FeynRules

a way to make BSM phenomenology easy.

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Outline

1. Motivation: a roadmap to BSM at the LHC
2. FeynRules
3. Model database and validation status
4. Summary - outlook

Outline

A roadmap to BSM at the LHC (1)

Models

Theoretical works

* **Pen&pencil stage.**
* Leading order, loop calculations, ...
* Electroweak, low energy constraints,...

Phenomenological works

* **Monte Carlo event generation.**
  $\Rightarrow$ **Feynman rules tables!**
* Generic detector simulation, ...
* Signal/background studies.

Experimental works

* **Validated experimental framework.**
  $\Rightarrow$ **Contains Monte Carlo generators!**
* Realistic detector simulation, ...
* Comparison with data.

$\Leftrightarrow$ **Data**

How to go from models to data?

A roadmap to BSM at the LHC (2)

Models

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Theoretical works

* **Pen&pencil stage.**
* Leading order, loop calculations, ...
* Electroweak, low energy constraints,...

↓↑

Phenomenological works

* **Monte Carlo event generation.**
  ⇒ **Feynman rules tables!**
* Generic detector simulation, ...
* Signal/background studies.

↓↑

Experimental works

* **Validated experimental framework.**
  ⇒ **Contains Monte Carlo generators!**
* Realistic detector simulation, ...
* Comparison with data.

⇔ **Data**

Solution 1: do it yourself!

- ✔ Control over the implementation.
- ✘ Incredibly hard.
- ✘ Not portable.
- ✘ Must be validated.
- ✘ Must be validated for exp. software.

A roadmap to BSM at the LHC (3)

Models

Theoretical works

* **Pen&pencil stage.**
* Leading order, loop calculations, ...
* Electroweak, low energy constraints,...

Phenomenological works

* **Monte Carlo event generation.**
  $\Rightarrow$ **Feynman rules tables!**
* Generic detector simulation, ...
* Signal/background studies.

Experimental works

* **Validated experimental framework.**
  $\Rightarrow$ **Contains Monte Carlo generators!**
* Realistic detector simulation, ...
* Comparison with data.

$\Leftrightarrow$ **Data**

Solution 2: existing MC.

- *e.g.* MadGraph, Sherpa, Pythia, Herwig, ...
- ✔ No new validation.
- ✔ Validated for exp. software.
- ✘ Not portable.
- ✘ Imposed conventions.
- ✘ Imposed implementation.

A roadmap to BSM at the LHC (4)

Models ⇔ **FEYNRULES**

Theoretical works

* **Pen&pencil stage.**
* Leading order, loop calculations, ...
* Electroweak, low energy constraints,...

Phenomenological works

* **Monte Carlo event generation.**
  ⇒ **Feynman rules tables!**
* Generic detector simulation, ...
* Signal/background studies.

Experimental works

* **Validated experimental framework.**
  ⇒ **Contains Monte Carlo generators!**
* Realistic detector simulation, ...
* Comparison with data.

⇔ **Data**

Solution 3: FeynRules.

- Communicates with MadGraph, Sherpa, (Pythia, Herwig), ...
- ✔ No new MC validation.
- ✔ MC validated for exp. software.
- ✔ Mathematica based.
- ✔ Portable.

Outline

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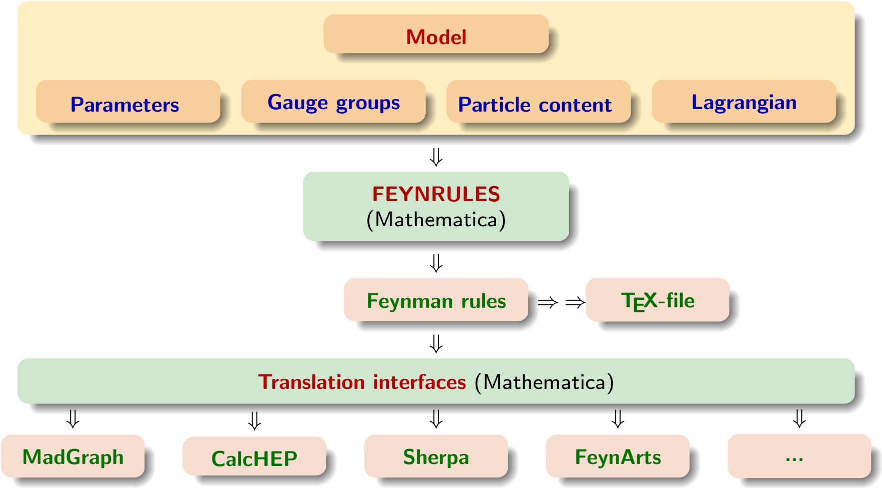
FeynRules


Model
Parameters
Gauge groups
Particle content
Lagrangian
FEYNRULES
(Mathematica)
Feynman rules
TEX-file
Translation interfaces (Mathematica)
MadGraph
CalcHEP
Sherpa
FeynArts
...

Example: QCD - Parameters

Parameters of the model

```
aS == {
    Description       -> "Strong coupling constant at MZ"
    Tex               -> Subscript[\[Alpha],s],
    ParameterType     -> External,
    BlockName         -> SMINPUTS,
    OrderBlock        -> 3,
    InteractionOrder -> {QCD, 2}},
gs == {
    Description       -> "Strong coupling constant",
    TeX               -> Subscript[g, s],
    ComplexParameter -> False,
    ParameterType     -> Internal,
    Value             -> Sqrt[4 Pi aS],
    InteractionOrder -> {QCD, 1},
    ParameterName     -> "G"}
```

* **All the information** needed by the MC codes.
* **TEX-form** (for the TEX-file).
* **Complex/real** parameters.
* **External/internal** parameters.

Example: QCD - Gauge group and gauge boson

The $SU(3)_C$ gauge group

```
SU3C == {
  Abelian              -> False,
  GaugeBoson           -> G,
  StructureConstant    -> f,
  DTerm                -> dSUN,
  Representations      -> {T, Colour},
  CouplingConstant     -> gs}
```

Gluon field definition

```
V[1] == {
  ClassName          -> G,
  SelfConjugate      -> True,
  Indices            -> Index[Gluon],
  Mass               -> 0,
  Width              -> 0,
  ParticleName       -> "g",
  PDG                -> 21,
  PropagatorLabel    -> "G",
  PropagatorType     -> C,
  PropagatorArrow    -> None}
```

* **Gauge boson** definition.
* **Gauge group** definition.
* Association of a **coupling constant**.
* Definition of the **structure functions**.
* Definition of the **representations**.

Example: QCD - Quark fields

The quark fields

```
F[1] == {
  ClassName        -> q,
  ClassMembers     -> {d, u, s, c, b, t},
  FlavorIndex      -> Flavour,
  SelfConjugate    -> False,
  Indices          -> {Index[Flavour],Index[Colour]},
  Mass             -> {MQ, MD, MU, MS, MC, MB, MT},
  Width            -> {WQ, 0, 0, 0, 0, 0, WT},
  ParticleName     -> {"d", "u", "s", "c", "b", "t"},
  AntiParticleName -> {"d~", "u~", "s~", "c~", "b~", "t~"},
  PDG              -> {1, 2, 3, 4, 5, 6},
  PropagatorLabel  -> {"q", "d", "u", "s", "c", "b", "t"},
  PropagatorType   -> Straight,
  PropagatorArrow  -> Forward}
```

- **Classes**: implicit sums in the Lagrangian.
- **All the information** needed by the MC codes.

Example: QCD - Lagrangian

The QCD Lagrangian

```
LQCD = -1/4 * FS[G, mu, nu, a] * FS[G, mu, nu, a] +

  I*qbar.Ga[mu].del[q, mu] - MQ[f] * qbar[s,f,c].q[s,f,c] +

  gs * G[mu,a] * qbar.Ga[mu].T[a].q
```

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_f \Big[\bar q_f \big(i\partial\!\!\!/ - m_f + g_s G\!\!\!/^{\,a} T^a \big) q_f \Big],$$

where we are summing over the quark flavours.

- **Gluon strength tensor**: automatically defined with the gauge group.
- **Implicit summations** $\Rightarrow$ easy debugging.

Example: QCD - Results

Results - let us do (some) phenomenology!

```
FeynmanRules[LQCD, FlavorExpand->False]

    Vertex 1
    Particle 1 : Vector , G
    Particle 2 : Dirac , q†
    Particle 3 : Dirac , q
    Vertex:
```

$$i\, g_s\, \gamma^{\mu_1}_{s_2,s_3}\, \delta_{f_2,f_3}\, T^a_{m_2,m_3}$$

```
    WriteFeynArtsOutput[LQCD]
    WriteCHOutput[LQCD]
    WriteMGOutput[LQCD]
    WriteSHOutput[LQCD]
```

Explicit **flavour expansion**: six vertices instead of one.

Outline

Model database

- **Publicly available (FeynRules v1.2.5)**:
  - * **The Standard Model** (SM) [N. Christensen, C. Duhr].
  - * **Higgs effective theory (large m_{top} approximation)** [C. Duhr].
  - * **The Three-Site Model** [N. Christensen].
    - 5D $SU(2) \times SU(2) \times U(1)$ theory in a slice of Anti-deSitter space.
    - Gauge invariant higgsless model.
    - Heavy ($\approx$ 400 GeV) and nearly degenerate extra gauge bosons.
    - SM-like plus new fermionic states.
  - * **The Hill Model** [P. Aquino, C. Duhr].
    - SM plus an additional scalar sector coupling only to the Higgs.
    - Two Higgs fields after mass matrix diagonalization.
- **Soon publicly available**:
  - * **The general MSSM** (with 105 free parameters) [BenjF].
  - * **Minimal universal extra dimensions** [P. Aquino].
  - * **Effective QCD for the pseudoscalar nonet** [C. Degrande].
  - * **Four generations models** with right-handed neutrinos [BenjF, M. Spannowsky].
  - * **Left-right symmetric models** [L. Basso].
  - * **Little Higgs model** [T. Figy].
  - * **Effective quantum gravity** [BenjF, C. Reuschle].
  - * **Type-III See-Saw model** [R. Franceschini].

Validation sheet

- **FeynArts/FormCalc:**
  - Use of the **FeynRules** version of the FeynArts model files.
  - **Check of the FormCalc-produced formulas with litterature.**
  - Used versions: **FormCalc-5.4** and **FormCalc-6.0**.
- **MadGraph/MadEvent**:
  - Comparison between (existing) **stock** and **FeynRules** model files.
  - Test of various $2 \longrightarrow 2$ and $2 \longrightarrow 3$ processes.
  - Used version: **MadGraph-4.4.17**.
- **CalcHEP/CompHEP:**
  - Comparison between (existing) **stock** and **FeynRules** model files.
  - **Test of both Feynman and unitary gauges.**
  - Test of various $2 \longrightarrow 2$ and $2 \longrightarrow 3$ processes.
  - Used version: **CalcHEP-2.5**.
- **Sherpa:**
  - To be done...

Example: validation status of the MSSM (1)

- **Handmade vs. automated implementation.**
  - * 2522 vertices, without the four-scalar interactions.
  - * **More that 10000 vertices, with the four-scalar interactions !!!**
- **FeynArts/FormCalc:** ongoing...
  - ✔ **FormCalc-5.4: all** $2 \rightarrow 2$ **SUSY particle pair hadroproduction processes**.
  - ✔ **FormCalc-6.0: in the flavour conserving MSSM (cMSSM) limit**.
  - ➠ **FormCalc-6.0: almost there in the general MSSM**.
- ✔ **MadGraph/MadEvent** (in the cMSSM limit):
  - * MG-Stock was validated by the CATPISS collaboration [Hagiwara *et al.* (2006)].
  - ✔ **320 decay widths.**
  - ✔ **456** $2 \rightarrow 2$ **SUSY processes.**
  - ✔ **2708** $2 \rightarrow 3$ **SUSY processes.**

The signs and absolute values of all the vertices have been checked.

- **CalcHEP/CompHEP (in the cMSSM):** ongoing check for $2 \rightarrow 2$ processes.
  - * **Some bugs found in the stock version!**

Example: validation status of the MSSM (2)

Some MadGraph and CalcHEP results

Process	MG-FR	MG-Stock	CH-FR	CH-Stock	Result
e+,e->e+,e-	7.5203×10^{2}	7.5216×10^{2}	7.5137×10^{2}	7.5137×10^{2}	OK: 0.105086%
e+,e->vm,vm~	1.5268×10^{-3}	1.5285×10^{-3}	1.5261×10^{-3}	1.5262×10^{-3}	OK: 0.15714%
e+,e->t,t~	1.1098×10^{-2}	1.1101×10^{-2}	1.1108×10^{-2}	1.1114×10^{-2}	OK: 0.144066%
e+,e->d,d~	5.6391×10^{-3}	5.6597×10^{-3}	5.6465×10^{-3}	5.6465×10^{-3}	OK: 0.36464%
e+,e->W+,W-	2.8014×10^{-1}	2.801×10^{-1}	2.8008×10^{-1}	2.8009×10^{-1}	OK: 0.0214202%
e+,e->Z,Z	1.535×10^{-2}	1.5347×10^{-2}	1.5347×10^{-2}	1.5347×10^{-2}	OK: 0.0195459%
e+,e->Z,a	6.2902×10^{-2}	6.2901×10^{-2}	6.292×10^{-2}	6.292×10^{-2}	OK: 0.0302016%
e+,e->sl5-,sl5+	3.2044×10^{-2}	3.2002×10^{-2}	3.2039×10^{-2}	3.2039×10^{-2}	OK: 0.131156%
e+,e->sl2-,sl2+	3.6401×10^{-2}	3.641×10^{-2}	3.64×10^{-2}	3.64×10^{-2}	OK: 0.0274688%
e+,e->sl5-,sl2+	2.0292×10^{-3}	2.0269×10^{-3}	2.0291×10^{-3}	2.0291×10^{-3}	OK: 0.113409%
e+,e->sl1-,sl1+	1.6061×10^{-3}	1.6061×10^{-3}	1.6054×10^{-3}	1.6054×10^{-3}	OK: 0.0435933%
e+,e->sv3,sv3~	9.5578×10^{-2}	9.5567×10^{-2}	9.554×10^{-2}	9.5542×10^{-2}	OK: 0.039766%
e+,e->su4,su4~	2.9679×10^{-3}	2.9676×10^{-3}	2.9692×10^{-3}	2.9692×10^{-3}	OK: 0.0539011%
e+,e->su1,su1~	1.9518×10^{-3}	1.9486×10^{-3}	1.9517×10^{-3}	1.9517×10^{-3}	OK: 0.164086%
e+,e->su6,su6~	2.2021×10^{-3}	2.2041×10^{-3}	2.202×10^{-3}	2.202×10^{-3}	OK: 0.0953224%
e+,e->su1,su6~	4.4196×10^{-4}	4.4134×10^{-4}	4.4155×10^{-4}	4.4155×10^{-4}	OK: 0.140383%
e+,e->sd4,sd4~	4.9197×10^{-4}	4.926×10^{-4}	4.9192×10^{-4}	4.9192×10^{-4}	OK: 0.138138%
e+,e->sd6,sd6~	2.0014×10^{-3}	2.0012×10^{-3}	2.0016×10^{-3}	2.0016×10^{-3}	OK: 0.019986%
e+,e->sd1,sd2~	2.1502×10^{-4}	2.149×10^{-4}	2.1494×10^{-4}	2.1494×10^{-4}	OK: 0.0558243%
e+,e->n1,n1	7.6112×10^{-3}	7.6075×10^{-3}	7.6077×10^{-3}	7.6076×10^{-3}	OK: 0.0486244%
e+,e->n1,n2	2.7949×10^{-3}	2.792×10^{-3}	2.7942×10^{-3}	2.7943×10^{-3}	OK: 0.103814%
e+,e->n2,n3	4.1779×10^{-4}	4.1709×10^{-4}	4.17×10^{-4}	4.1701×10^{-4}	OK: 0.189269%
e+,e->n2,n4	7.5931×10^{-4}	7.5959×10^{-4}	7.5912×10^{-4}	7.5914×10^{-4}	OK: 0.0618946%
e+,e->n4,n4	3.5319×10^{-5}	3.531×10^{-5}	3.5317×10^{-5}	3.5317×10^{-5}	OK: 0.0254853%
e+,e->x1+,x1-	1.204×10^{-2}	1.2038×10^{-2}	1.2039×10^{-2}	1.2039×10^{-2}	OK: 0.0166127%
e+,e->x2+,x2-	7.0411×10^{-3}	7.0479×10^{-3}	7.0494×10^{-3}	7.0494×10^{-3}	OK: 0.11781%
e+,e->Z,h1	7.6379×10^{-4}	7.6496×10^{-4}	7.6477×10^{-4}	7.6478×10^{-4}	OK: 0.153066%
e+,e->Z,h2	1.0024×10^{-7}	1.0007×10^{-7}	1.0017×10^{-7}	1.0017×10^{-7}	OK: 0.169737%
e+,e->h3,h1	9.9472×10^{-8}	9.9485×10^{-8}	9.9461×10^{-8}	9.9466×10^{-8}	OK: 0.0241272%
e+,e->h3,h2	7.172×10^{-4}	7.1771×10^{-4}	7.177×10^{-4}	7.1771×10^{-4}	OK: 0.0710846%
e+,e->H+,H-	1.7338×10^{-3}	1.7338×10^{-3}	1.7355×10^{-3}	1.7355×10^{-3}	OK: 0.0980025%

Example: validation status of minimal UED model

- ✔ **MadGraph/MadEvent**:
  - * No MG-Stock.
  - ✔ **118** $2 \to 2$ **processes.**
- ✔ **CalcHEP/CompHEP**: **118** $2 \to 2$ **processes.**
  - * Stock version: Datta, Kong and Matchev implementation.
  - * **One bug found in the stock version!**

Some results

Process	MG-FR	CH-FR	CH-Stock	Result
e1R-,e1R+>u,u~	1.107×10^{-1}	1.1094×10^{-1}	1.1094×10^{-1}	OK: 0.216567%
e1R-,e1R+>d,d~	3.277×10^{-2}	3.2795×10^{-2}	3.2795×10^{-2}	OK: 0.0762602%
e1R-,e1R+>e-,e+	2.5553×10^{-1}	2.5537×10^{-1}	2.5537×10^{-1}	OK: 0.0626346%
e1R-,e1R->e-,e-	1.0714	1.0714	1.0714	OK: 0.%
e1R-,m1R->e-,m-	6.5807×10^{-1}	6.5818×10^{-1}	6.5818×10^{-1}	OK: 0.0167142%
e1R-,m1R+>e-,m+	4.7857×10^{-1}	4.7682×10^{-1}	4.7682×10^{-1}	OK: 0.366343%
e1R-,e1R+>A,A	2.0803×10^{-1}	2.0788×10^{-1}	2.0788×10^{-1}	OK: 0.072131%
n11,n11~>u,u~	1.6364×10^{-1}	1.6354×10^{-1}	1.6354×10^{-1}	OK: 0.0611284%
n11,n11~>Z,Z	4.1402×10^{-1}	4.1349×10^{-1}	4.1349×10^{-1}	OK: 0.128095%
n11,n11~>W+,W-	5.9018×10^{-1}	5.9009×10^{-1}	5.901×10^{-1}	OK: 0.0152507%
e1L-,e1L+>u,u~	2.3023×10^{-1}	2.2977×10^{-1}	2.2977×10^{-1}	OK: 0.2%
e1L-,e1L+>d,d~	1.4289×10^{-1}	1.4274×10^{-1}	1.4275×10^{-1}	OK: 0.105031%
e1L-,e1L+>e-,e+	2.5×10^{-1}	2.4978×10^{-1}	2.4978×10^{-1}	OK: 0.0880387%
e1L-,n11~>d,u~	6.3986×10^{-1}	6.3998×10^{-1}	6.3999×10^{-1}	OK: 0.0203149%
e1L-,n11~>e-,n1~	6.3118×10^{-1}	6.3132×10^{-1}	6.3133×10^{-1}	OK: 0.0237622%
e1L-,n11>e-,n1	1.0519	1.0519	1.0519	OK: 0.%
B1,B1>u,u~	9.2638×10^{-2}	9.2548×10^{-2}	9.2548×10^{-2}	OK: 0.0971996%
B1,B1>d,d~	6.1392×10^{-3}	6.1347×10^{-3}	6.1347×10^{-3}	OK: 0.0733263%
B1,B1>e+,e-	1.8444×10^{-1}	1.8411×10^{-1}	1.8411×10^{-1}	OK: 0.17908%
Z1,Z1>u,u~	3.5574×10^{-1}	3.5556×10^{-1}	3.5556×10^{-1}	OK: 0.0506116%
Z1,Z1>d,d~	3.566×10^{-1}	3.5556×10^{-1}	3.5556×10^{-1}	OK: 0.292069%
Z1,Z1>e+,e-	1.3429×10^{-1}	1.3409×10^{-1}	1.3409×10^{-1}	OK: 0.149042%
Z1,Z1>W-,W+	2.8571×10^{1}	2.8573×10^{1}	2.8573×10^{1}	OK: 0.00699986%

Example: validation status of the Three-Site model

✔ **MadGraph/MadEvent**:

* No MG-Stock.
* ✔ **224** $2 \to 2$ **processes.**

✔ **CalcHEP/CompHEP**: **224** $2 \to 2$ **processes.**

* Stock version: N. Christensen's implementation.

Some results

Process	MG-FR	CH-FR	CH-Stock	Result
~W+,W->W+,W-	3.8293×10^{1}	3.8243×10^{1}	3.8218×10^{1}	OK: 0.19605%
~W-,W+>W+,W-	3.8365×10^{1}	3.8244×10^{1}	3.8219×10^{1}	OK: 0.381281%
~W+,W->Z,Z	4.6001×10^{1}	4.5986×10^{1}	4.5956×10^{1}	OK: 0.0978718%
~W-,W+>Z,Z	4.5986×10^{1}	4.5986×10^{1}	4.5956×10^{1}	OK: 0.0652585%
~W+,W->A,Z	1.6925×10^{1}	1.6891×10^{1}	1.688×10^{1}	OK: 0.266233%
~W-,W+>A,Z	1.684×10^{1}	1.6891×10^{1}	1.688×10^{1}	OK: 0.302392%
~Z,Z>W+,W-	8.2375×10^{1}	8.2402×10^{1}	8.2349×10^{1}	OK: 0.0643395%
~Z,A>W+,W-	6.8543×10^{1}	6.871×10^{1}	6.8666×10^{1}	OK: 0.243346%
~W+,W->A,A	6.0926×10^{-16}	-1.2302×10^{-31}	3.1165×10^{-32}	Discrepancy: 200.%
~W-,W+>A,A	6.098×10^{-16}	-1.2302×10^{-31}	3.1165×10^{-32}	Discrepancy: 200.%

Process	MG-FR	CH-FR	CH-Stock	Result
u1,D1>W+,G	6.4153×10^{-2}	6.4112×10^{-2}	6.4091×10^{-2}	OK: 0.0966907%
u1,D1>W+,~Z	3.8531×10^{-1}	3.8539×10^{-1}	3.8514×10^{-1}	OK: 0.0648904%
u1,D1>~W+,~Z	4.3576×10^{-1}	4.3594×10^{-1}	4.3566×10^{-1}	OK: 0.0642497%
~u1,D1>W+,G	1.0137	1.0139	1.0136	OK: 0.0295931%
~u1,D1>~W+,G	1.1532	1.1523	1.152	OK: 0.104112%
~u1,D1>~W+,~Z	2.8898×10^{-1}	2.8845×10^{-1}	2.8826×10^{-1}	OK: 0.249463%
u1,~D1>W+,G	1.0173	1.0139	1.0136	OK: 0.36437%
u1,~D1>~W+,G	1.1543	1.1523	1.1519	OK: 0.208135%
u1,~D1>~W+,~Z	2.9225×10^{-1}	2.9273×10^{-1}	2.9254×10^{-1}	OK: 0.164108%
~u1,~D1>W+,G	1.5625×10^{-1}	1.5605×10^{-1}	1.56×10^{-1}	OK: 0.160128%
~u1,~D1>~W+,G	1.0343	1.0358	1.0355	OK: 0.144921%
~u1,~D1>W+,~Z	2.7826	2.7837	2.7819	OK: 0.0646831%
~u1,~D1>~W+,~Z	2.5678	2.5706	2.5689	OK: 0.108983%

Outline

Summary: the philosophy of FeynRules

- **Theorist-friendly environment to develop new models.**
  Mathematica-based.

- **Filling the gap between model building and collider phenomenology.**
  1) Lagrangian → FeynRules → model files for your favourite Monte Carlo codes.
  2) Monte Carlo code → phenomenology.

- **Avoid separate implementations of a model on different programs.**
  FeynRules does it for you!

- **Exploit the strengths of the different programs!**

- **The validation of the existing models is ongoing.**

- Contact us to add your favourite **model**.
- Contact us to add your favourite **Monte Carlo tool**.
- Website: **http://feynrules.phys.ucl.ac.be** .