From Model Building to Events in a Straightforward Way
Status of Supersymmetric Models in FeynRules.

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Outline

1. Introduction: Monte Carlo generators for the Standard Model and New Physics.
2. The FeynRules approach.
3. Model database & validation procedures.
4. Summary - outlook.

Theoretical calculations for the LHC.

- **One of the goals of the LHC: which New Physics theory is the correct one?**
  [if any, the LHC might be one ring to rule them all out!]
  - We need **data** [which are hopefully coming this (next?) year].
  - We need **theoretical predictions for all models** [which is the aim of this talk].
    - For the Standard Model (SM) backgrounds.
    - For the Beyond the Standard Model (BSM) signals.

Confront data and theory.

- **Theoretical predictions:**
  - **Handmade calculations** ☹.
    - Not practical: factorial growth of the number of diagrams.
    - Tedious and error prone.
  - **Automated tools** ☺.
    - Easy to use!
    - Can be used to simulate the full collision environment.
    - There exists a vast zoology of tools.

Monte Carlo tools and discoveries at the LHC (1).

- **Matrix element-based event generators**.
  - **Reliable predictions** for shapes.
  - Can be **tuned** (to some extent) to the data.
  - Can be used to **describe the SM backgrounds**.
  - **Warning: for some distributions, accurate predictions are required**.
- **Best theoretical predictions**.
  - **Accurate** theoretical calculations.
    - Higher order QCD corrections.
    - Resummation.
    - Weak corrections.
    - ...
  - Mandatory for understanding and control of **physics and detector effets**.
  - **Reliable estimate of errors**.

Monte Carlo tools and discoveries at the LHC (2).

- **Establishing of an excess over the SM backgrounds**.
  * **Difficult task**.
  * Use of **Monte Carlo generators**.
  * **Warning: for some signals, accurate predictions are required**.
- **Confirmation of the excess**.
  * **Model building activities**.
    - ◇ Bottom-up approach.
    - ◇ Top-down approach.
  * **Implementation** of the new models in the Monte Carlo tools.
- **Clarification of the new physics**.
  * **Measurement of the parameters**.
  * Use of **precision predictions**.
  * **Sophistication of the analyses $\Leftrightarrow$ new physics and detector knowledge**.

Monte Carlo tools play a key role!

Monte Carlo tools for the Standard Model (1).

- **Automatized generation of leading-order matrix elements**.
  - * Based on **Feynman diagram techniques**.
    - ◇ CALCHEP/COMPHEP [Pukhov *et al.* (1999); Boss *et al.* (2004)].
    - ◇ MADGRAPH/MADEVENT [Maltoni, Stelzer (2003); Alwall *et al.* (2007)].
    - ◇ SHERPA [Gleisberg *et al.* (2004)].
    - ◇ WHIZARD/OMEGA [Moretti *et al.* (2001); Kilian *et al.* (2007)].
  - * Generators going **beyond the Feynman diagram techniques**.
    - ◇ ALPGEN [Mangano *et al.* (2002)].
    - ◇ COMIX [Gleisberg *et al.* (2008)].
    - ◇ HELAC [Cafarella *et al.* (2007)].

Monte Carlo tools for the Standard Model (2).

- **Automatization of next-to-leading order calculations**.
  - * **Real emission including the subtraction terms**.
    - ◇ Amegic++ (Catani-Seymour) [Gleisberg and Krauss (2008)].
    - ◇ Helac (Catani-Seymour) [Czakon, Papadopoulos, Worek (2009)].
    - ◇ Independent Catani-Seymour dipoles library [Hasegawa *et al.* (2008)].
    - ◇ MadDipole (Catani-Seymour) [Frederix, Gehrmann, Greiner (2008)].
    - ◇ MadFKS (Frixione, Kunszt, Signer) [Frederix *et al.* (2009)].
    - ◇ TevJet (Catani-Seymour) [Seymour and Tevlin (2008)].
  - * **Loop amplitudes**.
    - ◇ BlackHat (on-shell approach) [Berger *et al.* (2009)].
    - ◇ CutTools (generalized unitarity approach) [van Hameren *et al.* (2009)].
    - ◇ Golem (Feynman diagram approach) [Binoth *et al.* (2008)].
    - ◇ Rocket (generalized unitarity approach) [Ellis *et al.* (2009)].

Monte Carlo tools for the Standard Model (3).

- **From matrix elements to real life.**
  - **Parton showering & hadronization.**
    - ◇ PYTHIA [Sjostrand, Mrenna, Skands (2006, 2008)].
    - ◇ HERWIG [Corcella *et al.* (2001); Bahr *et al.* (2008)].
  - **Matching algorithm.**
    - ◇ CKKW [Catani, Krauss, Kuhn, Webber (2001)].
    - ◇ MLM [Mangano *et al.* (2007)].
    - ◇ ...
  - **Matching next-to-leading order with parton showering.**
    - ◇ MC@NLO [Frixione, Webber (2002)].
    - ◇ POWHEG [Nason (2004)].

**We will soon be able to accurately simulate any SM process.
What about BSM?**

Monte Carlo tools for BSM (1).

- **New physics theories**.
  - * There are a **lot of different** theories.
  - * Based on very **different ideas**.
  - * **In evolution** (regarding the discoveries).
- **Implementation in Monte Carlo tools**.
  - * A model consists in particles, parameters and vertices ($\equiv$ Feynman rules).
    - ◇ The Feynman rules **have to be derived**.
    - ◇ Each Feynman rule **has to be translated in informatic languages**.
  - * **Tedious, time-consuming, error prone task**.
  - * We need to iterate for each considered model.
  - * We need to iterate for each considered MC tool.

Monte Carlo tools for BSM (2).

- **Validation**.
  - **Comparison** with existing analytical and numerical results.
  - **Non systematic and partial**.
    - **Restricted set** of available results.
    - **No dedicated framework**.
    - **Warning: conventions**.
- **Distribution**.
  - Many models remain **private**.
  - **Exception:** popular models such as the MSSM.
  - Use of **many home-made and hacked versions** of existing models.
    $\Rightarrow$ Issues for validation, traceability and maintenance.

An efficient framework is needed:

- To **develop** new models.
- To **implement and validate** new models in MC tools.
- To **test** the models against the future data.

First steps towards a full automatization (1).

- **Starting from physical quantities**.
  - All the physics is included in the model **Lagrangian**.
    - ◇ Remark: the Lagrangian is **absent in the MC implementation**.
  - **Traceability.**
    - ◇ **Univocal definition of a model**.
    - ◇ **No dependance on the conventions used** by the MC tools.
  - **Flexibility.**
    - ◇ A modification of a model $\equiv$ change in the Lagrangian.
- **The** LanHep **package** [Semenov (1998)].
  - In the context of CalcHep/CompHep.
  - Allows to run several tests on the Lagrangian (**reducing errors**).
  - Interfaced to FeynArts.

First steps towards a full automatization (2).

Aims:

* To go **beyond** this scheme.
* To create a **general environment** to implement any Lagrangian-based model.
* To interface **several Monte Carlo generators**.
* **Robustness, easy validation and maintenance**.
* Easy integration in **experimental software frameworks**.
* Allowing for both **top-down and bottom-up approaches**.

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Main features of FeynRules [Christensen, Duhr (2009)].

- **The working environment is** Mathematica.
  * **Flexibility** for symbolic manipulations.
    - ◇ **Routines** to check a Lagrangian.
    - ◇ ...
  * Various **built-in features.**
    - ◇ **Matrix diagonalization**.
    - ◇ **Pattern recognition functions**.
    - ◇ ...
  * **New additional functions** can easily be added by users.
    - ◇ **Model spectrum calculator**.
    - ◇ ...

- **Interfaces to Monte Carlo codes**.
  * The philosophy, architecture and aim of the codes can be **different**.
  * **Maximization** of probability to have (at least) one (working) MC per model.
  * FeynRules **translates** models in terms of files readable by the MC tools.

FeynRules.

Model (e.g. from any theoretical paper)

Parameters | **Gauge groups** | **Particle content** | **Lagrangian**

⇓

FeynRules (Mathematica, "screen-typing")

⇓

Feynman rules ⇒ ⇒ **TEX-file**

⇓

Translation interfaces (Mathematica, single keystroke)

⇓ ⇓ ⇓ ⇓ ⇓

CalcHep | FeynArts | MadGraph | Sherpa | Whizard

⇓ ⇓ ⇓ ⇓ ⇓

Parton showering, hadronization, detector simulation & analysis!

A framework for LHC analyses (1).

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.**
  ⇒ **Automatized model implementation!**
* Generic detector simulation, ...
* Signal/background studies.

Experimental works

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

⇔ **Data**

FeynRules.

- ✔ Mathematica based.
- ✔ Linked to MC's.
- ✔ No MC modification (validated).
- ✔ Portable, documented.

A framework for LHC analyses (2).

1. **New physics is discovered at the LHC**.
2. **Model builders propose explanations**.
   * Bottom-up approach.
   * Top-down approach.
3. **Implementation phase**.
   * Direct implementation in FeynRules.
   * Incorporation of the new models inside the **experimental softwares**.
4. **Confrontation to the data.**
5. **Refinement of the model.**
   ⇒ Back to step 3.

Framework where both theorists and experimentalists have their place.

Scope and limitations.

- **Supported fields**.
  - * Scalar fields.
  - * Dirac and Majorana fermions [**Weyl fermions: in validation**].
  - * Vector fields.
  - * Ghost fields.
  - * **No spin 3/2**.
  - * Spin two fields.
- **The model must fulfil basic quantum field theory requirements**.
  - * Lorentz invariance.
  - * Gauge invariance.
  - * **Higher-dimensional operators are supported**.
- **Interfaces and Monte Carlo tools**.
  - * Only **scalars, Dirac and Majorana fermions, vector (and ghost) fields**.
  - * **Higher-dimensional operators** are not all supported.

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 (Dirac fermions)

The quark fields

```
F[1] == {
  ClassName          -> q,
  ClassMembers       -> {d, u, s, c, b, t},
  FlavorIndex        -> Flavour,
  SelfConjugate      -> False,
  Indices            -> {Index[Flavour],Index[Colour]},
  WeylComponents     -> {qL,qRbar},
  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 - Quark fields (Weyl fermions)

The quark fields

```
W[1] == {
  ClassName       -> qL,
  Chirality       -> Left,
  SelfConjugate   -> False,
  Indices         -> {Index[Flavour], Index[Colour]},
  FlavorIndex     -> Flavour,
  ClassMembers    -> {dL,uL,sL,cL,bL,tL},
  Unphysical      -> True},
W[2] == {
  ClassName       -> qR,
  Chirality       -> Left,
  SelfConjugate   -> False,
  Indices         -> {Index[Flavour], Index[Colour]},
  FlavorIndex     -> Flavour,
  ClassMembers    -> {dR,uR,sR,cR,bR,tR},
  Unphysical      -> True}
```

Example: QCD - Lagrangian

QCD Lagrangian:

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

The QCD Lagrangian

```
LQCD = -1/4 * FS[G, mu, nu, a] * FS[G, mu, nu, a] +
  I*qbar.Ga[mu].DC[q, mu] -
  MQ[f] * qbar[s,f,c].q[s,f,c] ;

LQCDW = -1/4 * FS[G, mu, nu, a] * FS[G, mu, nu, a] +
  I qR.Si[mu].DC[qRbar, mu] +  I qLbar.Sibar[mu].DC[qL, mu] -
  MQ[f] * (qR[s,f,c].qL[s,f,c] + qRbar[s,f,c].qLbar[s,f,c]);
```

* **Implicit summations** ⇒ easy debugging.

Example: QCD - Results

Results - let us do (some) phenomenology!

```
FeynmanRules[LQCD, FlavorExpand->False]
FeynmanRules[WeylToDirac[LQCDW], 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]
    WriteWOOutput[LQCD]
```

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Validation procedure - the four-star system (LH 2009).

- **Any model can be put on the FeynRules website.**
- **First star [DOC]:**
  * **Documentation**: description, references, ...
  * Complete model or theory fragment.
  * Consistency of the input parameters.
- **Second star [THEO]:**
  * **Basic sanity checks**: hermiticity, signs, ...
  * **Comparison with literature**.
  * Use of FeynArts/FormCalc possible.
- **Third star [1MC]:**
  * The MC is producing **reliable results for basic processes**.
  * Reproduction of the SM results for sectors independent on new physics.
  * Gauge invariance, behaviour at high energy.
  * **Numerical tables for cross sections (future references).**
- **Fourth star [nMC]:**
  * Reproduce the [1MC] step for more than one MC generator.
  * **Comparison tables for future references**.

Validation procedure & models - outlook.

- **Joint development with LanHep.**
  - Joint **validation** procedure.
  - Joint **model database**.
  - **Validation and distribution of private models**.
- **Implementation of new Lagrangians (with benchmark points)**.
  - Systematization of the BSM investigations at the LHC.
  - Implementations in FeynRules lead to **several ready-to-go solutions**.
    - CalcHep/CompHep.
    - MadGraph/MadEvent.
    - Sherpa.
    - Whizard.

Example: validation of the Standard Model.

CalcHep, CompHep, MadGraph/MadEvent, Sherpa and Whizard results

Process	CalcHEP Stock	CalcHEP Feynman	CalcHEP Unitary	CompHEP Feynman	MadGraph Stock	MadGraph Unitary	Sherpa Unitary	Whizard Stock	Whizard Feynman	Whizard Unitary	
$gg \to gg$	116490.	116490.	116490.	116490.	116680.	116120.	116490	115031.	116585.	116642.	Discrpency!
$u\bar{u} \to gg$	199.95	199.95	199.95	199.94	200.21	199.77	199.963	199.693	199.693	199.693	
$t\bar{t} \to gg$	64.595	64.595	64.595	64.592	64.467	64.537	64.5856	64.623	64.5601	64.5601	
$e^+e^- \to \mu^+\mu^-$	0.37194	0.37195	0.37195	0.37194	0.37202	0.37148	0.372011	0.372034	0.372028	0.372028	
$e^+e^- \to e^+e^-$	734.15	734.15	734.15	734.16	733.96	734.47	734.314	734.622	734.609	734.609	
$e^+e^- \to \nu_e\bar{\nu}_e$	49.143	49.145	49.145	49.145	results	results	49.1361	49.1139	49.1184	49.1184	
$t\bar{t} \to u\bar{u}$	16.018	16.018	16.018	16.018	16.012	16.022	16.0204	16.0214	16.0214	16.0214	
$u\bar{u} \to s\bar{s}$	9.7634	9.7634	9.7634	9.7631	9.7631	9.7692	9.76376	9.76348	9.76346	9.76348	
$u\bar{d} \to c\bar{s}$	0.3531	0.35311	0.35311	0.35312	0.35274	0.35318	0.353149	0.353212	0.353215	0.353215	
$u\bar{s} \to c\bar{d}$	0.0010187	0.0010187	0.0010187	0.0010187	0.0010186	0.0010182	0.00101879	0.00101897	0.00101898	0.00101898	
$W^+W^- \to t\bar{t}$	44.534	44.535	44.535	44.534	44.647	44.485	44.5503	44.4991	44.4992	44.4992	
$t\bar{t} \to ZZ$	1.2534	1.2534	1.2534	1.2534	1.254	1.2559	1.25321	1.25431	1.25432	1.25432	
$t\bar{t} \to Z\gamma$	1.3119	1.3119	1.3119	1.312	1.3139	1.3113	1.31197	1.31261	1.31202	1.31202	
$t\bar{t} \to \gamma\gamma$	0.088486	0.088486	0.088486	0.088485	0.088527	0.088462	0.0884835	0.0884519	0.0884983	0.0884983	
$u\bar{u} \to W^+W^-$	1.7736	1.7737	1.7737	1.7737	1.7698	1.776	1.77424	1.77412	1.77413	1.77413	
$u\bar{u} \to ZZ$	0.19345	0.19347	0.19347	0.19346	0.19357	0.19318	0.193462	0.192923	0.192927	0.192927	
$u\bar{u} \to Z\gamma$	0.33811	0.33812	0.33812	0.33811	0.3381	0.3384	0.334504	0.338125	0.338124	0.338124	Discrpency!
$u\bar{u} \to \gamma\gamma$	0.18322	0.18322	0.18322	0.18323	0.18332	0.18329	0.183224	0.183377	0.183373	0.183373	
$\tau^+\tau^- \to W^+W^-$	5.3681	5.3684	5.3684	5.3686	5.3517	5.3637	5.36799	5.36556	5.3656	5.3656	
$\tau^+\tau^- \to ZZ$	0.31816	0.31817	0.31817	0.31816	0.31852	0.31805	0.318256	0.31799	0.317993	0.317993	
$\tau^+\tau^- \to Z\gamma$	2.0057	2.0057	2.0057	2.0057	2.0083	2.0044	1.98453	1.99948	2.00799	2.00799	Discrpency!
$\tau^+\tau^- \to \gamma\gamma$	2.7791	2.7791	2.7791	2.779	2.7773	2.7756	2.77911	2.77248	2.77711	2.77711	
$ZZ \to ZZ$	1.9606	1.9606	1.9606	1.9606	1.9565	1.9555	1.96071	1.96046	1.96046	1.96046	
$W^+W^- \to \gamma\gamma$	20.825	20.825	20.825	20.824	20.827	20.804	20.8182	20.8527	20.8171	20.8171	
$W^+W^- \to ZZ$	272.62	272.63	272.63	272.62	272.36	272.11	272.694	272.422	272.425	272.425	
$W^+W^- \to W^+W^-$	1318.1	1318.2	1318.2	1318.2	1317.2	1318.8	1318.45	1320.05	1320.03	1320.03	
$hh \to hh$	1.8569	1.857	1.857	1.857	-	1.8567	1.85587	1.86179	1.86179	1.86179	
$ZZ \to hh$	6.3027	6.3029	6.3029	6.3029	6.311	6.3137	6.30265	6.29227	6.31003	6.31003	
$hh \to W^+W^-$	94.47	94.473	94.473	94.473	94.815	94.833	94.5793	94.5073	94.5077	94.5077	

Supersymmetric models and their validation (1).

- **The MSSM** [Duhr, BenjF (in prep)].
  * **Publicly available**: http://feynrules.phys.ucl.ac.be/view/Main/MSSM .
  * **References**: analytical results, stock versions of CalcHep, MadGraph.
  * **Validation**: FeynArts + CalcHep, MadGraph.
  * **On-going**: Sherpa, Whizard.
- **The NMSSM** [Braam, BenjF, Reuter (in prep)].
  * Started at **Les Houches 2009**.
  * **Private** (expected to be out in early 2010).
  * **Validation**: analytical results, stock version of Whizard (cf. Felix's talk).
  * **Validation**: CalcHep, MadGraph.
  * **On-going**: FeynArts, Sherpa, Whizard.
- **The MSSM with R-parity violation**. [Duhr, BenjF; Andrea, BenjF (in prep)].
  * **Private** (expected to be out mid 2010).
  * **On-going validation**.

Supersymmetric models and their validation (2).

- **The MSSM with Dirac gauginos**.

  [Bruneliere, Das, Duhr, Fox, BenjF, Henderson, Kribs, Martin, Roy, ...].

  * Started at **Les Houches 2009**.
  * **Still private** (available in early 2010).
  * **References**: analytical results, stock versions of CalcHep, MadGraph.
  * **On-going validation**.

- **Other supersymmetric models**.

  * **Larger time-scale**.
  * **Contact us** if you want to implement a new model (or do it yourself).

The (almost) most general MSSM - model

- **A general version of the MSSM** (any usual limit easily taken).
  * **Sfermion sector.**
    - 6×6 and 3×3 CP and flavour violating mixing matrices.
    - *e.g.*
$$\Big(\tilde u_1, \tilde u_2, \tilde u_3, \tilde u_4, \tilde u_5, \tilde u_6\Big)^T = R^{\tilde u}\Big(\tilde u_L, \tilde c_L, \tilde t_L, \tilde u_R, \tilde c_R, \tilde t_R\Big)^T,$$
$$\Big(\tilde d_1, \tilde d_2, \tilde d_3, \tilde d_4, \tilde d_5, \tilde d_6\Big)^T = R^{\tilde d}\Big(\tilde d_L, \tilde s_L, \tilde b_L, \tilde d_R, \tilde s_R, \tilde b_R\Big)^T.$$
  * **Higgs sector.**
    - Only 2×2 mixing considered for the moment.
    - **To be generalized in version 1.2.0**.
$$\Big(\tilde h_1, \tilde h_2, \tilde h_3\Big)^T = R^h\Big(\sqrt{2}\Re\{H_1^0\}, \sqrt{2}\Re\{H_2^0\}, A^0_{\rm tree}\Big)^T$$
  * **Gaugino/higgsino sector.**
    - Written in the mass basis (contrary to the rest of the Lagrangian).
    - **Is changed, in version 1.1.4** (present development version).
- **105 free parameters.**
  * The **SLHA-FR format** (SLHA2-like format).
  * C++ translator SLHA1/2 $\Leftrightarrow$ SLHA-FR **(v1.2.0 is coming)**.

The (almost) most general MSSM - validation [Duhr, BenjF].

- **Handmade vs. automated implementation.**
  - * 2522 vertices, without the four-scalar interactions.
  - * **More that 10000 vertices, with the four-scalar interactions !!!**
- FeynArts/FormCalc.
  - ✔ All $2 \to 2$ SUSY hadroproduction processes checked with litterature. [Bozzi, BenjF, Herrmann, Klasen (2007); BenjF, Herrmann, Klasen (2009; in prep.)].
- MadGraph/MadEvent (in the cMSSM limit):
  - * MG-Stock was validated by the CATPISS collaboration [Hagiwara *et al.* (2006)].
  - ✔ **320 decay widths.**
  - ✔ **626** $2 \to 2$ **SUSY processes.**
  - ✔ **2708** $2 \to 3$ **SUSY processes.**
  - **TO DO**: check the general MSSM.
    - ◇ With XSusy [BenjF, Herrmann (in prep.)]
    - ◇ With the stock version of Whizard [Herrmann].

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

- CalcHep/CompHep (in the cMSSM):
  - ✘ **626** $2 \to 2$ **SUSY processes** $\Rightarrow$ **Bugs found in the stock version!**

The (almost) most general MSSM - validation [Duhr, BenjF].

Some MadGraph/MadEvent and CalcHep results

Process	MG-FR	MG-ST	CH-FR	CH-ST	Comparison
b,b~>mu+,mu-	7.01173×10^{-3}	7.00622×10^{-3}	7.0113×10^{-3}	7.0114×10^{-3}	δ = 0.0786383 %
b,b~>e+,e-	7.01047×10^{-3}	7.00913×10^{-3}	7.0113×10^{-3}	7.0114×10^{-3}	δ = 0.0323792 %
b,b~>tau+,tau-	7.23656×10^{-3}	7.2231×10^{-3}	7.2351×10^{-3}	7.2352×10^{-3}	δ = 0.186166 %
b,b~>ve,ve~	8.38141×10^{-3}	8.38607×10^{-3}	8.3842×10^{-3}	8.3843×10^{-3}	δ = 0.0556675 %
b,b~>vm,vm~	8.3868×10^{-3}	8.38046×10^{-3}	8.3842×10^{-3}	8.3843×10^{-3}	δ = 0.0756488 %
b,b~>vt,vt~	8.38227×10^{-3}	8.38318×10^{-3}	8.3842×10^{-3}	8.3843×10^{-3}	δ = 0.0242298 %
b,b~>u,u~	2.19296	2.19098	2.1931	2.1931	δ = 0.0966848 %
b,b~>t,t~	4.74685×10^{1}	4.74541×10^{1}	4.7307×10^{1}	4.7308×10^{1}	δ = 0.340907 %
b,b~>d,d~	2.19374	2.19428	2.1944	2.1944	δ = 0.0301166 %
b,b~>b,b~	2.34515×10^{4}	2.34471×10^{4}	2.3448×10^{4}	2.3448×10^{4}	δ = 0.0188769 %
b,b~>W+,W-	1.33248	1.33234	1.3331	1.3331	δ = 0.0573475 %
b,b~>Z,Z	1.39592×10^{-1}	1.39525×10^{-1}	1.3982×10^{-1}	1.3982×10^{-1}	δ = 0.210885 %
b,b~>Z,a	2.8492×10^{-2}	2.85038×10^{-2}	2.8503×10^{-2}	2.8504×10^{-2}	δ = 0.0420335 %
b,b~>g,g	5.55219×10^{1}	5.54535×10^{1}	5.5504×10^{1}	5.5504×10^{1}	δ = 0.12333 %
b,b~>sd1,sd1~	3.40163×10^{-1}	3.40348×10^{-1}	3.401×10^{-1}	3.4009×10^{-1}	δ = 0.0759557 %
b,b~>sd2,sd2~	2.58964×10^{-1}	2.59026×10^{-1}	2.5914×10^{-1}	2.5915×10^{-1}	δ = 0.0716753 %
b,b~>sd1,sd2~	6.07283×10^{-1}	6.07465×10^{-1}	6.0701×10^{-1}	6.0701×10^{-1}	δ = 0.0749837 %
b,b~>su1,su1~	2.88616×10^{-1}	2.89041×10^{-1}	2.8884×10^{-1}	2.8625×10^{-1}	δ = 0.97026 %
b,b~>su6,su6~	5.91346×10^{-3}	5.91497×10^{-3}	5.9124×10^{-3}	5.2701×10^{-3}	δ = 11.5309 %
b,b~>su1,su6~	1.15552×10^{-2}	1.15752×10^{-2}	1.1567×10^{-2}	8.7247×10^{-3}	δ = 28.0835 %
b,b~>n1,n1	1.73348×10^{-4}	1.73503×10^{-4}	1.7329×10^{-4}	1.7329×10^{-4}	δ = 0.12272 %
b,b~>n1,n2	7.25698×10^{-4}	7.25803×10^{-4}	7.2617×10^{-4}	7.2618×10^{-4}	δ = 0.0664021 %
b,b~>n1,n3	4.87872×10^{-4}	4.89162×10^{-4}	4.8893×10^{-4}	4.8893×10^{-4}	δ = 0.26393 %
b,b~>n1,n4	2.90254×10^{-4}	2.89831×10^{-4}	2.8994×10^{-4}	2.8994×10^{-4}	δ = 0.146048 %
b,b~>n2,n2	5.74033×10^{-3}	5.74407×10^{-3}	5.7423×10^{-3}	5.7424×10^{-3}	δ = 0.0651865 %
b,b~>n2,n3	2.73662×10^{-3}	2.73514×10^{-3}	2.7398×10^{-3}	2.7399×10^{-3}	δ = 0.173711 %
b,b~>n2,n4	2.0141×10^{-3}	2.01493×10^{-3}	2.0149×10^{-3}	2.015×10^{-3}	δ = 0.0448974 %
b,b~>n3,n3	4.54157×10^{-5}	4.54171×10^{-5}	4.5409×10^{-5}	4.5409×10^{-5}	δ = 0.0178662 %
b,b~>n3,n4	1.08667×10^{-2}	1.08477×10^{-2}	1.0845×10^{-2}	1.0845×10^{-2}	δ = 0.199685 %
b,b~>n4,n4	2.16226×10^{-4}	2.15906×10^{-4}	2.1573×10^{-4}	2.1574×10^{-4}	δ = 0.229686 %

The (almost) most general MSSM - to do list [Duhr, BenjF].

- **From an almost most general model to the most general one.**
  * Generalization of the **Higgs sector**.
- MadGraph/MadEvent and CalcHep/CompHep.
  * **Check with XSusy and Whizard** for the general model case.
- Sherpa:
  * **Ongoing validation**: one issue related to Majorana particles remaining. [+ possible hidden stuff].
- Whizard:
  * **Starting validation** (the FR-interface must be validated at the same time).
- **We have automatically generated model files for several tools.**
  * CalcHep/CompHep.
  * FeynArts/FormCalc.
  * MadGraph/MadEvent.
  * Sherpa (?).
  * Whizard (?).
  * **Can be used for phenomenology**.
  * Stock versions are working too.

The Next-to-Minimal Supersymmetric Standard Model

[Braam, BenjF, Reuter].

- **Implementation in FeynRules** (not yet public).
  - **General mixings.**
    - The **general** NMSSM has been implemented.
    - Extended neutralino sector.
    - Extended Higgs sector.
  - **105 + 10 free parameters.**
    - The **SLHA-FR format** (SLHA2-like format).
    - C++ translator SLHA1/2 $\Leftrightarrow$ SLHA-FR **(seems to work)**.

- MadGraph **and** CalcHep **model files**.
  - **Validation against the stock version of** Whizard.
  - **See Felix's talk.**

- **We have automatically generated model files for several tools.**
  - CalcHep/CompHep.
  - FeynArts/FormCalc.
  - MadGraph/MadEvent.
  - Sherpa (?).
  - Whizard (?).
  - **Can be used for phenomenology**.
  - Stock versions (if existing) are working too.

Outline

From model building to events using FeynRules

- **A powerful prospecting chain**:
  * **Model implementation**: FeynRules.
  * **Events**: CalcHep, MadGraph, Sherpa, Whizard, ...
  * **Parton showering and hadronization**: Pythia, Herwig, ...
  * **Detector effects**: Delphes, PGS, CMSSW, Athena...
  * **The phenomenology of 'any' model can easily be investigated**.

  Remark: CalcHep: LanHep or Sarah can be used (instead of FeynRules).

- **Experimental softwares**
  * Contain matrix-element generators.
  * FeynRules is supported by the MC people (if an interface exists).
  * **No software modifications required to include FeynRules models.** ☺
    [One single copy paste is the only thing to do!]

- **Implementation and validation of new models**.
  * Is any important/interesting model not integrated in MC tools?
  * Is any important validation criteria missing?

Summary: the philosophy of FeynRules

* **Flexible 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 MC codes.
  2) Monte Carlo code → phenomenology.

  FeynRules **is not tied to any generator.**

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

  Exploit the strengths of the different programs!

* **Traceability, portability and documentation**.
  Test of a model against data: all model information in the FeynRules files.

* **The validation of models is not neglected!**
  Different generators, gauges, etc...