

FeynRules

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

Benjamin Fuks (IPHC Strasbourg)

In collaboration with N. Christensen (MSU), C. Duhr (UCL) & MadGraph people.

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

Outline

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

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.**
⇒ **Feynman rules tables!**
- * Generic detector simulation, ...
- * Signal/background studies.

Experimental works

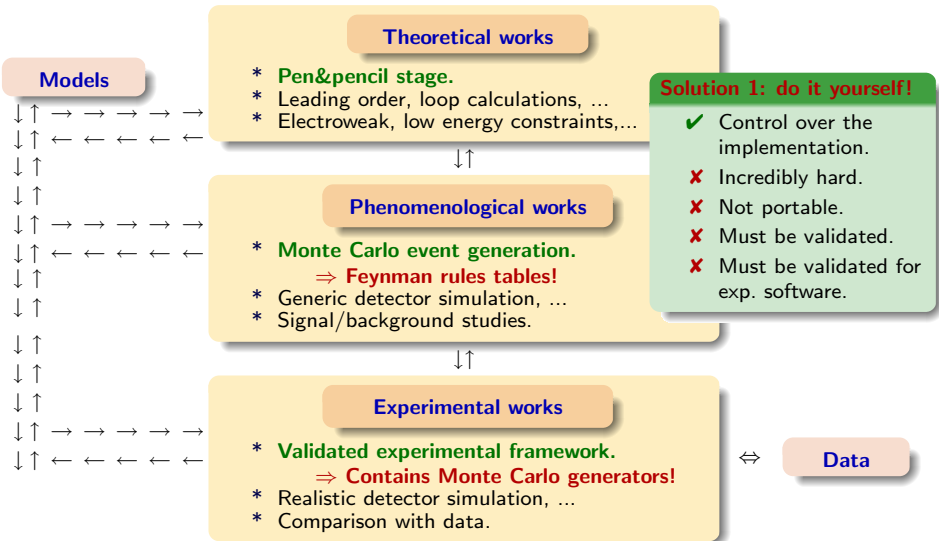
- * **Validated experimental framework.**
⇒ **Contains Monte Carlo generators!**
- * Realistic detector simulation, ...
- * Comparison with data.



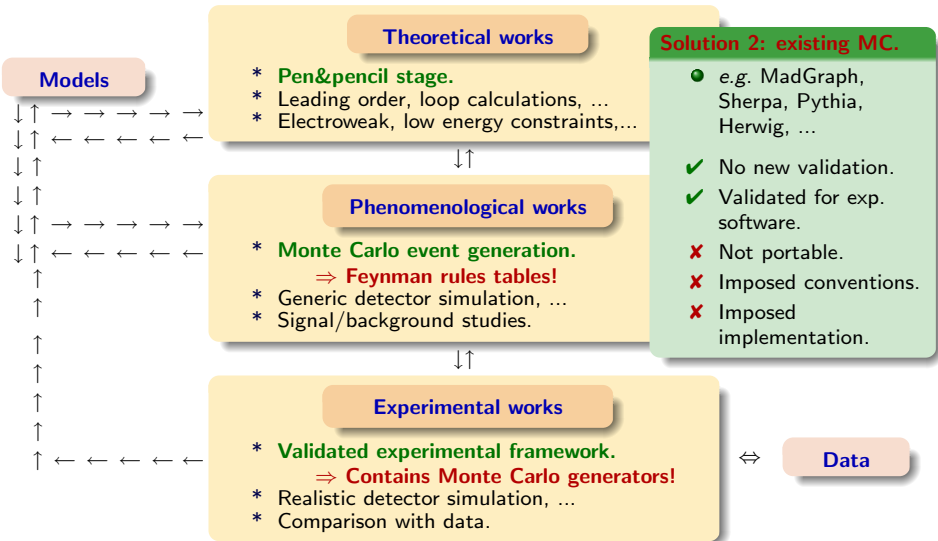
Data

How to go from models to data?

A roadmap to BSM at the LHC (2)



A roadmap to BSM at the LHC (3)



A roadmap to BSM at the LHC (4)

Models

F
E
Y
N
R
U
L
E
S



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

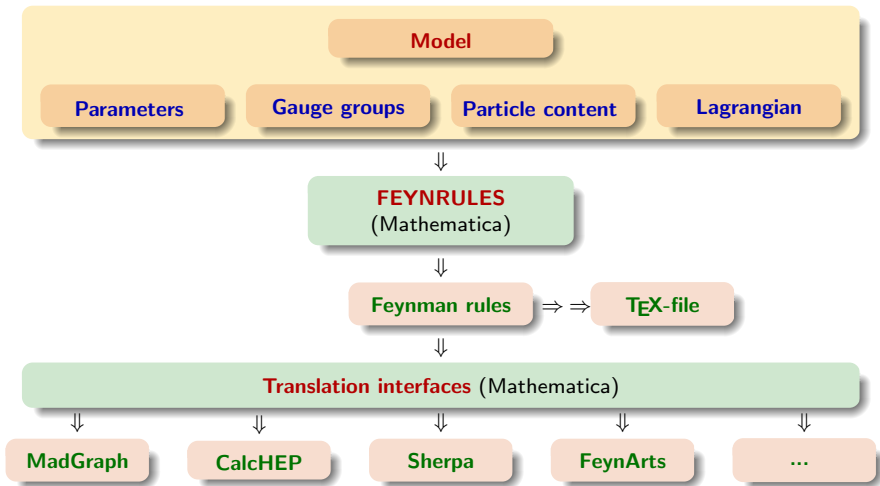
Solution 3: FeynRules.

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

Outline

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

FeynRules



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
```

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \sum_f \left[\bar{q}_f (i\not{\partial} - m_f + g_s \not{G} T^a) q_f \right],$$

where we are summing over the quark flavours.

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

Example: QCD (5)

Results

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

Vertex 1

Particle 1 : Vector , G

Particle 2 : Dirac , q†

Particle 3 : Dirac , q

Vertex:

$$i g_s \gamma_{s_2, s_3}^{\mu_1} \delta_{f_2, f_3} T_{m_2, m_3}^a$$

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

Let us do phenomenology!

```
WriteFeynArtsOutput [LQCD]
```

```
WriteCHOutput [LQCD]
```

```
WriteMGOutput [LQCD]
```

```
WriteSHOutput [LQCD]
```

Outline

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

Model description

- **General version of the MSSM.**
 - * **All possible mixings in the scalar sector.**
⇒ 6×6 flavour violating mass matrices.
 - * **All possible complex phases.**
 - * **105 additional free parameters.**
⇒ SLHA2-like format: the **SLHA-FR format**.
⇒ C++ translator SLHA1/2 ⇔ 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 than 10000 vertices, with the four-scalar interactions !!!**

Validation status

● FeynArts/FormCalc:

- * Check of the FC-produced formulas with litterature.
- ✓ **FormCalc-5.4: all $2 \rightarrow 2$ 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 $2 \rightarrow 2$ SUSY processes.**
- ✓ **2708 $2 \rightarrow 3$ SUSY processes.**

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

● CalcHEP/CompHEP (in the cMSSM): 112 $2 \rightarrow 2$ 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->s15-,s15+	3.2044×10^{-2}	3.2002×10^{-2}	3.2039×10^{-2}	3.2039×10^{-2}	OK: 0.131156%
e+,e->s12-,s12+	3.6401×10^{-2}	3.641×10^{-2}	3.64×10^{-2}	3.64×10^{-2}	OK: 0.0274688%
e+,e->s15-,s12+	2.0292×10^{-3}	2.0269×10^{-3}	2.0291×10^{-3}	2.0291×10^{-3}	OK: 0.113409%
e+,e->s11-,s11+	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,n3	2.7949×10^{-3}	2.792×10^{-3}	2.7942×10^{-3}	2.7943×10^{-3}	OK: 0.103814%
e+,e->n2,n2	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%

Outline

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

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!**