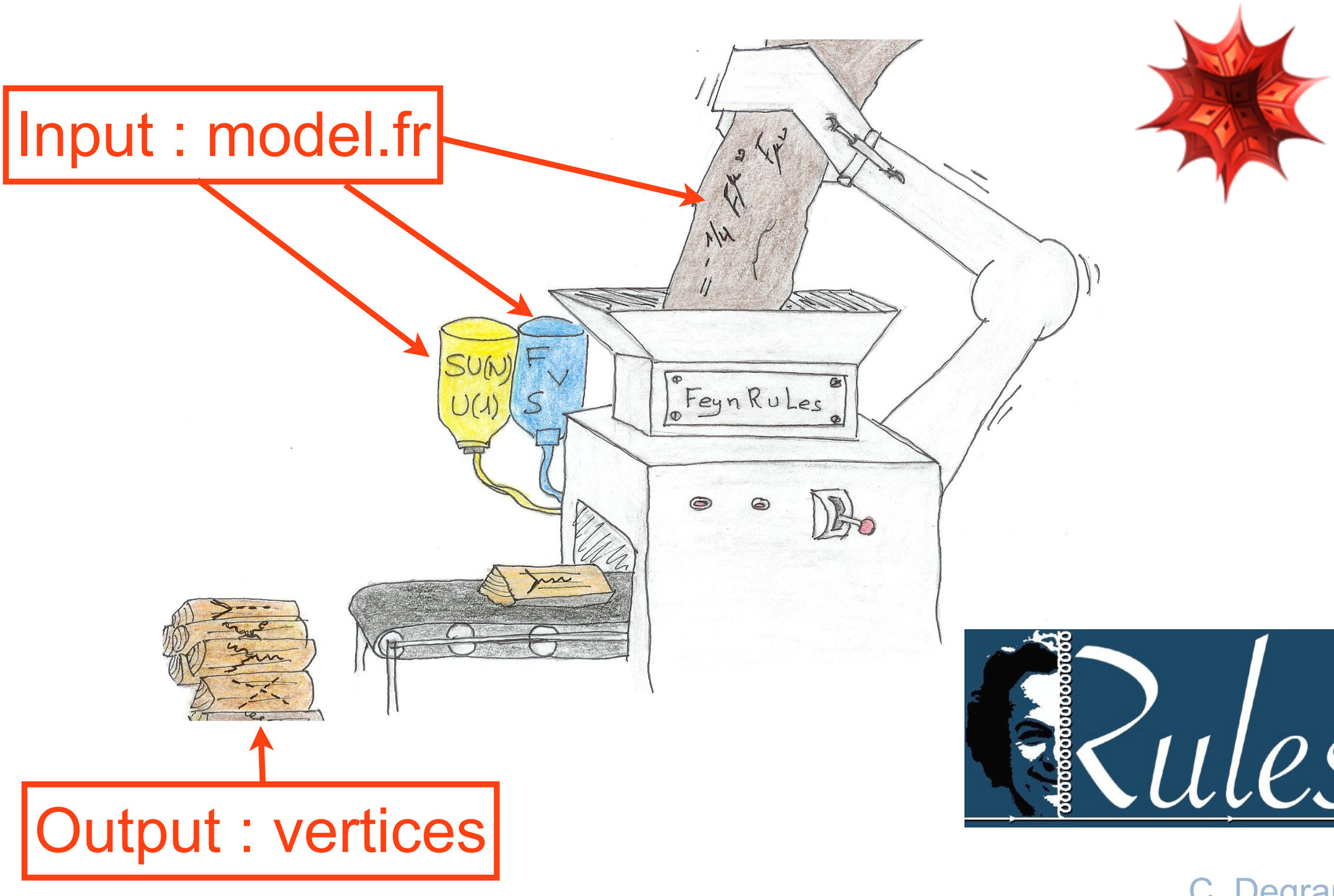
Loop computation

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

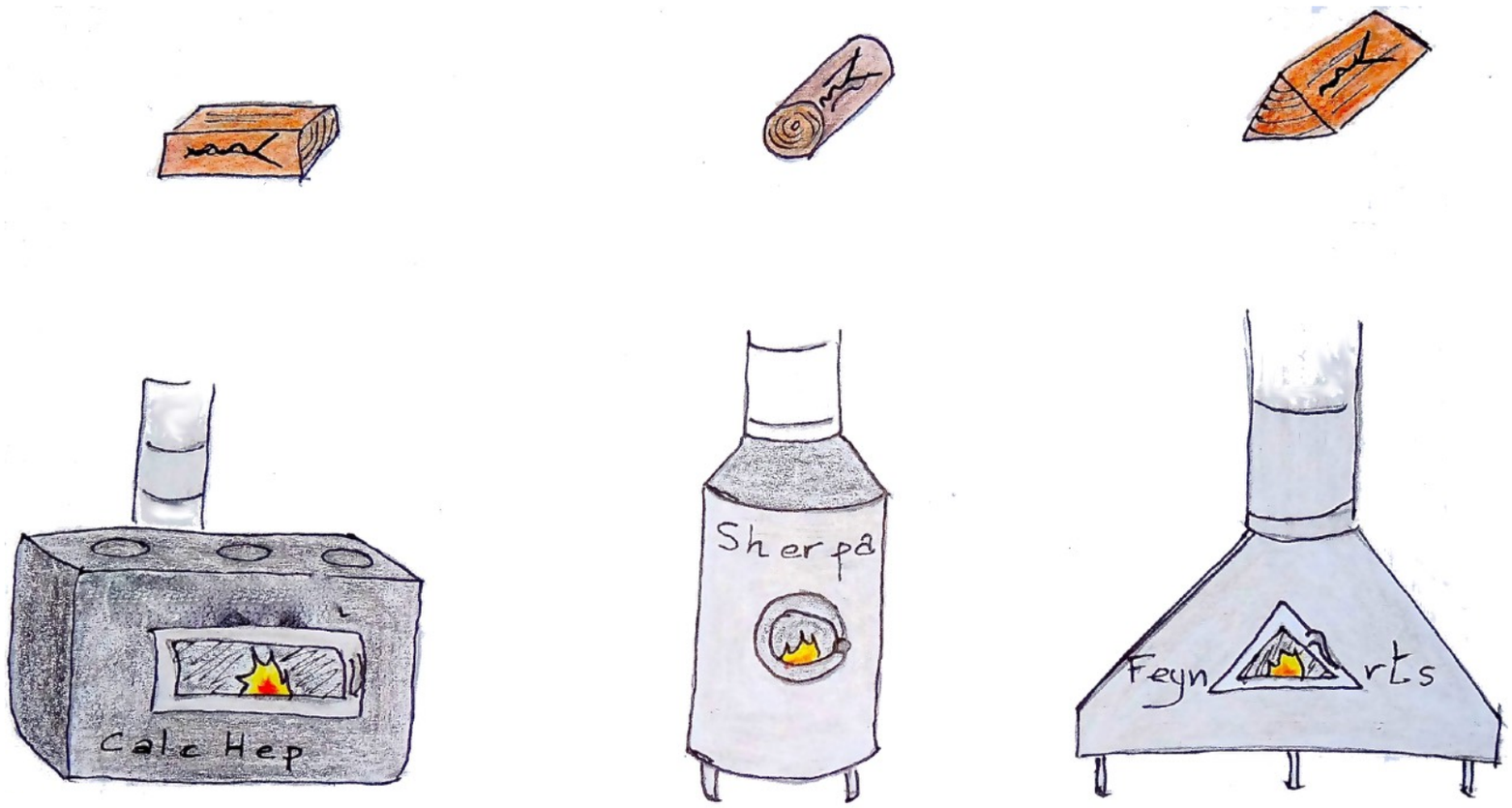
- Box, Triangle, Bubble and Tadpole are known scalar integrals
- Loop computation = find the coefficients
  - Unitarity
  - Multiple cuts
  - Tensor reduction (OPP)

Automated computation for BSM

FeynRules in a nutshell



Feynman rules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

C. Degrande

Feynman Rules

FeynRules takes care of all the conventions cross-check ME and event generation

Predefined basis for most ME

Coupling (function of the parameters)

$$\begin{pmatrix} \bar{u} & 1 \\ u & 2 \\ g & 3 \end{pmatrix}$$

Color representation

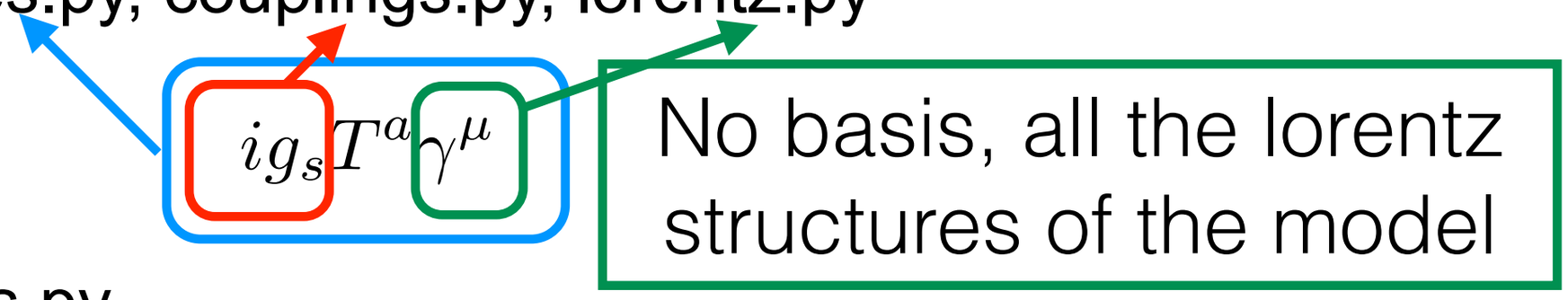
Lorentz (Metric/Levi-Civita tensors, Momenta,Dirac matrices)

$$ig_s \; T^{a_3}_{i_1 i_2} \; \gamma^{\mu_3}$$

C. Degrande

UFO

- Generic output with the **full** model information
  - coupling_orders.py, parameters.py, particles.py, write_param_card.py, __init__.py,
  - vertices.py, couplings.py, lorentz.py



  - decays.py
  - CT_vertices.py, CT_couplings.py (For NLO)
- Python module used in MadGraph, Herwig, Gosam, Sherpa

model file

```
(****************** This is a template model file for FeynRules ***********)

(********** Index definition *********)

IndexRange[ Index[Generation] ] = Range[3]

IndexFormat[Generation, f]

(***** Parameter list ******)

M$Parameters = {
}
(***** Gauge group list ******)

M$GaugeGroups = {
}
(***** Particle classes list ******)

M$ClassesDescription = {
}
```

Definition of variables
in Mathematica syntaxe

Model information

```
M$ModelName = "my_new_model";

M$Information = {
          Authors      -> {"Mr. X", "Ms. Y"},
          Institutions -> {"UC Louvain"},
          Emails       -> {"X@uclouvain.be", "Y@uclouvain.be},
          Date         -> "01.03.2013",
          References   -> {"reference 1", "reference 2"},
          URLs         -> {"http://feynrules.irmp.ucl.ac.be"},
          Version      -> "1.0"
                };
```

Good practice for credit, issue(s) tracking

Indices definition

Used in parameters, gauge groups and fields

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]   = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Tells FR to remplace summed indices by the explicite sum

Tells FA/FC **not** to remplace summed indices by the explicite sum

Indices definition

Used in parameters, gauge groups and fields

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]   = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Tells FR to remplace summed indices by the explicite sum

Tells FA/FC **not** to remplace summed indices by the explicite sum

Format:

```
IndexStyle[ Colour, i ];
IndexStyle[ Gluon, a ];
```

Indices definition

Used in parameters, gauge groups and fields

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]   = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Tells FR to remplace summed indices by the explicite sum

Tells FA/FC **not** to remplace summed indices by the explicite sum

Format:

```
IndexStyle[ Colour, i ];
IndexStyle[ Gluon, a ];
```

Predefined indices: Lorentz, Spin, Spin1, Spin2

Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
            ...
};
```

```
aEWM1 == {
   ParameterType    -> External,
   BlockName        -> SMINPUTS,
   OrderBlock       -> 1,
   Value            -> 127.9,
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z
pole"
  },
```

Numerical value

Compulsory!

Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
            ...
};
```

```
MW == {
  ParameterType -> Internal,
  Value         -> Sqrt[MZ^2/2+Sqrt[MZ^4/4-Pi/Sqrt[2]*aEW/
Gf*MZ^2]],
  TeX           -> Subscript[M,W],
  Description   -> "W mass"
 },
```

Expression

Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
            ...
};
```

```
aEWM1 == {
  ParameterType    -> External,
  BlockName        -> SMINPUTS,
  OrderBlock       -> 1,
  Value            -> 127.9,
  InteractionOrder -> {QED,-2},
  Description      -> "Inverse of the EW coupling constant at the Z
pole"
 },
```

For the LHA cards

Dependence in the expansion parameters

Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
            ...
};
```

```
aEWM1 == {
  ParameterType   -> External,
  BlockName       -> SMINPUTS,
  OrderBlock      -> 1,
  Value           -> 127.9,
  InteractionOrder -> {QED,-2},
  Description     -> "Inverse of the EW coupling constant at the Z
pole"
  },
```

For the LHA cards

Dependence in the expansion parameters

Interaction order

In the SM : QCD the power of g_s

QED the power of e

```
aEWM1 == { ...
  InteractionOrder -> {QED,-2},
  Description      -> "Inverse of the EW coupling constant at the Z pole"
 },
```

```
vev == {...
  InteractionOrder -> {QED,-1},
  Description      -> "Higgs vacuum expectation value"
 },
```

Interaction order

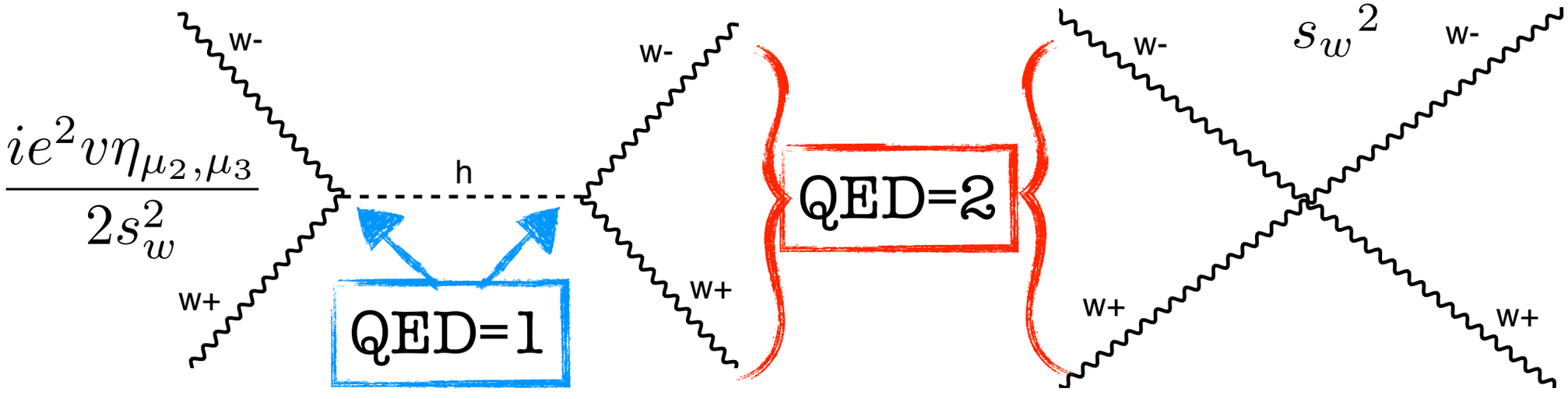
In the SM : QCD the power of g_s

QED the power of e

```
aEWM1 == { ...
  InteractionOrder -> {QED,-2},
  Description      -> "Inverse of the EW coupling constant at the Z pole"
 },
```

```
vev == {...
  InteractionOrder -> {QED,-1},
  Description      -> "Higgs vacuum expectation value"
 },
```

$$-\frac{ie^2\left(\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}+\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4}-2\eta_{\mu_1,\mu_2}\eta_{\mu_3,\mu_4}\right)}{{s_w}^2}$$



Interaction order

In the SM : QCD the power of g_s

QED the power of e

```
vev == {...
   InteractionOrder -> {QED,-1},
   Description      -> "Higgs vacuum expectation value"
  },
```

```
yu == {...
   InteractionOrder -> {QED, 1},
   Description      -> "Up-type Yukawa couplings"
  },
```

Such that masses have QED=0

However y_t is not a small parameter!

Interaction order

```
M$InteractionOrderHierarchy = {  {QCD, 1},
                                 {QED, 2}};
```

$$g_s \sim e^2$$

Interaction order

```
M$InteractionOrderHierarchy = {  {QCD, 1},
                                 {QED, 2}};
```

$$g_s \sim e^2$$

$$\mathcal{L} = \mathcal{L} + \sum_i \frac{1}{\Lambda^2} \mathcal{O}_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

`NP` the power of Λ^{-2}

`,{NP, 2}`

Interaction order

```
M$InteractionOrderHierarchy = {  {QCD, 1},
                                 {QED, 2}};
```

$$g_s \sim e^2$$

$$\mathcal{L} = \mathcal{L} + \sum_i \frac{1}{\Lambda^2} \mathcal{O}_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

NP the power of Λ^{-2}

,{NP, 2}

```
M$InteractionOrderLimit = {{NP,1}};
```

Max power per diagram of Λ^{-2} is 1

C. Degrande

Fields definition I

```
M$ClassesDescription = {
    spin1[1] == { options1 },
    spin1[2] == { options2 },
    spin2[1] == { options3 },
    ...}
```

Fields definition I

S	0
W,F	1/2
V	1
RW,R	3/2
T	2
U	-1

```
M$ClassesDescription = {
  spin1[1] == { options1 },
  spin1[2] == { options2 },
  spin2[1] == { options3 },
  ...}
```

Fields definition I

S	0
W,F	1/2
V	1
RW,R	3/2
T	2
U	-1

```
M$ClassesDescription = {
  spin1[1] == { options1 },
  spin1[2] == { options2 },
  spin2[1] == { options3 },
  ...}
```

Unique Id

Fields definition I

ClassName->..., SelfConjugate->...,
Indices->...,QuantumNumbers->...,
FlavorIndex->..., ClassMembers,
Mass->..., Witdh->..., PDG->...,
Definitions->..., Unphysical->...,
Chirality->..., MajoranaPhase->...,
WeylComponents->...,
Goldstone->..., Ghost->..., ...(Format)

S	0
W,F	1/2
V	1
RW,R	3/2
T	2
U	-1

```
M$ClassesDescription = {
  spin1[1] == { options1 },
  spin1[2] == { options2 },
  spin2[1] == { options3 },
  ...}
```

Unique Id

C. Degrande

Fields definition II

```
F[3] == {   ClassName       -> uq,
  ClassMembers    -> {u, c, t},
  Indices         -> {Index[Generation], Index[Colour]},
  FlavorIndex     -> Generation,
  SelfConjugate   -> False,
  Mass            -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
  Width           -> {0, 0, {WT,1.50833649}},
  QuantumNumbers  -> {Q -> 2/3},
  PDG             -> {2, 4, 6},
  ...
}
```

Fields definition II

Spin index

```
F[3] == {   ClassName       -> uq,
  ClassMembers    -> {u, c, t},
  Indices         -> {Index[Generation], Index[Colour]},
  FlavorIndex     -> Generation,
  SelfConjugate   -> False,
  Mass            -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
  Width           -> {0, 0, {WT,1.50833649}},
  QuantumNumbers  -> {Q -> 2/3},
  PDG             -> {2, 4, 6},
  ...
}
```

Fields definition II

Generation index distinguishes the class members

```
F[3] == {   ClassName       -> uq,
  ClassMembers     -> {u, c, t},
  Indices          -> {Index[Generation], Index[Colour]},
  FlavorIndex      -> Generation,
  SelfConjugate    -> False,
  Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
  Width            -> {0, 0, {WT,1.50833649}},
  QuantumNumbers   -> {Q -> 2/3},
  PDG              -> {2, 4, 6},
  ...
}
```

Fields definition II

```
F[3] == {   ClassName       -> uq,
  ClassMembers    -> {u, c, t},
  Indices         -> {Index[Generation], Index[Colour]},
  FlavorIndex     -> Generation,
  SelfConjugate   -> False,
  Mass            -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
  Width           -> {0, 0, {WT,1.50833649}},
  QuantumNumbers  -> {Q -> 2/3},
  PDG             -> {2, 4, 6},
  ...
}
```

Same representation

Fields definition II

```
F[3] == {   ClassName       -> uq,
  ClassMembers    -> {u, c, t},
  Indices         -> {Index[Generation], Index[Colour]},
  FlavorIndex     -> Generation,
  SelfConjugate   -> False,
  Mass            -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
  Width           -> {0, 0, {WT,1.50833649}},
  QuantumNumbers  -> {Q -> 2/3},
  PDG             -> {2, 4, 6},
  ...
}
```

External parameters

Fields definition II

```
F[3] == {   ClassName       -> uq,
  ClassMembers    -> {u, c, t},
  Indices         -> {Index[Generation], Index[Colour]},
  FlavorIndex     -> Generation,
  SelfConjugate   -> False,
  Mass            -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
  Width           -> {0, 0, {WT,1.50833649}},
  QuantumNumbers  -> {Q -> 2/3},
  PDG             -> {2, 4, 6},
  ...
}
```

External parameters

Generic label

```
Mass -> {MW, Internal}
Mass -> {MZ, 91.188}
Mass -> {{MU,0}, {MC,0}, {MT, 174.3}}
Mass -> {Mu, {MU, 0}, {MC, 0}, {MT, 174.3}}
```

Fields definition II

```
F[3] == {   ClassName       -> uq,
  ClassMembers    -> {u, c, t},
  Indices         -> {Index[Generation], Index[Colour]},
  FlavorIndex     -> Generation,
  SelfConjugate   -> False,
  Mass            -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
  Width           -> {0, 0, {WT,1.50833649}},
  QuantumNumbers  -> {Q -> 2/3},
  PDG             -> {2, 4, 6},
  ...
}
```

Not used in FR but by following codes

Fields definition III

Interaction eigenstates

```
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]}
  }
```

FR does not export them to matrix element code

Physical fields

Fields definition IV

```
U[11] == {
   ClassName     -> ghB,
   Unphysical    -> True,
   SelfConjugate -> False,
   Ghost         -> B,
   Definitions   -> { ghB -> -sw ghZ + cw ghA}
  },

S[2] == {
   ClassName      -> G0,
   SelfConjugate  -> True,
   Goldstone      -> Z,
   ...
  },
```

ClassName of the boson

Gauge Groups

```
M$GaugeGroups = {
 U1Y == {
  Abelian          -> True,
  CouplingConstant -> g1,
  GaugeBoson       -> B,
  Charge           -> Y
 },...
 SU3C == {
  Abelian          -> False,
  CouplingConstant  -> gs,
  GaugeBoson       -> G,
  StructureConstant -> f,
  Representations   -> {T,Colour},
  SymmetricTensor   -> dSUN
 }
};
```

Gauge Groups

```
M$GaugeGroups = {
 U1Y == {
  Abelian         -> True,
  CouplingConstant -> g1,
  GaugeBoson      -> B,
  Charge          -> Y
 },...
 SU3C == {
  Abelian         -> False,
  CouplingConstant  -> gs,
  GaugeBoson      -> G,
  StructureConstant -> f,
  Representations   -> {T,Colour},
  SymmetricTensor   -> dSUN
 }
};
```

Gauge Groups

```
M$GaugeGroups = {
 U1Y == {
  Abelian          -> True,
  CouplingConstant -> g1,
  GaugeBoson       -> B,
  Charge           -> Y
 },...
 SU3C == {
  Abelian          -> False,
  CouplingConstant -> gs,
  GaugeBoson       -> G,
  StructureConstant -> f,
  Representations  -> {T,Colour},
  SymmetricTensor  -> dSUN
 }
};
```

Gauge Groups

```
M$GaugeGroups = {
 U1Y == {
  Abelian          -> True,
  CouplingConstant -> g1,
  GaugeBoson       -> B,
  Charge           -> Y
 },...
 SU3C == {
  Abelian          -> False,
  CouplingConstant  -> gs,
  GaugeBoson       -> G,
  StructureConstant -> f,
  Representations   -> {T,Colour},
  SymmetricTensor   -> dSUN
 }
};
```

Generator label

Associated index

Gauge groups

FS[A, mu, nu, a] ⇒ $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a{}_{bc} A^b_\mu A^c_\nu$

abelian

DC[phi, mu] ⇒ $D_\mu \phi = \partial_\mu \phi - i g A^a_\mu T_a \phi$

Lagrangian

$$\mathcal{L}^{\mathcal{QCD}} \equiv -\frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} + i\bar{d} \not{D} d$$

```
L = -1/4 FS[G, mu, nu, a] FS[G, mu, nu, a]
          +  I dqbar.Ga[mu].DC[dq, mu]
```

FeynRules creates the “anti”-particle name

Dot to avoid commuting the fermions

```
dqbar.Ga[mu].T[a].dq
    → Ga[mu,s,r] T[a,i,j] dqbar[s,f,i].dq[r,f,j]
```

FeynRules restores the indices internally

Running FeynRules

In Mathematica :

Loading Feynrules

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

Loading the model

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

Extracting the Feynman rules

```
vertsQCD = FeynmanRules[ LQCD ];
```

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

Outputting the Lagrangian

```
WriteUFO[ L ]
```

Running FeynRules

In Mathematica :

Loading Feynrules

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

Loading the model

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

All the model files should be loaded at once

Extracting the Feynman rules

```
vertsQCD = FeynmanRules[ LQCD ];
```

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

Outputting the Lagrangian

```
WriteUFO[ L ]
```

Running FeynRules

In Mathematica :

Loading Feynrules

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

Loading the model

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

Extracting the Feynman rules

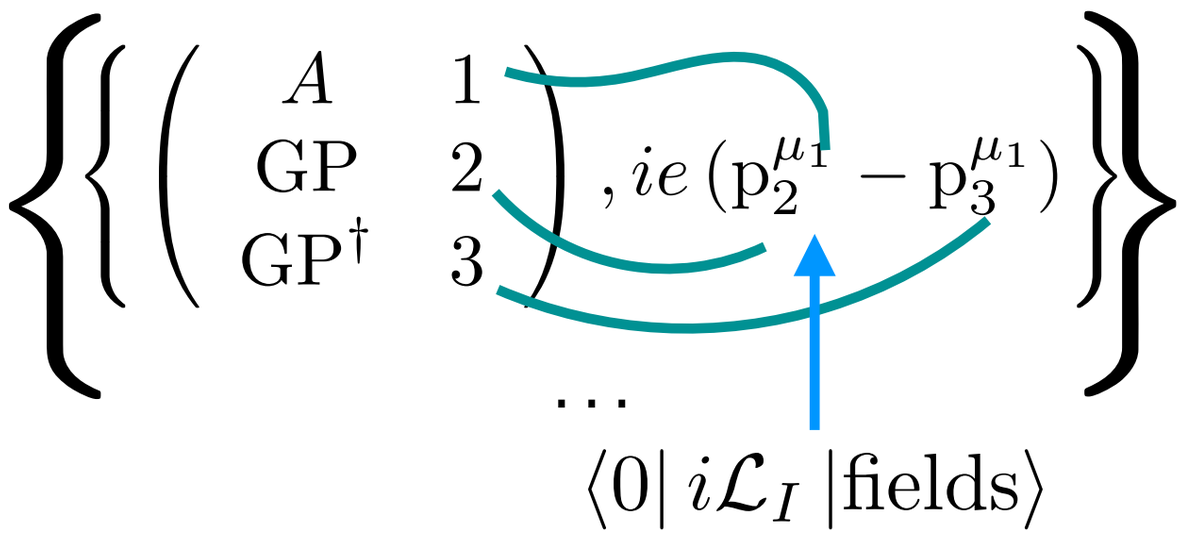
```
vertsQCD = FeynmanRules[ LQCD ];
```

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

Outputting the Lagrangian

```
WriteUFO[ L ]
```



All momenta are incoming

Running FeynRules

In Mathematica :

Loading Feynrules

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

Loading the model

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

Extracting the Feynman rules

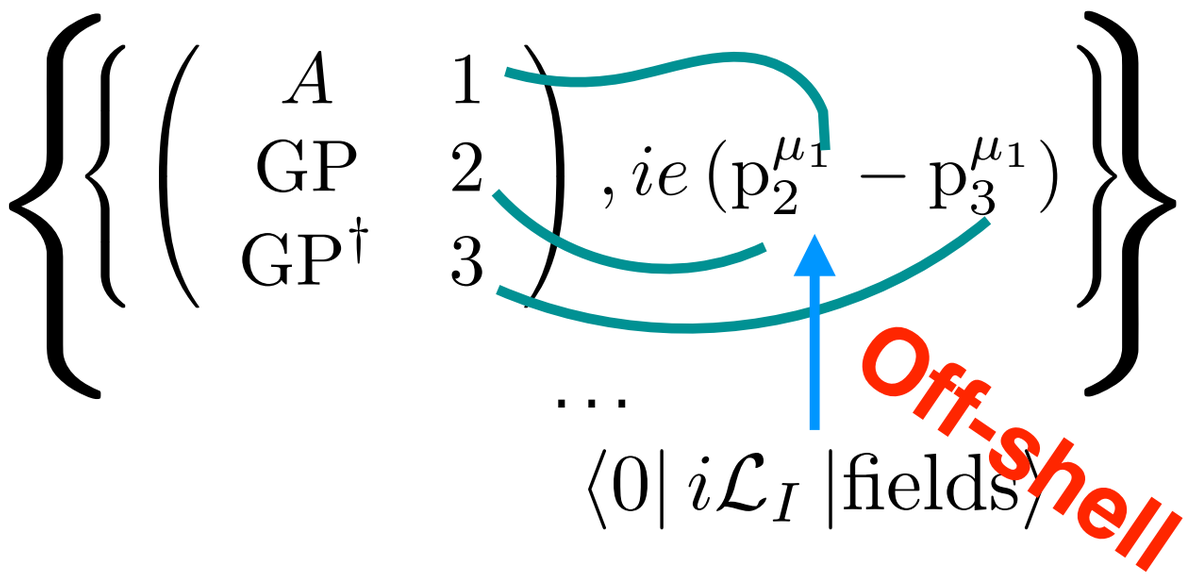
```
vertsQCD = FeynmanRules[ LQCD ];
```

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

Outputting the Lagrangian

```
WriteUFO[ L ]
```



All momenta are incoming

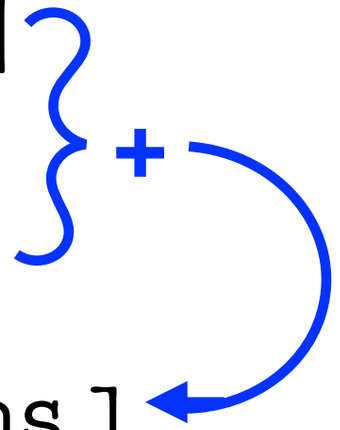
Checks

CheckHermiticity[L, options]

CheckDiagonalKineticTerms[L, options]

CheckDiagonalMassTerms[L, options]

CheckDiagonalQuadraticTerms[L, options]



CheckKineticTermNormalisation[L, options]

$$\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 \qquad \frac{1}{2}\bar{\lambda}i\partial\!\!\!/\lambda - \frac{1}{2}m\bar{\lambda}\lambda \qquad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2A_\mu A^\mu$$

$$\partial_\mu\phi^\dagger\partial^\mu\phi - m^2\phi^\dagger\phi \qquad \bar{\psi}i\partial\!\!\!/\psi - m\bar{\psi}\psi \qquad -\frac{1}{2}F^\dagger_{\mu\nu}F^{\mu\nu} - m^2A^\dagger_\mu A^\mu$$

CheckMassSpectrum[L, options]

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Toolbox

ExpandIndices[L, options]

GetKineticTerms[L, options]

GetMassTerms[L, options]

GetQuadraticTerms[L, options]

GetInteractionTerms[L, options]

SelectFieldContent[L, list]

Check your model in MG

check gauge/ permutation/ Lorentz + your process

play with coupling order, check the diagrams

check the behaviour of your model, high energy, resonance

BSM at one loop

- Why
  - LHC : QCD correction are larges
  - loop induced processes may dominate (DM DM to 2 photons, scalar production ‘a la Higgs’)
- How :
  - Automated based on development done in FeynRules and MadGraph5_aMC@NLO

R_2

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

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

d 4 ε

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

Finite set of vertices that can be computed once for all

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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

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

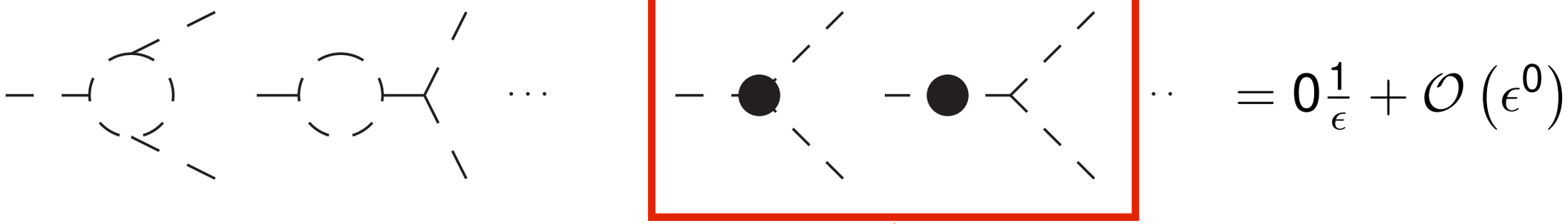
$$\int d^n\bar{q}\frac{\tilde{q}^2}{\bar{D}_i\bar{D}_j\bar{D}_k} = -\frac{i\pi^2}{2}+\mathcal{O}(\epsilon)\,,$$

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

Only R = R_1+R_2 is gauge invariant ⇨ Check

UV

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



Relations fixed by the Lagrangian (finite part)

Finite set of vertices that can be computed once for all

C. Degrande

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

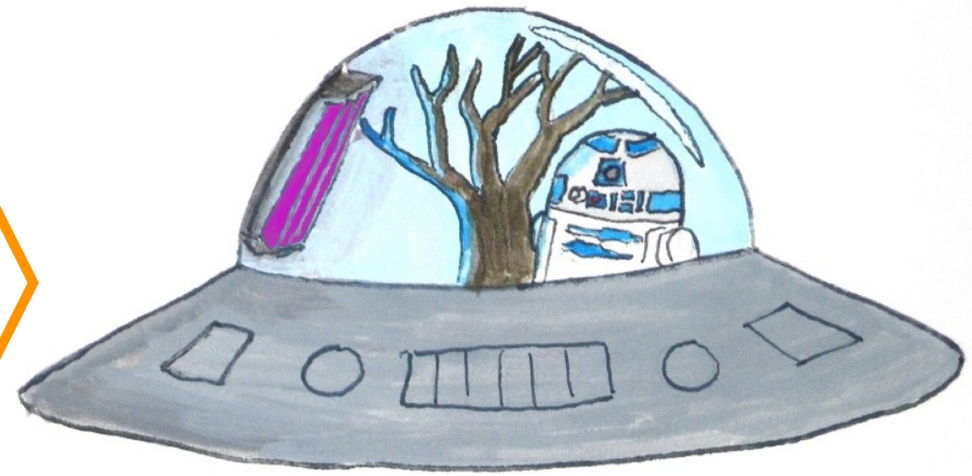
How does it work?

FeynRules

Renormalize the Lagrangian

model.mod

model.gen



model.nlo

FeynArts

Write the amplitudes

NLOCT.m

Compute the NLO vertices

Restrictions/Assumptions

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

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

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

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

C. Degrande

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

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

C. Degrande

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 ===

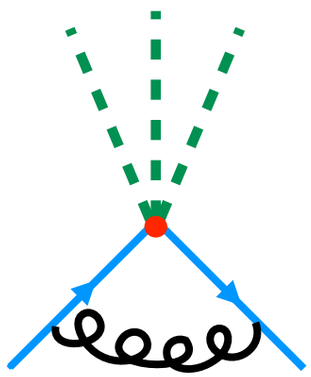
1/1 passed, 0/1 failed=== Finite ===

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

C. Degrande

EFT at NLO



In the loop:
same as SM
+axial anomaly

$$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$$

$$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$$

$$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$

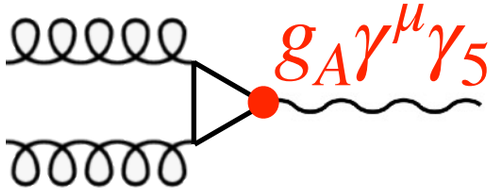
$$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$$

More momenta: higher rank of the integral numerator

Additional gamma and colour algebra

$$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$$

Axial anomaly



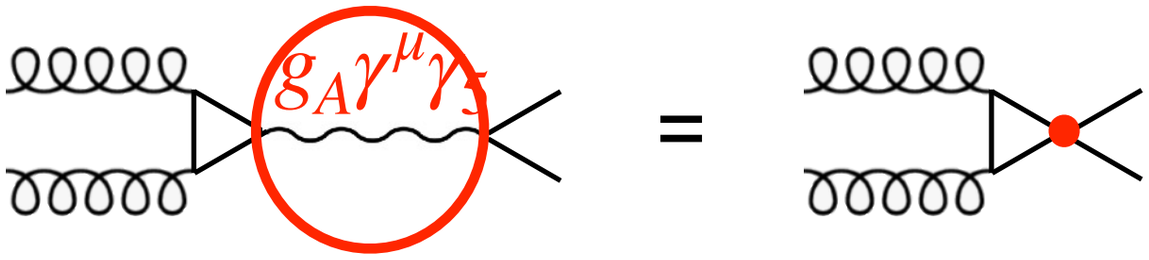
SM:

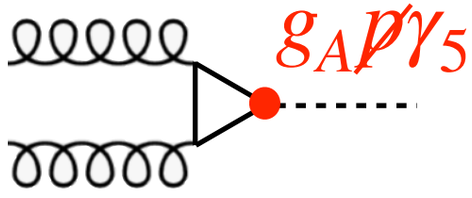
$$g_A^u = g_A^c = g_A^t = -\,g_A^d = -\,g_A^s = -\,g_A^b$$

SMEFT:

$$g_A^u \neq g_A^c \neq g_A^t \neq -\,g_A^d \neq -\,g_A^s \neq -\,g_A^b$$

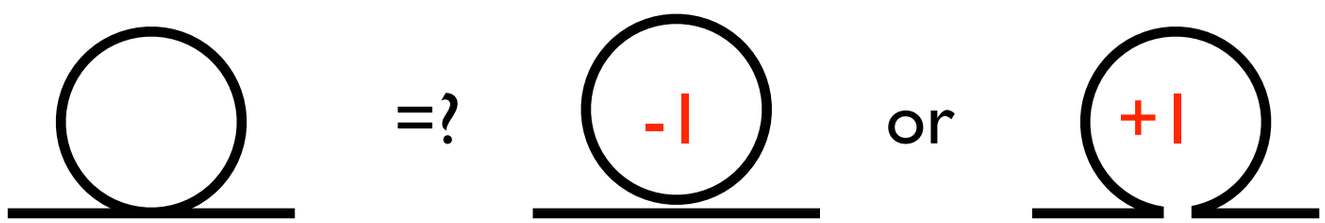
+ modification of quarks-gluon vertex (chromo)



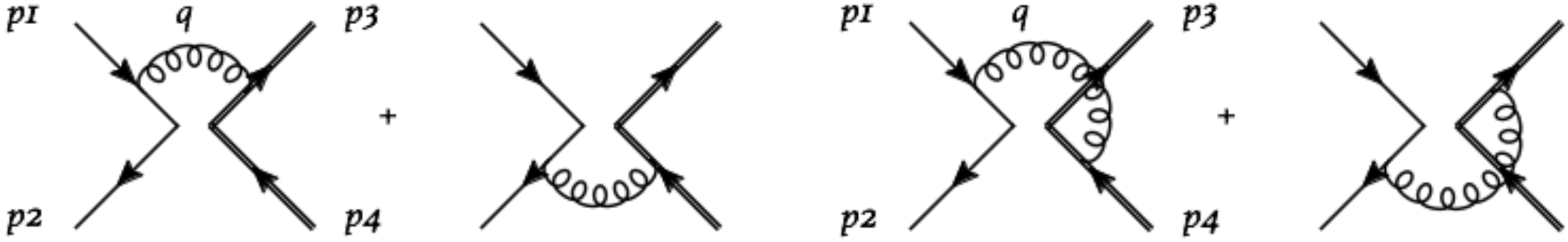


$$\propto \epsilon^{p_1 p_2 \mu_1 \mu_2}$$

EFT at NLO



Evanescent operators: $O_{ut}^{(8)} = \left(\bar{u}\gamma^{\mu}T^{A}u\right)\left(\bar{t}\gamma_{\mu}T^{A}t\right)$



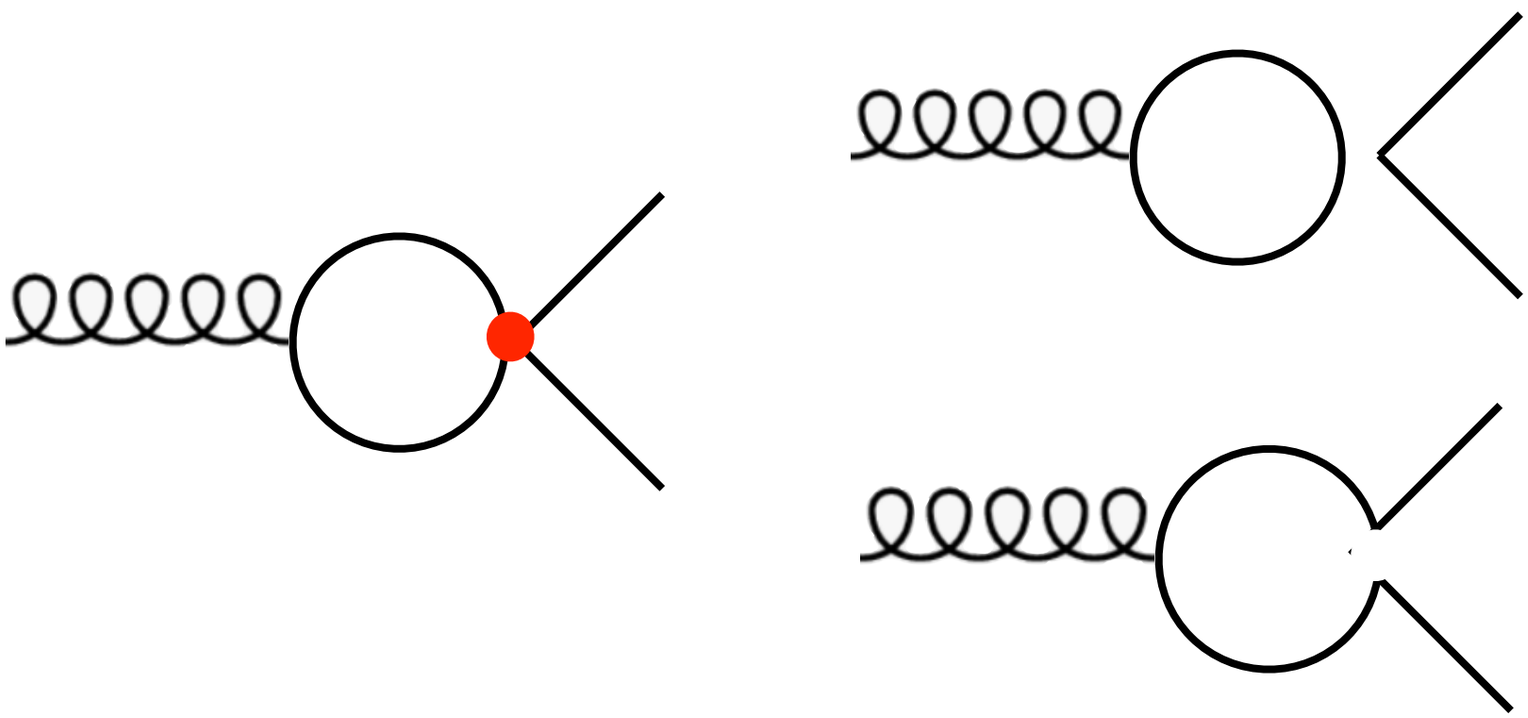
$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}P_R \otimes \gamma_{\mu}\gamma_{\nu}\gamma_{\rho}P_R = E + (16 - 4a\varepsilon)\gamma^{\mu}P_R \otimes \gamma_{\mu}P_R$$
$$\gamma^{\mu}\gamma^{\nu}\gamma^{\rho}P_R \otimes \gamma_{\rho}\gamma_{\nu}\gamma_{\mu}P_R = -E + [4 - (12 - 4a)\varepsilon]\gamma^{\mu}P_R \otimes \gamma_{\mu}P_R$$

Extra R2 (gauge invariant)
Change the UV matching

C. Degrande

4F to 2F R2

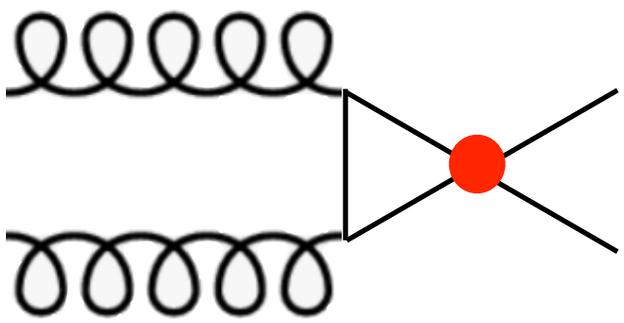
$$\mathcal{O}^1 = \bar{t}_R \gamma^\mu t_R \bar{t}_R \gamma^\mu t_R \sim \bar{t}_R \gamma^\mu T^a t_R \bar{t}_R \gamma^\mu T^a t_R = \mathcal{O}^8$$



<u>R2 difference :</u>

- gauge inv.
- basis dependent

Connected by gauge invariance and operator to



SMEFT@NLO

- C.D., G. Durieux, F. Maltoni, K. Mimasu, E Vryonidou, C. Zhang, 2008.11743

Tutorial

Notation	Spin	Mass	SU(3)	SU(2)	U(1)
Φ_1	0	M_1	1	1	0
Φ_2	0	M_2	1	1	0
U	1/2	M_U	3	1	2/3
E	1/2	M_E	1	1	-1

$$M_U > M_2 > M_L > M_1$$

$$\mathcal{L}_{\text{s.m.}} = -\frac{m_1^2}{2}\phi_1^2 - \frac{m_2^2}{2}\phi_2^2 - m_{12}^2\phi_1\phi_2$$

+Gauge kinetic term

$$\mathcal{L}_{\text{f.m.}} = M_U\bar{U}U + M_E\bar{E}E$$

$$\mathcal{L}_{\text{Yuk}} = \lambda_1\phi_1\bar{U}P_R u + \lambda_2\phi_2\bar{U}P_R u + \lambda_1'\phi_1\bar{E}P_R e + \lambda_2'\phi_2\bar{E}P_R e$$

$$pp \to \bar{U}U$$

$$U \to u\Phi_1\,,$$

$$U \to u\Phi_2\,, \quad \Phi_2 \to eE\,, \quad E \to e\Phi_1$$

Step 0

- Download FeynRules 2.0 from
  - https://feynrules.irmp.ucl.ac.be
- Copy the SM directory in feynrules/models and rename it Tutorial
- Create a model file Tutorial.fr (text file)

Step 1 : Model information

```
M$ModelName = "Tutorial";
M$Information = {Authors -> {"C.
Degrande"},
Version -> "1.0",
Date -> "21. 07. 2014",
Institutions -> {“UCLouvain"},
Emails ->
{“celine.degrande@uclouvain.be“}
};
```

Step 2 : parameters

- 9 new external parameters :
  - m_1, m_2, m_{12}, M_U, M_E, λ_1, λ_2, λ_1', λ_2'

See Step 3

```
M$Parameters = {
...
MM1 == {
ParameterType -> External,
Value -> 200},
...
};
```

Step 2 : parameters

- 9 new external parameters :
  - m_1, m_2, m_{12}, M_U, M_E, λ_1, λ_2, λ_1', λ_2'

See Step 3

```
M$Parameters = {
...
MM1 == {
ParameterType -> External,
Value -> 200},
...
};
```

InteractionOrder ->{NP, 1},

Step 2 : parameters

- 3 internal parameters : M_1, M_2, ϑ

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} -\sin\theta & \cos\theta \\ \cos\theta & \sin\theta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

Interaction eigenstates

Mass eigenstates

- `ParameterType` is `Internal`
- `Value` is a Mathematica expression

Step3 : fields

U	E	ϕ_1	ϕ_2	Φ_1	Φ_2
uv	ev	pi1	pi2	p1	p2

S

```
M$ClassesDescription = {
...
F[100] == {
ClassName -> uv,
SelfConjugate -> False,
Indices -> {Index[Colour]},
QuantumNumbers -> {Y -> 2/3, Q -> 2/3},
Mass -> {Muv, 500},
Width -> {Wuv,1}
},
…
}
```

Unique ID (check in SM.fr)

Defined in SM

{Mpel, Internal}

Step 3 : fields

U	E	ϕ_1	ϕ_2	Φ_1	Φ_2
uv	ev	pi1	pi2	p1	p2

```
S[100] == {
ClassName -> pi1,
SelfConjugate -> True,
Indices -> {},
Unphysical -> True,
Definitions -> {pi1 -> - Sin[th] p1 +
Cos[th] p2}
},
```

Step 4 : Lagrangian

```
$FeynRulesPath =
SetDirectory[“~/feynrules"];
<< FeynRules`

SetDirectory[ $FeynRulesPath <> "/Models/
Tutorial”]

LoadModel["SM.fr", "Tutorial.fr"]
LoadRestriction["DiagonalCKM.rst",
"Massless.rst"]
```

Step 4 : Lagrangian

```
1/2 del[pi1, mu]del[pi1, mu] - 1/2 MM1^2 pi1^2
Lint:=lam1 pi1 uvbar.ProjP.t
HC[Lint]

I uvbar.Ga[mu].DC[uv, mu] - Muv uvbar.uv
```

Step 4 : Lagrangian

```
1/2 del[pi1, mu]del[pi1, mu] - 1/2 MM1^2 pi1^2
Lint:=lam1 pi1 uvbar.ProjP.t
HC[Lint]

I uvbar.Ga[mu].DC[uv, mu] - Muv uvbar.uv
```

Fermion anti-commute

Step 5 : run FeynRules

```
vertices = FeynmanRules[ LNew ];
CheckMassSpectrum[ LNew ]
ComputeWidths[vertices];
PartialWidth[ {uv, t, p1} ]
TotWidth[ uv ]
BranchingRatio[ {uv, t, p1}]
SetDirectory[“~/mg5amcnlo/models”];
WriteUFO[ LSM + LNew ];
```

Step 6 : run in MadGraph

run checks!

Run your process as in the SM

Check diagrams, distributions, …

Step 7 : NLO

```
Lren = OnShellRenormalization[LSM + LNew, QCDOnly -> True,
FlavorMixing -> False]; // Timing

SetDirectory["~/FeynArts-3.8/Models"];
WriteFeynArtsOutput[Lren, GenericFile -> False,
  Output -> "Tutorial"]; // Timing

Quit[]
```

```
SetDirectory["~/FeynArts-3.xx"];
<< FeynArts`
SetDirectory[“~/feynrules-current"]
<< NLOCT`

SetDirectory[“~/feynrules-current/Models/tutorial“]
WriteCT["Tutorial/Tutorial", "Lorentz", QCDOnly -> True,
 Exclude4ScalarsCT -> True,
 ZeroMom -> {{aS, {F[14], V[4], -F[14]}}}] // Timing
```

Step 7 : NLO

```
Quit[]

SetDirectory[“~/feynrules-current/Models/tutorial“]
Get[“Tutorial.nlo"]

SetDirectory["~/mg5amcnlo/models"];
WriteUFO[LSM + LNew, Output -> "Tutorial_NLO",
 R2Vertices -> R2$vertlist, UVCounterterms -> UV$vertlist]
```

More information

Tutorial of MC4BSM 1209.0297v1

FeynRules manual

NLOCT manual : 1406.3030