Automatic evaluation of UV and R2 terms for beyond the Standard Model Lagrangians

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FeynRules 2014

Plan

- Introduction
- Rational terms
- UV counterterms
- NLOCT
- Validation
- Perspectives and conclusion

Loop computation

$$\mathcal{A}^{1-loop} = \sum_i d_i \text{ Box}_i + \sum_i c_i \text{ Triangle}_i + \sum_i b_i \text{ Bubble}_i + \sum_i a_i \text{ Tadpole}_i + R$$

- Box, Triangle, Bubble and Tadpole are known scalar integrals
- Loop computation = find the coefficients
  - Unitarity
  - Multiple cuts
  - Tensor reduction (OPP)

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Introduction

- Goal : Automate the one-loop computation for BSM models
- Required ingredients :
  - Tree-level vertices — Done(FeynRules)
  - R2 vertices (OPP)
  - UV counterterm vertices — Missing
- Solution : UFO at NLO

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R_2

$$\bar{A}(\bar{q}) = \frac{1}{(2\pi)^4}\int d^d\bar{q}\,\frac{\bar{N}(\bar{q})}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}}, \qquad \bar{D}_i = (\bar{q}+p_i)^2 - m_i^2$$

$$\bar{N}(\bar{q}) = N(q) + \tilde{N}(\tilde{q}, q, \epsilon)$$

d 4 ε

$$R_2 \equiv \lim_{\epsilon\to 0}\frac{1}{(2\pi)^4}\int d^d\bar{q}\,\frac{\tilde{N}(\tilde{q}, q, \epsilon)}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}}$$

Finite set of vertices that can be computed once for all

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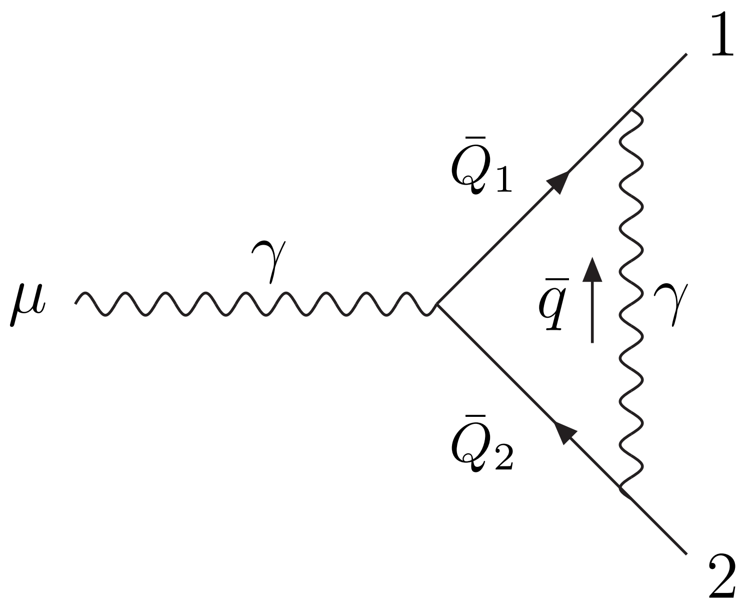
R_2 example



$$\bar{Q}_1 = \bar{q} + p_1 = Q_1 + \tilde{q}$$
$$\bar{Q}_2 = \bar{q} + p_2 = Q_2 + \tilde{q}$$

$$\bar{D}_0 = \bar{q}^2$$
$$\bar{D}_1 = (\bar{q} + p_1)^2$$
$$\bar{D}_2 = (\bar{q} + p_2)^2$$

't Hooft Veltman scheme

$$\bar{\eta}^{\bar{\mu}\,\bar{\nu}}\bar{\eta}_{\bar{\mu}\,\bar{\nu}} = d,$$
$$\bar{\gamma}^{\bar{\mu}}\bar{\gamma}_{\bar{\mu}} = d\,\mathbb{1},$$

$$\begin{aligned}\bar{N}(\bar{q}) &\equiv e^3 \left\{\bar{\gamma}_{\bar{\beta}} \left(\not{\bar{Q}}_1 + m_e\right) \gamma_\mu \left(\not{\bar{Q}}_2 + m_e\right) \bar{\gamma}^{\bar{\beta}}\right\} \\ &= e^3 \left\{\gamma_\beta(\not{Q}_1 + m_e)\gamma_\mu(\not{Q}_2 + m_e)\gamma^\beta \right. \\ &- \left. \epsilon\,(\not{Q}_1 - m_e)\gamma_\mu(\not{Q}_2 - m_e) + \epsilon\tilde{q}^2\,\gamma_\mu - \tilde{q}^2\,\gamma_\beta\gamma_\mu\gamma^\beta\right\}\end{aligned}$$

$$\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_0\bar{D}_1\bar{D}_2} = -\frac{i\pi^2}{2} + \mathcal{O}(\epsilon)\,,$$
$$\int d^n\bar{q}\frac{q_\mu q_\nu}{\bar{D}_0\bar{D}_1\bar{D}_2} = -\frac{i\pi^2}{2\epsilon}g_{\mu\nu} + \mathcal{O}(1)$$

$$\mathrm{R}_2 = -\frac{ie^3}{8\pi^2}\gamma_\mu$$

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R_1

Due to the ε dimensional parts of the denominators

Like for the 4 dimensional part but with a different set of integrals

$$\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j} = -\frac{i\pi^2}{2}\left[m_i^2+m_j^2-\frac{(p_i-p_j)^2}{3}\right]+\mathcal{O}(\epsilon)\,,$$

$$\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j\bar{D}_k} = -\frac{i\pi^2}{2}+\mathcal{O}(\epsilon)\,,$$

$$\int d^n\bar{q}\frac{\tilde{q}^4}{\bar{D}_i\bar{D}_j\bar{D}_k\bar{D}_l} = -\frac{i\pi^2}{6}+\mathcal{O}(\epsilon)\,.$$

Only $R = R_1+R_2$ is gauge invariant ⇨ Check

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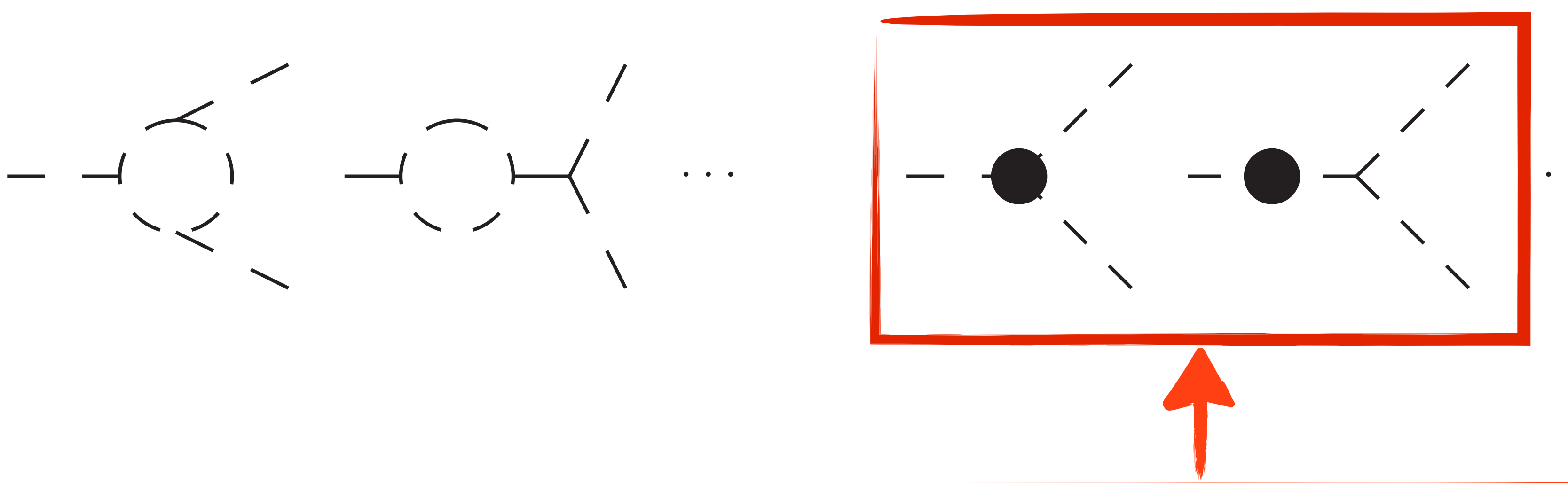
UV

$$\bar{A}(\bar{q}) = \frac{1}{(2\pi)^4} \int d^d\bar{q} \frac{\bar{N}(\bar{q})}{\bar{D}_0 \bar{D}_1 \dots \bar{D}_{m-1}} = K \frac{1}{\epsilon} + \mathcal{O}\left(\epsilon^0\right)$$



$$\dots = 0\frac{1}{\epsilon} + \mathcal{O}\left(\epsilon^0\right)$$

Relations fixed by the Lagrangian (finite part)

Finite set of vertices that can be computed once for all

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Renormalization

External parameters

$$
\begin{aligned}
x_0 &\rightarrow x + \delta x, \\
\phi_0 &\rightarrow (1 + \frac{1}{2}\delta Z_{\phi\phi})\phi + \sum_{\chi} \frac{1}{2}\delta Z_{\phi\chi}\chi,
\end{aligned}
$$

Same for the conjugate field

Internal parameters are renormalised by replacing the external parameters in their expressions

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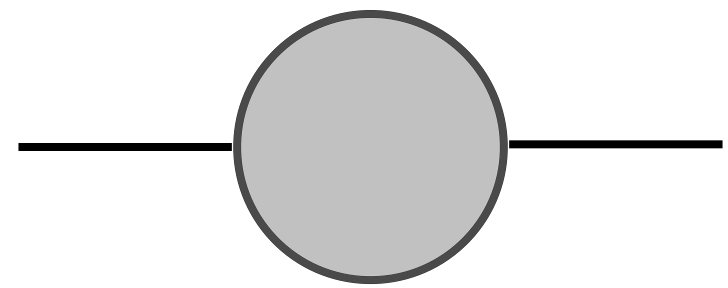
Renormalization conditions

On-shell scheme (or complex mass scheme):

Renormalized mass = Physical mass

Two-point function vanishes on-shell (No external bubbles)



$$i\delta_{ij}\left(\not{p}-m_i\right)+i\left[f_{ij}^{L}\left(p^2\right)\not{p}\gamma_- + f_{ij}^{R}\left(p^2\right)\not{p}\gamma_+ + f_{ij}^{SL}\left(p^2\right)\gamma_- + f_{ij}^{SR}\left(p^2\right)\gamma_+\right]$$

$$\begin{aligned}
\cancel{\widetilde{\Re}}\left[f_{ij}^{L}\left(p^2\right)m_i + f_{ij}^{SR}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0\\
\cancel{\widetilde{\Re}}\left[f_{ij}^{R}\left(p^2\right)m_i + f_{ij}^{SL}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0\\
\cancel{\widetilde{\Re}}\left[2m_i\frac{\partial}{\partial p^2}\left[\left(f_{ii}^{L}\left(p^2\right)+f_{ii}^{R}\left(p^2\right)\right)m_i + f_{ii}^{SL}\left(p^2\right)+f_{ii}^{SR}\left(p^2\right)\right] + f_{ii}^{L}\left(p^2\right)+f_{ii}^{R}\left(p^2\right)\right]\Big|_{p^2=m_i^2} &= 0
\end{aligned}$$

Similar for the vectors and scalars

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Renormalization conditions

Zero momentum scheme available for the gauge couplings

$$\Gamma^{\mu}_{FFV}\left(p_1,p_2\right) = igT^a\delta_{f_1,f_2}\left[\gamma^\mu\left(\frac{\delta g}{g}+\frac{1}{2}\delta Z_{VV}+\frac{1}{2}\delta Z^R_{FF}+\frac{1}{2}\delta Z^L_{FF}+\frac{g'_V}{2g}\delta Z_{V'V}\right)\right.$$
$$+\gamma^\mu\gamma_5\left(\frac{1}{2}\delta Z^R_{FF}-\frac{1}{2}\delta Z^L_{FF}+\frac{g'_A}{2g}\delta Z_{V'V}\right)$$
$$\left.+\left(\gamma^\mu h^V\left(k^2\right)+\gamma^\mu\gamma_5 h^A\left(k^2\right)+\frac{(p_1-p_2)^\mu}{2m}h^S\left(k^2\right)+\frac{k_\mu}{2m}h^P\left(k^2\right)\right)\right]$$

$$\frac{\delta g}{g}+\frac{1}{2}\delta Z_{VV}+\frac{1}{2}\delta Z^R_{FF}+\frac{1}{2}\delta Z^L_{FF}+\frac{g'_V}{2g}\delta Z_{V'V}+h^V(0)+h^S(0) = 0$$
$$\frac{1}{2}\delta Z^R_{FF}-\frac{1}{2}\delta Z^L_{FF}+\frac{g'_A}{2g}\delta Z_{V'V}+h^A(0) = 0.$$

By gauge invariance

$$\frac{\delta g}{g}+\frac{1}{2}\delta Z_{VV}+\frac{g'_V}{2g}\delta Z_{V'V}+\frac{g'_A}{2g}\delta Z_{V'V}=0$$

Only from two-point functions

$\overline{\text{MS}}$ scheme for everything else (option for all)

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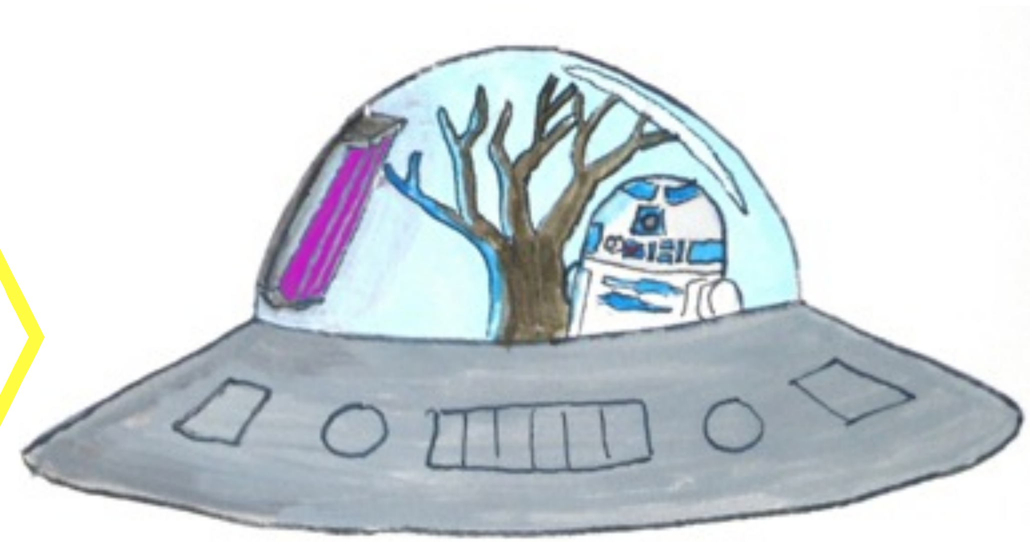
How does it work?

FeynRules

Renormalize the Lagrangian

model.mod

model.gen



model.nlo

FeynArts

Write the amplitudes

NLOCT.m

Compute the NLO vertices

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How does it work?

FeynRules :

```
...
Lren = OnShellRenormalization[ LSM , QCDOnly ->True];
WriteFeynArtsOutput[ Lren , Output -> "SMrenoL",
GenericFile -> False]
```

FeynArts / NLOCT :

```
WriteCT[ "SMrenoL/SMrenoL" , "Lorentz", Output->
“SMQCDreno”, QCDonly -> True]
```

FeynRules :

```
...
Get["SMQCDreno.nlo"];
WriteUFO[ LSM , UVCounterterms -> UV$vertlist ,
 R2Vertices -> R2$vertlist]
```

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model.nlo

Model information (FR+FeynArts model/generic files)

```
R2$vertlist = {
{{{anti[u], 1}, {u, 2}}, ((-I/12)*gs^2*
IndexDelta[Index[Colour, Ext[1]], Index[Colour, Ext[2]]]*IPL[{u, G}]*
(TensDot[SlashedP[2], ProjM][Index[Spin, Ext[1]], Index[Spin, Ext[2]]] +
TensDot[SlashedP[2], ProjP][Index[Spin, Ext[1]], Index[Spin, Ext[2]]]))/Pi^2},
...
}
```

~FeynRules syntaxe

UV$vertlist (ε is FR$Eps)

```
FR$InteractionOrderPerturbativeExpansion = {{QCD, 1}, {QED, 0}};
```

QCDOnly

NLOCT$assumptions

WriteCT[...,Assumptions->{...}]

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UFO@NLO

- CT_vertices.py

```
V_1 = CTVertex(name = 'V_1',
               type = 'R2',
               particles = [ P.g, P.g, P.g ],
               color = [ 'f(1,2,3)' ],
               lorentz = [ L.VVV2 ],
               loop_particles = [ [ [P.b], [P.c], [P.d], [P.s], [P.t], [P.u] ], [ [P.g] ] ],
               couplings = {(0,0,0):C.R2GC_273_53,(0,0,1):C.R2GC_273_54})
```

UV

- CT_couplings.py

```
UVGC_271_34 = Coupling(name = 'UVGC_271_34',
                       value = {-1:'( 0 if MB else -(complex(0,1)*G**2)/(24.*cmath.pi**2) ) +
(complex(0,1)*G**2)/(24.*cmath.pi**2)',0:'( -(complex(0,1)*G**2*reglog(MB/MU_R))/
(12.*cmath.pi**2) if MB else 0 )'},
                       order = {'QCD':2})
```

Pole

Finite

- In coupling_order.py

```
QCD = CouplingOrder(name = 'QCD',
                    expansion_order = 99,
                    hierarchy = 1,
                    perturbative_expansion = 1)

QED = CouplingOrder(name = 'QED',
                    expansion_order = 99,
                    hierarchy = 2)
```

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Restrictions/Assumptions

- Renormalizable Lagrangian, maximum dimension of the operators is 4
- Feynman Gauge
- $\{\gamma_\mu, \gamma_5\} = 0$
- ‘t Hooft-Veltman scheme
- On-shell scheme for the masses and wave functions
- $\overline{\text{MS}}$ by default for everything else (zero-momentum possible for fermion gauge boson interaction)

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NLOCT

- Amplitudes from FeynArts (discard irrelevant diagrams like ghost boxes)

EFT :No discard diagrams, Higher adjacencies, list of amplitudes

- Compute terms at the generic level

$$\vec{c}\cdot\vec{L} = \sum_i c_i L_i$$

Remove too high dimension

- Feynman parameters

propagators>4

- Remove terms with an odd or too low rank
- Dirac algebra

More than one fermion chain

- Gather loop momentum

$$q^\mu q^\nu q^\rho q^\sigma \quad \to \quad q^4 \frac{1}{d(d+2)} \left(\eta^{\mu\nu}\eta^{\rho\sigma} + \eta^{\mu\rho}\eta^{\nu\sigma} + \eta^{\mu\sigma}\eta^{\rho\nu}\right)$$

$$q^\mu q^\nu \quad \to \quad q^2 \frac{1}{d}\eta^{\mu\nu}.$$

Generic

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NLOCT

- Replace momentum integrals

$$\int d^dq \frac{\epsilon}{q^2-m^2}\Big|_{R_2} = i\pi^2 m^2, \qquad \mu^{2\epsilon}\int d^dq \frac{a\epsilon+b}{q^2-m^2}\Big|_{UV} = i\pi^2 m^2\left(\frac{b}{\bar\epsilon}+a+b-b\log\left(\frac{m^2}{\mu^2}\right)\right),$$

$$\int d^dq \frac{\epsilon}{(q^2-\Delta)^2}\Big|_{R_2} = i\pi^2, \qquad \mu^{2\epsilon}\int d^dq \frac{a\epsilon+b}{(q^2-\Delta)^2}\Big|_{UV} = i\pi^2(a\epsilon+b)\left(\frac{1}{\bar\epsilon}-\log\left(\frac{\Delta}{\mu^2}\right)\right),$$

$$\int d^dq \frac{q^2\,(a\,\epsilon+b)}{(q^2-\Delta)^2}\Big|_{R_2} = i\pi^2(2a-b)\Delta, \qquad \mu^{2\epsilon}\int d^dq \frac{q^2\,(a\,\epsilon+b)}{(q^2-\Delta)^2}\Big|_{UV} = i\pi^2(2a\epsilon+b\epsilon+2b)\left(\frac{1}{\bar\epsilon}-\log\left(\frac{\Delta}{\mu^2}\right)\right)\Delta,$$

$$\int d^dq \frac{q^2\,(a\,\epsilon+b)}{(q^2-\Delta)^3}\Big|_{R_2} = i\pi^2\left(a-\frac{1}{2}b\right), \qquad \mu^{2\epsilon}\int d^dq \frac{q^2\,(a\,\epsilon+b)}{(q^2-\Delta)^3}\Big|_{UV} = i\pi^2\frac{b}{\bar\epsilon},$$

$$\int d^dq \frac{q^4\,(a\,\epsilon+b)}{(q^2-\Delta)^4}\Big|_{R_2} = i\pi^2\left(a-\frac{5}{6}b\right), \qquad \mu^{2\epsilon}\int d^dq \frac{q^4\,(a\,\epsilon+b)}{(q^2-\Delta)^4}\Big|_{UV} = i\pi^2\frac{b}{\bar\epsilon},$$

generic for rank>4 and # propagator>4

- Integrate over the Feynman parameters (but for the two-point UV finite terms)
- Replace masses and couplings by their values for each field insertion

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NLOCT

- Perform the color algebra for triplets and octets

End R_2

- Write the renormalization conditions (fix p^2)
- Do the integration over the feynman parameters for the UV-finite parts

$$b_0\left(p^2, m_1, m_2\right) \equiv \int_0^1 dx \log\left(\frac{p^2(x-1)x + x\left(m_1^2 - m_2^2\right) + m_2^2 - i\epsilon_p}{\mu^2}\right)$$

$$b_0\left(0,0,0\right) = \frac{1}{\bar{\epsilon}}$$

- Solve the renormalization conditions
- Replace the counterterms by their values in the CT vertices

Merge R2EFT with NLOCT

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UV splitting

$$A^{loop} = A^{UV} \frac{1}{\bar{\epsilon}_{UV}} + A^{UV fin}$$

- UV divergent part of the vertex is the opposite of the loop amplitude

$$-i\delta^{a_1 a_2} \delta Z_{gg} \left(p_1^{\mu_2} p_2^{\mu_1} - p_1 \cdot p_2 \eta^{\mu_1 \mu_2}\right) =$$
$$-A^{UV} \frac{1}{\bar{\epsilon}_{UV}} - i\delta^{a_1 a_2} \delta Z_{gg}^{UV fin} \left(p_1^{\mu_2} p_2^{\mu_1} - p_1 \cdot p_2 \eta^{\mu_1 \mu_2}\right)$$

- Renormalization condition are solved for the UV finite part only
- Advantage
  - 2HDM ymb=4.7, MB=0
  - EFT : no need for the operators remove by EOM

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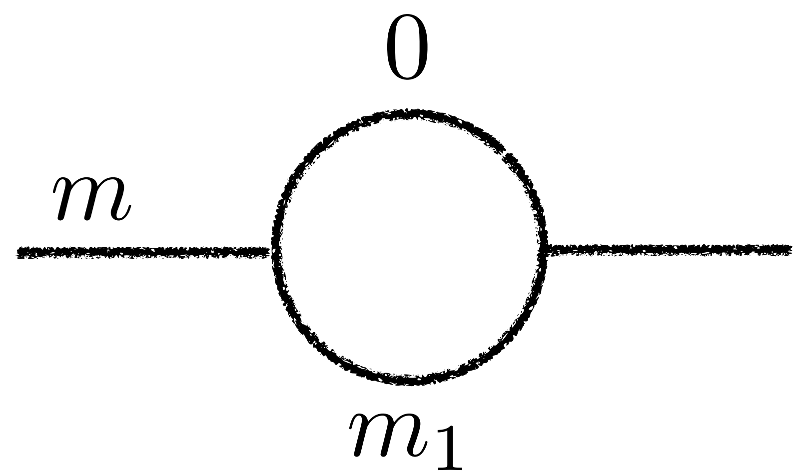
Real/Complex masses



Real masses

$m \in \mathbb{R}$ $\quad m_1^2 < m^2 \quad \Re\left(\log\left[p^2 - m_1^2\right] + i\pi\right)\Big|_{p^2=m^2}$

$m_1^2 > m^2 \quad \Re\left(\log\left[m_1^2 - p^2\right]\right)\Big|_{p^2=m^2}$

Complex masses

$$\log\left[m_1^2 - p^2\right]\Big|_{p^2=m^2}$$

Faster!

All cases are kept unless the users put some assumptions

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R2 :Validation

- tested* on the SM (QCD:P. Draggiotis et al. +QED:M.V. Garzelli et al)
- tested* on MSSM (QCD:H.-S. Shao, Y.-J. Zhang) : test the Majorana

*Analytic comparison of the expressions

UV Validation

- SM QCD : tested* (W. Beenakker, S. Dittmaier, M. Kramer, B. Plumper)
- SM EW : tested* (expressions given by H.-S. Shao from A. Denner)

*Analytic comparison of the expressions

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Tests in event generators

- aMC@NLO
- The SM QCD has been tested by V. Hirschi (Comparison with the built-in version)
- The MSSM QCD and SM EW are tested by H.-S. Shao and V. Hirschi
- 2HDM QCD is currently tested (p p > S, H^+ t)
  - gauge invariance
  - pole cancelation
- Anomalous top

SM tests

=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.2565695610e+01	-1.2565705416e+01	-1.2565696276e+01	3.9018817097e-07	Pass

=== Born ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	1.8518318521e-06	1.8518318521e-06	1.8518318521e-06	8.0617231411e-15	Pass

=== Single pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.9397426502e+01	-1.9397426502e+01	-1.9397426504e+01	5.5894073017e-11	Pass

=== Double pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-5.6666666667e+00	-5.6666666667e+00	-5.6666666667e+00	3.0015206007e-14	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-5.3971186943e+01	-5.3971193753e+01	-5.3971189940e+01	6.3091071914e-08	Pass

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	6.4168774056e-05	6.4168764370e-05	6.4168764370e-05	7.5467680882e-08	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-3.7439549398e+01	-3.7439549398e+01	-3.7439549397e+01	6.8122965983e-12	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-8.6666666667e+00	-8.6666666667e+00	-8.6666666667e+00	2.2443585452e-14	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	-5.3769573669e+01	-5.3769573347e+01	-5.3769566412e+01	6.7475496780e-08	Pass

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SM tests

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	3.1531233900e-04	3.1531235770e-04	3.1531235770e-04	2.9654886777e-08	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	-3.7464897007e+01	-3.7464897007e+01	-3.7464897007e+01	4.2333025503e-12	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	-8.6666666667e+00	-8.6666666667e+00	-8.6666666667e+00	2.1316282073e-14	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z z g	-5.9990384275e+00	-5.9990511729e+00	-5.9990379587e+00	1.1013604745e-06	Pass

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z z g	2.2616997126e-06	2.2617000449e-06	2.2617000449e-06	7.3450366526e-08	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z z g	-1.5469587040e+01	-1.5469587040e+01	-1.5469587040e+01	1.5226666708e-11	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z z g	-5.6666666667e+00	-5.6666666667e+00	-5.6666666667e+00	2.6645352591e-15	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > h t t~	2.9740187004e+01	2.9740187005e+01	2.9740187036e+01	5.3265970697e-10	Pass

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SM tests

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > h t t~	1.1079653971e-07	1.1079653974e-07	1.1079653974e-07	1.3190849004e-10	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > h t t~	-7.0825709000e+00	-7.0825709000e+00	-7.0825709000e+00	5.0901237085e-13	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > h t t~	-6.0000000000e+00	-6.0000000000e+00	-6.0000000000e+00	1.7023419711e-15	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > z t t~	3.6409017466e+01	3.6409021125e+01	3.6409021117e+01	5.0242920154e-08	Pass

=== Born ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > z t t~	7.0723041711e-07	7.0723046101e-07	7.0723046101e-07	3.1039274206e-08	Pass

=== Single pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > z t t~	-7.1948086812e+00	-7.1948086773e+00	-7.1948086773e+00	2.7349789963e-10	Pass

=== Double pole ===

Process	Stored MadLoop v4	ML5 opt	ML5 default	Relative diff.	Result
g g > z t t~	-6.0000000000e+00	-6.0000000000e+00	-6.0000000000e+00	2.5165055225e-15	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.2565695610e+01	-1.2565705416e+01	-1.2565696276e+01	3.9018817097e-07	Pass

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SM tests

=== Born ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	1.8518318521e-06	1.8518318521e-06	1.8518318521e-06	8.0617231411e-15	Pass

=== Single pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-1.9397426502e+01	-1.9397426502e+01	-1.9397426504e+01	5.5894073017e-11	Pass

=== Double pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d d~ > w+ w- g	-5.6666666667e+00	-5.6666666667e+00	-5.6666666667e+00	3.0015206007e-14	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-1.1504816412e+01	-1.1504816557e+01	-1.1504815497e+01	4.6089385415e-08	Pass

=== Born ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	2.3138920858e-06	2.3138920858e-06	2.3138920858e-06	4.3012538015e-15	Pass

=== Single pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-2.8637049838e+01	-2.8637049838e+01	-2.8637049838e+01	1.5718407645e-13	Pass

=== Double pole ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > a g g	-8.6666666667e+00	-8.6666666667e+00	-8.6666666667e+00	1.7421961310e-15	Pass

=== Summary ===

1/1 passed, 0/1 failed=== Finite ===

Process	Stored ML5 opt	ML5 opt	ML5 default	Relative diff.	Result
d~ d > z g g	-1.0306105482e+01	-1.0306105654e+01	-1.0306102645e+01	1.4600800434e-07	Pass

+2/3

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Plan

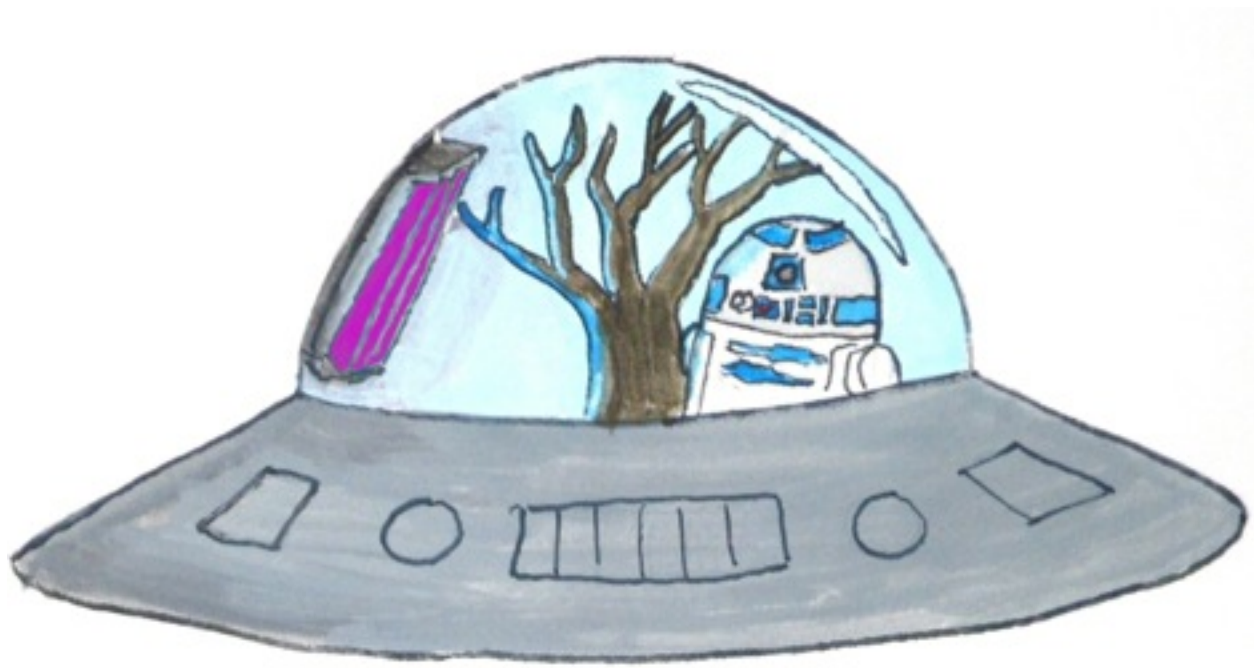
- Introduction
- Rational terms
- UV counterterms
- NLOCT
- Validation
- Perspectives and conclusion

Perspectives

- Phenomenology
- 2HDM
  - Charged Higgs
  - Higgs pair production,…
- Anomalous top (FCNC from dimension-six operators)
  - single top, …
- MSSM
  - Pre-SUSY simplified model

Conclusion

- Automatic BSM@NLO
  - renormalizable
  - Feynman gauge
- Next version
  - EFT
  - Any gauge
  - other renormalization scheme (EW)
- With the help of the FeynRules and Madgraph_aMC@NLO teams



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