BSM with FeynRules
Towards NLO: status and plans

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ERC Miniworkshop @ CERN
January 27, 2012

Outline

1. Status of FEYNRULES.
2. FEYNRULES at NLO - Status and plans.
3. Summary.

Implementation of BSM theories in Monte Carlo tools.

- A model consists in:
  - * **Particles**,
  - * **Parameters**,
  - * **Interactions** ($\equiv$ Feynman rules).
- The Feynman rules **have to be derived (from a Lagrangian)**.
  - **Translated in a programming language**.
    $\Rightarrow$ **Tedious, time-consuming, error prone**.
  - **Iterations** for each model.
  - **Iterations** for each MC tool.
  - Beware: **Lorentz and color structures**.
  - Beware: **validation**.

Redundancies of the work.

A framework for LHC analyzes.

[Christensen, de Aquino, Degrande, Duhr, BenjF, Herquet, Maltoni, Schumann (EPJC '11)]

Idea ≡ **Theory**
↘ **Lagrangian**
↘ FeynRules
↘ **Matrix elements (MC generators)**
↘ **Parton showering** ≡ **Phenomenology**
↘ **Hadronization**
↘ **Generic detector**
↘ **Realistic detector**
↘ **Data** ≡ **Experiment**

FeynRules in a nutshell.

[Christensen, Duhr (CPC '09); Christensen, Duhr, BenjF (in prep)]

- **A framework for LHC analyzes based on FeynRules to**:
  - * **Develop new models**.
  - * **Implement (and validate)** new models in Monte Carlo tools.
  - * Facilitate **phenomenological** investigations of the models.
  - * **Test** the models against data.

- **Main features**
  - * FeynRules is a Mathematica package.
  - * FeynRules derives **Feynman rules from a Lagrangian**.
  - * **Requirements**: locality, Lorentz and gauge invariance.
  - * **Supported fields**: scalar, fermion, vector, tensor, ghost, superfield.
  - * **Interfaces**: export the Feynman rules to Monte Carlo generators.
    CalcHep, FeynArts, MadGraph, Sherpa, Whizard
  - * **Universal FeynRules output**: MadGraph5 and GoSam.

FeynRules-1.6 - status.

- **Current public version: 1.6.0**.
  - * **To be download on http://feynrules.irmp.ucl.ac.be/**.
  - * Contains the **superspace module**. [Duhr, BenjF (CPC '11)]
  - * Contains the **UFO interface** ⇒ MadGraph5, GoSam. [Degrande, Duhr, BenjF, Grellscheid, Mattelaer, Reiter (2011)]
  - * Supports **color sextets**.
  - * Contains the new FeynArts **interface**. ⇒ **Generic Lorenz structures allowed**.
  - * Interfaced to Whizard. [Christensen, Duhr, BenjF, Reuter, Speckner (2010)]
  - * Other interfaces: CalcHep/CompHep, MadGraph4, Sherpa.
  - * **Manual currently being updated** [Christensen, Duhr, BenjF (in prep)].

- **Current online model database**.
  - * **http://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage/** .
  - * Standard Model and simple extensions (10).
  - * Supersymmetric models (4).
  - * Extra-dimensional models (4).
  - * Strongly coupled and effective field theories (4).

Outline.

NLO calculations with MadGraph - aMC@NLO.

- **Real emission**.
  - * Must include the appropriate **subtraction terms**.
    ⇒ MadFKS [Frederix, Frixione, Maltoni, Stelzer (JHEP '09)].
  - * The tree-level Feynman rules are the **only required components**.

☺ **No particular problem for BSM ⇒ problem solved.** ☺
(Use of FeynRules, its interfaces to MC tools)

- **One-loop virtual amplitudes**.
  - * Several algorithms have been proposed in the last few years.
    ⇒ MadLoop [Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau (JHEP '11)].
    ⇒ based on OPP reduction [Ossola, Papadopolous, Pittau (NPB '07)].
  - * Requirements:
    - ⋄ **Tree-level Feynman rules**.
    - ⋄ **UV renormalization counterterms**.
    - ⋄ **Rational R_2 terms**.

☹ **The two latter must be included by hand.** ☹

NLO calculations in the context of FeynRules.

- **Counterterms and R_2 terms**.
  - * ↯ **Non-automatic steps**.
  - * ☼ **Can be derived from the tree-level Lagrangian**.

☺ **All the information is already there at the FeynRules-level.** ☺

- **Automatic renormalization in the $\overline{\text{MS}}$-scheme with FeynRules**
  1. **Automated extraction of the renormalized Lagrangian** ✓.
  2. **Modification of the FeynArts interface to include counterterms** ✓.
  3. **Calculation of the renormalization constants with FormCalc**.
     - ►**Self-energies**: 80% done.
     - ►**Vertices** ✗
  4. **Re-injection in FeynRules** ✗.
- **Automatic R_2 terms** ✗.
- **The UFO at NLO**: basically there [UFO people + Hirschi]

Automatic renormalization with FeynRules.

- **Expansion of the renormalization constants (works with full Lagrangians)**.
  * The **type of the interactions** in the loops can be specified.
  * The **loop-level** can be specified.

```
ExtractCounterterms[l[s,f],{aS,1}]
```

$$\blacktriangleright l_{sf} \to l_{sf} + \frac{\alpha_s}{4\pi}\Big[(\delta Z_{ll}^{L(1)})_{ff'}\ (P_L)_{ss'} + (\delta Z_{ll}^{R(1)})_{ff'}\ (P_R)_{ss'}\Big]\ l_{s'f'}$$

```
ExtractCounterterms[ydo,{{aS,2},{aEW,1}}]
```

$$\blacktriangleright y_d \to y_d + \frac{\alpha_s}{2\pi}\delta y_d^{(1,0)} + \frac{\alpha}{2\pi}\delta y_d^{(0,1)} + \frac{\alpha_s^2}{4\pi^2}\delta y_d^{(2,0)} + \frac{\alpha_s\alpha}{4\pi^2}\delta y_d^{(1,1)} + \frac{\alpha_s^2\alpha}{8\pi^3}\delta y_d^{(2,1)}$$

- **Treatment of the internal parameters**.
  * Automatic computation of the relations among renormalization constants.
  * **Only** the ren. cnsts of the **external parameters** will have to be computed.

g_s and α_s at first order in QCD.

$$g_s = 2\sqrt{\pi\alpha_s} \qquad \Rightarrow \qquad \delta g_s^{(1)} = \frac{\sqrt{\alpha_s}}{2\sqrt{\pi}}\delta\alpha_s^{(1)}$$

Outline.

Conclusions.

- **FeynRules provides a platform to**:
  * **Develop** new models.
  * Investigate their **phenomenology**.
- **FeynRules and leading order tools**.
  * **Many interfaces** exist.
  * **Any model** (renormalizable or not) can be exported to at least one MC.
  * **MC event generation at LO**: the problem is solved (up to spin-3/2 fields).
- **NLO challenges**.
  * **Achievement of the UFO @ NLO format**.
    ►Easter '12.
  * **Automatic renormalization**.
    ►Summer '12.
  * **Automatic R_2 terms**.
    ►Summer '12 ?
- **Full merging to the NLO tools**.