_1})).(\bar{\gamma}\cdot(-\overline{p_2}-\overline{p_3})).\bar{\gamma}^7.(\varphi(\overline{p},m_\mu))}{(\overline{p_2}+\overline{p_3})^2-m_W^2}$$

Out[∘]=

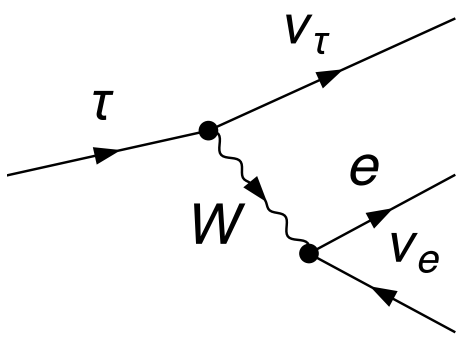
$$16\, G_F^2 \left(\frac{1}{(\overline{p_2}+\overline{p_3})^2 - m_W^2}\right)^2 \Big(-2\, m_e^2\, (\overline{p}\cdot\overline{p_1})\, (\overline{p_2}\cdot\overline{p_3})^2 - 2\, m_e^2\, m_W^2\, (\overline{p}\cdot\overline{p_3})\, (\overline{p_1}\cdot\overline{p_2}) - 2\, m_e^2\, m_W^2\, (\overline{p}\cdot\overline{p_2})\, (\overline{p_1}\cdot\overline{p_3}) + 2\, m_e^2\, m_W^2\, (\overline{p}\cdot\overline{p_1})\, (\overline{p_2}\cdot\overline{p_3}) + m_e^4\, (-(\overline{p}\cdot\overline{p_1}))\, (\overline{p_2}\cdot\overline{p_3}) + 2\, m_e^2\, (\overline{p}\cdot\overline{p_2})\, (\overline{p_1}\cdot\overline{p_2})\, (\overline{p_2}\cdot\overline{p_3}) + 2\, m_e^2\, (\overline{p}\cdot\overline{p_3})\, (\overline{p_1}\cdot\overline{p_2})\, (\overline{p_2}\cdot\overline{p_3}) + 2\, m_e^2\, (\overline{p}\cdot\overline{p_2})\, (\overline{p_1}\cdot\overline{p_3})\, (\overline{p_2}\cdot\overline{p_3}) + 2\, m_e^2\, (\overline{p}\cdot\overline{p_3})\, (\overline{p_1}\cdot\overline{p_3})\, (\overline{p_2}\cdot\overline{p_3}) - 4\, m_e^2\, m_W^2\, (\overline{p}\cdot\overline{p_3})\, (\overline{p_1}\cdot\overline{p_3}) + 4\, m_W^4\, (\overline{p}\cdot\overline{p_3})\, (\overline{p_1}\cdot\overline{p_2})\Big)$$

Out[∘]=

$$64\, G_F^2\, (\overline{p}\cdot\overline{p_3})\, (\overline{p_1}\cdot\overline{p_2})$$

In[∘]:=

```
(* SM: tau → nu_tau e- antinu_e *)
feynman = InsertFields[topology,
   {F[2, {3}]} → {F[1, {3}], F[2, {1}], -F[1, {1}]}, InsertionLevel → {Classes},
   Model → {SM, UnitarySM}, GenericModel → {Lorentz, UnitaryLorentz}];
Paint[feynman, Numbering → None, SheetHeader → False,
  ColumnsXRows → {4, 1}, ImageSize → {1032, 256}];
amplitude[0] =
 FCFAConvert[CreateFeynAmp[feynman, GaugeRules → {FAGaugeXi[W | Z] → Infinity}],
  IncomingMomenta → {p}, OutgoingMomenta → {p1, p2, p3},
  UndoChiralSplittings → True , ChangeDimension → 4,
  DropSumOver → True, List → False, SMP → True,
  Contract → True, DropSumOver → True, FinalSubstitutions →
   {SMP["e"] → Sqrt[8 / Sqrt[2] * SMP["G_F"] * SMP["m_W"] ^ 2 × SMP["sin_W"] ^ 2]}]
FCClearScalarProducts[];
SP[p, p] = SMP["m_tau"] ^ 2;
SP[p1, p1] = 0;
SP[p2, p2] = SMP["m_e"] ^ 2;
SP[p3, p3] = 0;
squareamplitude[0] = (amplitude[0] (ComplexConjugate[amplitude[0]])) //
    FermionSpinSum[#, ExtraFactor → 1 / 2] & // DiracSimplify // Factor
squareamplitude[1] = squareamplitude[0] // FCE // ReplaceAll[#, {p2 + p3 → 0}] & //
    FeynAmpDenominatorExplicit //
   Series[#, {SMP["m_W"], Infinity, 0}] & // Normal
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```



Out[ ]=

$$-\frac{2\sqrt{2}\;G_F\,m_W^2\,(\varphi(\overline{p_2},m_e)).\bar{\gamma}^{\text{Lor2}}.\bar{\gamma}^{7}.(\varphi(-\overline{p_3}))\,(\varphi(\overline{p_1})).\bar{\gamma}^{\text{Lor2}}.\bar{\gamma}^{7}.(\varphi(\overline{p},m_\tau))}{(\overline{p_2}+\overline{p_3})^2-m_W^2}-\frac{2\sqrt{2}\;G_F\,(\varphi(\overline{p_2},m_e)).(\bar{\gamma}\cdot(\overline{p_2}+\overline{p_3})).\bar{\gamma}^{7}.(\varphi(-\overline{p_3}))\,(\varphi(\overline{p_1})).(\bar{\gamma}\cdot(-\overline{p_2}-\overline{p_3})).\bar{\gamma}^{7}.(\varphi(\overline{p},m_\tau))}{(\overline{p_2}+\overline{p_3})^2-m_W^2}$$

Out[ ]=

$$16\,G_F^2\,{\frac{1}{(\overline{p_2}+\overline{p_3})^2-m_W^2}}^{2}\Big(-2\,m_e^2\,(\overline{p}\cdot\overline{p_1})\,(\overline{p_2}\cdot\overline{p_3})^2-2\,m_e^2\,m_W^2\,(\overline{p}\cdot\overline{p_3})\,(\overline{p_1}\cdot\overline{p_2})-2\,m_e^2\,m_W^2\,(\overline{p}\cdot\overline{p_2})\,(\overline{p_1}\cdot\overline{p_3})+2\,m_e^2\,m_W^2\,(\overline{p}\cdot\overline{p_1})\,(\overline{p_2}\cdot\overline{p_3})+m_e^4\,(-(\overline{p}\cdot\overline{p_1}))\,(\overline{p_2}\cdot\overline{p_3})+2\,m_e^2\,(\overline{p}\cdot\overline{p_2})\,(\overline{p_1}\cdot\overline{p_2})\,(\overline{p_2}\cdot\overline{p_3})+2\,m_e^2\,(\overline{p}\cdot\overline{p_3})\,(\overline{p_1}\cdot\overline{p_2})\,(\overline{p_2}\cdot\overline{p_3})+2\,m_e^2\,(\overline{p}\cdot\overline{p_2})\,(\overline{p_1}\cdot\overline{p_3})\,(\overline{p_2}\cdot\overline{p_3})+2\,m_e^2\,(\overline{p}\cdot\overline{p_3})\,(\overline{p_1}\cdot\overline{p_3})\,(\overline{p_2}\cdot\overline{p_3})-4\,m_e^2\,m_W^2\,(\overline{p}\cdot\overline{p_3})\,(\overline{p_1}\cdot\overline{p_3})+4\,m_W^4\,(\overline{p}\cdot\overline{p_3})\,(\overline{p_1}\cdot\overline{p_2})\Big)$$

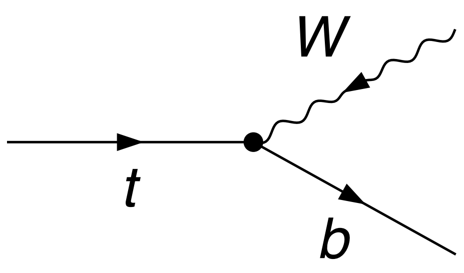
Out[ ]=

$$64\,G_F^2\,(\overline{p}\cdot\overline{p_3})\,(\overline{p_1}\cdot\overline{p_2})$$

In[ ]:=

```
topology = CreateTopologies[0, 1 → 2];
```

In[∘]:=
```
(* SM: t → W+ b *)
feynman = InsertFields[topology,
   {F[3, {3}]} → {-V[3], F[4, {3}]}, InsertionLevel → {Classes},
   Model → {SM, UnitarySM}, GenericModel → {Lorentz, UnitaryLorentz}];
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, DropSumOver → True, FinalSubstitutions →
   {SMP["e"] → Sqrt[8 / Sqrt[2] * SMP["G_F"] * SMP["m_W"] ^ 2 × SMP["sin_W"] ^ 2]}]
FCClearScalarProducts[];
SP[p, p] = SMP["m_tau"] ^ 2;
SP[p1, p1] = SMP["m_W"] ^ 2;
SP[p2, p2] = SMP["m_b"] ^ 2;
SP[p1, p2] = (SMP["m_tau"] ^ 2 - SMP["m_W"] ^ 2 - SMP["m_b"] ^ 2) / 2;
SP[p, p1] = SP[p1, p1] + SP[p1, p2];
SP[p, p2] = SP[p1, p2] + SP[p2, p2];
squareamplitude[0] = (amplitude[0] (ComplexConjugate[amplitude[0]])) //
      DoPolarizationSums[#, p1] & // FermionSpinSum[#, ExtraFactor → 1 / 2] & //
    DiracSimplify // Simplify // SUNSimplify
masslesssquareamplitude[0] =
 squareamplitude[0] // ReplaceAll[#, {SMP["m_b"] → 0}] & // Simplify
(* output = feynman diagrams, amplitude,
squared amplitude, massless squared amplitude *)
```



Out[∘]=

$$\frac{2^{3/4}\,\delta_{\text{Col1 Col3}}\,\sqrt{G_F\,m_W^2\,(\sin(\theta_W))^2}\;(\varphi(\overline{p_2},m_b)).(\overline{\gamma}\cdot\overline{\varepsilon}^*(p_1)).\overline{\gamma}^7.(\varphi(\overline{p},m_t))}{\sin(\theta_W)}$$

Out[∘]=

$$\sqrt{2}\;C_A\,G_F\left(-2\,m_b^2\,m_\tau^2+m_b^2\,m_W^2+m_b^4+m_\tau^4+m_\tau^2\,m_W^2-2\,m_W^4\right)$$

Out[∘]=

$$\sqrt{2}\;C_A\,G_F\left(m_\tau^4+m_\tau^2\,m_W^2-2\,m_W^4\right)$$

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

CPU Time used: 3.94 s.

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


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

Out[ ]=

Null