FeynRules

An easy implementation of the NMFV MSSM in Monte Carlo generators.

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Interplay of Collider and Flavour Physics
2nd general meeting @ CERN
March 17, 2009

Outline

1. Motivation: a roadmap to BSM at the LHC
2. FeynRules
3. Implementation of the NMFV MSSM
4. Summary - outlook

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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

↓↑ → → → → →
↓↑ ← ← ← ← ←

Theoretical works

* **Pen&pencil stage.**
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↓↑

Phenomenological works

* **Monte Carlo event generation.**
  ⇒ **Feynman rules tables!**
* Generic detector simulation, ...
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↓↑

Experimental works

* **Validated experimental framework.**
  ⇒ **Contains Monte Carlo generators!**
* Realistic detector simulation, ...
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⇔ **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, ...
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↓↑

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 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.

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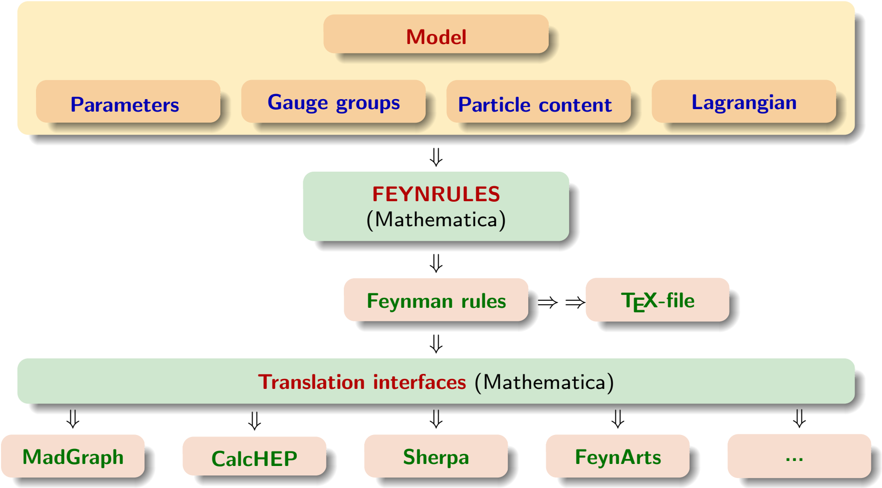
FeynRules


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

Example: QCD (1)

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 (2)

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}
```

The $SU(3)_C$ gauge group

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

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

Example: QCD (3)

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(4)

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
```

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

where we are summing over the quark flavours.

- **Gluon strength tensor**: automatically defined with the gauge group.
- **Implicit summations** ⇒ eaysy debugging.

Example: QCD (5)

Results

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

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

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

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

Let us do phenomenology!

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

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Model description

- **General version of the MSSM**.
  - **All possible mixings in the scalar sector.**
    $\Rightarrow$ 6×6 flavour violating mass matrices.
  - **All possible complex phases.**
  - **105 additional free parameters**.
    $\Rightarrow$ SLHA2-like format: the **SLHA-FR format**.
    $\Rightarrow$ $\mathrm{C}++$ translator SLHA1/2 $\Leftrightarrow$ SLHA-FR.

- **Lagrangian as easy as possible**.
  - Partially written in the interaction basis.
  - Partially written in the mass basis.

- **Handmade vs. automated implementation.**
  - 2522 vertices, without the four-scalar interactions.
  - **More that 10000 vertices, with the four-scalar interactions !!!**

Validation status

- **FeynArts/FormCalc:**
  - * Check of the FC-produced formulas with litterature.
  - ✔ **FormCalc-5.4: all** $2 \to 2$ **SUSY particle pair hadroproduction processes**.
  - ✔ **FormCalc-6.0: in the cMSSM**.
  - ➠ **FormCalc-6.0: problematic issue with the general MSSM**.
- ✔ **MadGraph/MadEvent** (in the cMSSM):
  - * Comparison between **stock** and **FeynRules** versions of the model.
  - * MG-Stock was validated by the CATPISS collaboration [Hagiwara *et al.* (2006)].
  - ✔ **320 decay widths.**
  - ✔ **456** $2 \to 2$ **SUSY processes.**
  - ✔ **2708** $2 \to 3$ **SUSY processes.**

> * The sign and absolute value of any vertex have been checked.

- **CalcHEP/CompHEP (in the cMSSM): 112** $2 \to 2$ processes.
  - * Comparison between **stock** and **FeynRules** versions of the model.
  - * Feynman gauge and unitary gauge.

Example of results

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%

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Summary - Outlook

- **FeynRules.**
  - **Mathematica package computing Feynman rules from a Lagrangian.**
  - Generic output.
  - Generating model file feeding ~~some~~ as many MC codes as possible.
    [contact us to add your favourite MC tool].
  - The model library is getting bigger and bigger.
    [contact us to add your favourite model].
  - The validation of the existing models is ongoing.

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 file for your Monte Carlo code.
  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!**