From model building to phenomenology with \textsc{FeynRules} 
Application to supersymmetry.

Benjamin Fuks (IPHC Strasbourg / Université de Strasbourg)

In collaboration with N. Christensen and C. Duhr. 
+ P. de Aquino, C. Degrande, D. Grellscheid, W. Link, 

Theory Seminar @ DESY Hamburg 
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Outline

1. Monte Carlo tools and New Physics investigations at the LHC.
4. Supersymmetric model building with FeynRules - the superfield module.
5. Web validation and model database.
6. Conclusions.
Monte Carlo tools and discoveries at the LHC (1).

- 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].
  - We need theoretical predictions for any model [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.
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**Confront data and theory.**

- **Theoretical predictions:**
  
  * **Handmade calculations 😞.**
    ◦ Not practical: factorial growth of the number of diagrams.
    ◦ Tedium and error prone.
  
  * **Automated tools 😊.**
    ◦ Easy to use!
    ◦ Can be used to simulate the full collision environment.
Monte Carlo tools and discoveries at the LHC (2).

- **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.
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- **Best theoretical predictions.**
  - Accurate theoretical calculations.
    - Higher order QCD corrections.
    - Resummation.
    - Weak corrections.
    - ...
  - Mandatory for understanding and control of physics and detector effects.
  - Reliable estimate of errors.
Monte Carlo tools and discoveries at the LHC (3).

- **Establishing of an excess over the SM backgrounds.**
  - **Difficult task.**
  - Use of **Monte Carlo generators.**
  - **Warning:** for some signals, accurate predictions are required.
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  - *Difficult task.*
  - *Use of [Monte Carlo generators].*
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- **Confirmation of the excess.**
  - *Model building activities.*
    - ◊ Bottom-up approach.
    - ◊ Top-down approach.
  - *Implementation* of the new models in the Monte Carlo tools.
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- Clarification of the new physics.
  - Measurement of the parameters.
  - Use of precision predictions.
  - Sophistication of the analyses ⇔ new physics and detector knowledge.
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Monte Carlo tools play a key role!
But how is new physics presently investigated in particle physics?
A framework for BSM analyzes at the LHC (1).

Model building

- Pen&pencil stage.
- Leading order, loop calculations, ...
- Electroweak, low energy constraints,...
A framework for BSM analyzes at the LHC (1).

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**Phenomenology**

- **Monte Carlo event generator.**
- Matrix element calculation.
- Parton showering / hadronization.
- Generic detector simulation.

Idea ⇔ Model building

⇒ Publications

⇓

Idea ⇔ Phenomenology

⇒ Publications
A framework for BSM analyzes at the LHC (1).

- **Model building**
  - *Pen&-pencil stage.*
  - *Leading order, loop calculations, ...*
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- **Phenomenology**
  - *Monte Carlo event generator.*
  - *Matrix element calculation.*
  - *Parton showering / hadronization.*
  - *Generic detector simulation.*

- **Experiment**
  - *Experimental framework.*
  - *Matrix elements, parton showering, hadronization.*
  - *Realistic detector simulation.*
  - *Comparison with data.*
A framework for LHC analyzes (2).

- **New physics theories.**
  
  * There are a lot of different theories.
  
  * Based on very different ideas.
  
  * **In evolution** (especially regarding the discoveries).
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Implementation in Monte Carlo tools.

* A model consists in particles, parameters and vertices (≡ Feynman rules).
  ◊ The Feynman rules have to be derived.
  ◊ Each rule has to be translated in an programming language.
* Tedious, time-consuming, error prone task.
* We need to iterate for each considered model.
* We need to iterate for each considered MC tool.
A framework for LHC analyzes (2).

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Redundancies of the work.
A framework for LHC analyzes (3).

- **Validation.**
  - * Necessary at each step.
    - * Error-prone.
    - * Time-consuming.
  - * Comparison with existing analytical and numerical results.
  - * Non systematic and partial.
    - ◊ Restricted set of available results.
    - ◊ No dedicated framework.
    - ◊ Warning: conventions.
A framework for LHC analyzes (3).

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- **Distribution.**
  - Many models remain private.
  - Exception: popular models, e.g., the MSSM.
  - Use of many home-made and hacked versions of existing models.
    ⇒ Issues about documentation, traceability, maintenance, ...
A framework for LHC analyzes (4).

We need an efficient framework:

- To **develop** new models.
- To **implement (and validate)** new models in MC tools.
- To **test** the models against the future data.
- **Enhancing communication** between theory and experiment.
A framework for LHC analyzes (5).

Idea → Lagrangian → FeynRules → Matrix elements (MC generators) → Parton showering → Hadronization → Generic detector → Realistic detector → Data → Phenomenology → Theory → Experiment
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The **FeynRules** approach (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.
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- **First steps in that direction.**
  - The **LanHep** package [Semenov (1998)].
  - In the context of **CalcHEP/CompHEP**.
  - Allows to run several tests on the Lagrangian (**reducing errors**).
  - Interfaced to **FeynArts**.
The **FeynRules** approach (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**.
The \textbf{FeynRules} approach (3).
The **FeynRules** approach (4).
The **FeynRules** approach (5).
Main features of **FeynRules** (1) \cite{Christensen, Duhr (2009)}.

\begin{itemize}
  \item Parameters
  \item Gauge groups
  \item Particle content
  \item Lagrangian
  \item \( \Downarrow \)
  \item FeynRules
  \item \( \Downarrow \)
  \item Feynman rules \( \Rightarrow \Rightarrow \) \( \text{\LaTeX}-file \)
  \item Translation interfaces
  \item \( \Downarrow \)
  \item CalcHep
  \item FeynArts
  \item MadGraph
  \item Sherpa
  \item Whizard (*)
  \item \( \Downarrow \)
  \item Parton showering, hadronization, detector simulation & analysis!
\end{itemize}

\( (*) \) \cite{Christensen, Duhr, BenjF, Reuter, Speckner (2010)}
Main features of **FeynRules** (2) [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**.
    ◦ ...

Supersymmetry with **FeynRules**

Benjamin Fuks - Theory Seminar @ DESY Hamburg - 09.11.2010 - 18
Main features of **FeynRules** (2) [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.
Main features of **FeynRules** (3) [Christensen, Duhr (2009)].

- **Public version:** v1.4.10: http://feynrules.phys.ucl.ac.be

- **Supported fields.**
  - Spin 0, $\frac{1}{2}, 1, 2$ fields.
  - Ghost fields.
  - Dirac or Majorana fermions.

- **The model must fulfil basic quantum field theory requirements.**
  - Lorentz invariance.
  - Gauge invariance.
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- **Model database.** [Christensen, de Aquino, Duhr, BenjF, Herquet, Maltoni, Schumann (2009)]
  * The Standard Model.
  * The most general two-Higgs-doublet model.
  * The minimal Higgsless model.
  * Various SUSY models (MSSM, RPV, NMSSM, RMSSM, ...)
  * Extra dimensions (universal, large, Randall-Sundrum).
  * Effective field theories (Composite top, Little Higgs,...).
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 including Weyl fermions.
Example: QCD - Quark fields (Weyl fermions)

**The quark fields**

\[
W[1] = \{
\begin{array}{c}
\text{ClassName} \rightarrow qL, \\
\text{Chirality} \rightarrow \text{Left}, \\
\text{SelfConjugate} \rightarrow \text{False}, \\
\text{Indices} \rightarrow \{\text{Index[Flavour]}, \text{Index[Colour]}\}, \\
\text{FlavorIndex} \rightarrow \text{Flavour}, \\
\text{ClassMembers} \rightarrow \{dL,uL,sL,cL,bL,tL\}, \\
\text{Unphysical} \rightarrow \text{True},
\end{array}
\]

\[
W[2] = \{
\begin{array}{c}
\text{ClassName} \rightarrow qR, \\
\text{Chirality} \rightarrow \text{Left}, \\
\text{SelfConjugate} \rightarrow \text{False}, \\
\text{Indices} \rightarrow \{\text{Index[Flavour]}, \text{Index[Colour]}\}, \\
\text{FlavorIndex} \rightarrow \text{Flavour}, \\
\text{ClassMembers} \rightarrow \{dR,uR,sR,cR,bR,tR\}, \\
\text{Unphysical} \rightarrow \text{True},
\end{array}
\]
Example: QCD - Lagrangian

**QCD Lagrangian:**

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

**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]);
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, \( q^\dagger \)
Particle 3: Dirac, q

Vertex:

\[
ig_\mu \gamma_{\mu_1} \gamma_{\mu_2,\mu_3} \delta_{f_2,f_3} T^a \gamma_{m_2,m_3}
\]

WriteFeynArtsOutput[LQCD]
WriteCHOutput[LQCD]
WriteMGOOutput[LQCD]
WriteSHOutput[LQCD]
WriteWOOutput[LQCD]
Validation procedure - the four-star system (LH 2009).

- Any model can be put on the FeynRules website.
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- **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.
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- **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: example.

CalcHep, CompHep, MadGraph, Sherpa and Whizard results
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New developments in **FeynRules**.

- **FeynRules-2010 workshop on automatized tools for BSM physics.**
  Belyaev, Christensen, de Aquino, Degrande, Duhr, BenjF, Grellscheid, Hahn, Link, Maltoni, Mattelaer, Speckner, Wiebusch (to appear in 2011)
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- Development projects started:
  - Mass diagonalization: 50% done.
  - New **FeynArts** interface: 99% done.
  - Superfields: 100% done.
  - UFO-ALOHA: 99% done.
  - Web validation: still private.
Automatized mass diagonalization [Christensen, Wiebusch].

**Scope.**

* Expression of the Lagrangian in terms of **gauge-eigenstates**, e.g.,

\[ \mathcal{L} = -\bar{\phi} \cdot \bar{q}_L \cdot y^u \cdot u_R \]

* Inclusion in the model file of the **mixing relations**, e.g.,

\[ q_u = U^{CKM} q'_u \]
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\[ \Rightarrow \text{Mass-eigenstates basis.} \]
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  \[ q_u = U^{CKM} q_u' \]
- Automatic diagonalization of the gauge-eigenstates basis.
  \[ \Rightarrow \text{Mass-eigenstates basis.} \]

**The module provides:**
- The mass matrix to be diagonalized.
  \[ M = -\frac{v}{2\sqrt{2}} y^u \]
- The rotation matrix \( U^{CKM} \) and the **rotation rules**,\n  \[ \text{Diagonalization(HEigensystem, CKMU, \{mu,mc,mt\})} \rightarrow M \]
  \[ (P_+)_s (CKMU(1,1)^* u_{q_s,1,c} + CKMU(2,1)^* u_{q_s,2,c} + CKMU(3,1)^* u_{q_s,3,c}) \].
The new **FeynArts** interface [Degrande, Duhr].

- **The old FeynArts interface cannot handle any higher-order operator.**
  - ⇒ is based on the default generic couplings available in FeynArts.

- **A new FeynArts interface has been developed.**
  - ⇒ Able to handle arbitrary Lorentz structures.
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- **FeynRules output:**
  - * A **.mod-file**: model-dependent coupling strengths.
  - * A **.gen-file**: generic (model-independent) Lorentz structures.

- **A new version of *FormCalc* will be released** [Hahn].
  - ⇒ Able to deal with **multi-fermion interactions**.
The new \texttt{FeynArts} interface - $\mathcal{L} = g_1 \phi \cdot \bar{Q}_L \bar{\sigma}^{\mu\nu} T^a t_R G^a_{\mu\nu}$.

\textbf{.gen-file:}

```plaintext
AnalyticalCoupling[s1 F[j1, mom1], s2 F[j2, mom2], s3 V[j3, mom3, {li3}], s4 V[j4, mom4, {li4}], s5 S[j5, mom5] ] ==
G[+1][s1 F[j1], s2 F[j2], s3 V[j3], s4 V[j4], s5 S[j5]].

{MetricTensor[li3,li4]NonCommutative[ChiralityProjector[-1]],
MetricTensor[li3,li4]NonCommutative[ChiralityProjector[+1]],
NonCommutative[DiracMatrix[li3], DiracMatrix[li4],
ChiralityProjector[-1] ], NonCommutative[DiracMatrix[li3],
DiracMatrix[li4], ChiralityProjector[+1] ]}
```

\textbf{.mod-file:}

```plaintext
C[ -F[9, {i}] , F[9, {j}] , V[4, {a}] , V[4, {b}] , S[1] ] ==
{{I*gc78*Conjugate[G1]*(SUNT[a, b, i, j] - SUNT[b, a, i, j])},
{I*G1*gc78*(SUNT[a, b, i, j] - SUNT[b, a, i, j])},
{(-I)*gc78*Conjugate[G1]*(SUNT[a, b, i, j] - SUNT[b, a, i, j])},
{(-I)*G1*gc78*(SUNT[a, b, i, j] - SUNT[b, a, i, j])}}
```
The new \texttt{FeynArts} interface - $\mathcal{L} = g_1 \phi \cdot \bar{Q}_L \bar{\sigma}^{\mu\nu} T^a t_R G^a_{\mu\nu}$.

- \textbf{After running \texttt{FeynArts}}:
UFO & ALOHA (1) [de Aquino, Duhr, Grellscheid, Link, Mattelaer].

- **Scope**: **FeynRules interface producing a universal output.**
  - **UFO** = Universal **FeynRules** output.
  - Contains **all the model information**.
  - Not tied to any MC generator.

- **Self-contained Python module**.
  - **Library** of **Python** objects.
  - Reproduces the **full FeynRules model**.

- **Will be used by** **MadGraph-5, Herwig++, Golem**.
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- **ALOHA:** automatized generation of *Helas* routines.
  - Starts from the *UFO*.
  - Use the UFO to generate the required *Helas* routines on the fly.
  - **Example:** UFO ⇒ ALOHA ⇒ *MadGraph-5*
**Example:** $gg \rightarrow t\bar{t}H$ with $\mathcal{L} = \frac{g_1}{\phi} \cdot \bar{Q}_L \bar{Q}_R T^a t_R G^a_{\mu\nu}$. 

```plaintext
gg > t t~ H
INFO: Process has 16 diagrams

gg > t t~ H
INFO: Generating Helas calls for process: g g > t t~ h
INFO: Processing color information for process: g g > t t~ h
Export UFO model to MG4 format
ALOHA: aloha creates FFV8 routines
ALOHA: aloha creates FFVV8 routines
ALOHA: aloha creates FFVS2 routines
ALOHA: aloha creates FFVVS2 routines
```
Outline

1. Monte Carlo tools and New Physics investigations at the LHC.
4. Supersymmetric model building with FeynRules - the superfield module.
5. Web validation and model database.
6. Conclusions.
Why superfields (1)?

Example 1: the superpotential for (s)leptons.

* Terribly expressed in terms of components fields, i.e., scalars, Dirac and Majorana fermions, vector fields:

\[
\mathcal{L}_W = (y^e)_{ij} \left[ \tilde{E}_R^i \tilde{L}^j \cdot F_{HD} + \tilde{E}_R^i H_D \cdot F_L^j + \tilde{L}^j \cdot H_D F_E^i \\
+ \tilde{E}_R^i (\bar{\psi}_L^c j P_L \psi_{HD}) + \tilde{L}^j \cdot (\bar{\psi}_H^D P_L \psi_e^i) + (\bar{\psi}_e^i P_L \psi_L^j) \cdot H_D \right]
\]
**Why superfields (1)?**

- **Example 1: the superpotential for (s)leptons.**
  - Terribly expressed in terms of **components fields**, i.e., scalars, **Dirac and Majorana fermions**, vector fields:
    \[
    \mathcal{L}_W = (y^e)_{ij} \left[ \tilde{E}_R^i \tilde{L}^j \cdot F_{HD} + \tilde{E}_R^i H_D \cdot F_{L}^j + \tilde{L}^i \cdot H_D F_E^i \\
    + \tilde{E}_R^i (\bar{\psi}_L^c P_L \psi_{HD}) + \tilde{L}^i \cdot (\bar{\psi}_D P_L \psi_e^i) + (\bar{\psi}_e^i P_L \psi_L^j) \cdot H_D \right]
    \]

  - Not very nicely expressed in terms of **components fields**, i.e., scalars, **Weyl fermions**, vector fields:
    \[
    \mathcal{L}_W = (y^e)_{ij} \left[ \tilde{E}_R^i \tilde{L}^j \cdot F_{HD} + \tilde{E}_R^i H_D \cdot F_{L}^j + \tilde{L}^i \cdot H_D F_E^i \\
    + \tilde{E}_R^i (\chi_L^j \cdot \tilde{H}_D) + \tilde{L}^i \cdot (\tilde{H}_D \cdot \chi_E^i) + (\chi_E^i \cdot \chi_L^j) \cdot H_D \right]
    \]
Why superfields (1)?

- **Example 1: the superpotential for (s)leptons.**
  - Terribly expressed in terms of **components fields**, i.e., scalars, **Dirac and Majorana fermions**, vector fields:
    \[
    \mathcal{L}_W = (y^e)_{ij} \left[ \tilde{E}_R^i \tilde{L}^j \cdot F_{HD} + \tilde{E}_R^i H_D \cdot F_{L}^j + \tilde{L}^j \cdot H_D F_E^i 
    + \tilde{E}_R^i (\bar{\psi}_L^e \chi_{L}^i) P_L \psi e^i_H D + (\bar{\psi}_e^i P_L \psi L^i_j) \cdot H_D \right]
    \]
  - Not very nicely expressed in terms of **components fields**, i.e., scalars, **Weyl fermions**, vector fields:
    \[
    \mathcal{L}_W = (y^e)_{ij} \left[ \tilde{E}_R^i \tilde{L}^j \cdot F_{HD} + \tilde{E}_R^i H_D \cdot F_{L}^j + \tilde{L}^j \cdot H_D F_E^i 
    + \tilde{E}_R^i (\chi_{L}^i \cdot \tilde{H}_D) + \tilde{L}^j \cdot (\tilde{H}_D \cdot \chi_{E}^i) + (\chi_{E}^i \cdot \chi_{L}^i) \cdot H_D \right]
    \]
  - Naturally expressed in terms of **superfields (1 terms):**
    \[
    \mathcal{L}_W = \left. \left[ - (y^e)_{ij} E^i (L^j \cdot H_D) \right] \right|_{\theta, \bar{\theta}}
    \]
Why superfields (2)?

Example 1: the superpotential for (s)leptons.

* Terribly expressed in terms of components fields, i.e., scalars, Dirac and Majorana fermions, vector fields:

\[
\mathcal{L}_W = (y^e)_{ij} \left[ \tilde{E}_R^i \tilde{L}^j \cdot F_{HD} + \tilde{E}_R^i H_D \cdot F_L^j + \tilde{L}^j \cdot H_D F_E^i \\
+ \tilde{E}_R^i (\bar{\psi}_L^c \psi_{HD}) + \tilde{L}^j \cdot (\bar{\psi}_{HD} \psi_L^e) + (\bar{\psi}_e^i P_L \psi_L^j) \cdot H_D \right]
\]

* Are the charge conjugated fields correct?
* Are the signs in the fermion flows correct?
* The superfield formalism seems more convenient...

\[
\mathcal{L}_W = \left[ - (y^e)_{ij} E^i (L^j \cdot H_D) \right]_{\theta \cdot \theta}
\]
Why superfields (3)?

- Example 2: kinetic and gauge interactions terms for left-handed (s)quarks.
  * Terribly expressed in terms of components fields, i.e., scalars, Dirac and Majorana fermions, vector fields:
    \[ \mathcal{L}_{\text{kin}} = \ldots \quad \text{[Censured: too ugly to appear on a slide].} \]
Why superfields (3)?

- **Example 2**: kinetic and gauge interactions terms for left-handed (s)quarks.
  * Terribly expressed in terms of **components fields**, i.e., scalars, **Dirac and Majorana fermions**, vector fields:
    \[
    \mathcal{L}_{\text{kin}} = \ldots \quad \text{[Censured: too ugly to appear on a slide]}
    \]

  * Not very nicely expressed in terms of **components fields**, i.e., scalars, **Weyl fermions**, vector fields:
    \[
    \begin{align*}
    \mathcal{L}_{\text{kin}} &= D_\mu \tilde{Q}_i^\dagger D^\mu \tilde{Q}_i^i + \frac{i}{2} (\chi^i Q \sigma^\mu D_\mu \tilde{\chi} Q_i - D_\mu \chi^i Q \sigma^\mu \tilde{\chi} Q_i) + F_i^\dagger F_i^i \\
    & \quad + i\sqrt{2} \left[ \frac{1}{6} g' \tilde{Q}_i^\dagger \tilde{B} \cdot \tilde{\chi} Q_i + g \tilde{W}_k \cdot \tilde{\chi} Q_i \frac{\sigma^k}{2} \tilde{Q}_i^i + g_s \tilde{G}^a \cdot \tilde{\chi} Q_i \frac{T^a}{2} \tilde{Q}_i^i \right] \\
    & \quad - g' D_B \tilde{Q}_i^\dagger \tilde{Q}_i^i - g D_{W_k} \tilde{Q}_i^\dagger \tilde{Q}_i^i \frac{\sigma^k}{2} \tilde{Q}_i^i - g_s D_{G^a} \tilde{Q}_i^\dagger \tilde{Q}_i^i \frac{T^a}{2} \tilde{Q}_i^i
    \end{align*}
    \]
Why superfields (3)?

- **Example 2: kinetic and gauge interactions terms for left-handed (s)quarks.**
  - Terribly expressed in terms of components fields, i.e., scalars, Dirac and Majorana fermions, vector fields:
    
    \[ \mathcal{L}_{\text{kin}} = \ldots \quad \text{[Censored: too ugly to appear on a slide].} \]

  - Not very nicely expressed in terms of components fields, i.e., scalars, Weyl fermions, vector fields:
    
    \[
    \mathcal{L}_{\text{kin}} = D_{\mu} \tilde{Q}_{i}^{\dagger} D^{\mu} \tilde{Q}^{i} + \frac{i}{2} (\chi_{Q}^{i} \sigma^{\mu} D_{\mu} \tilde{\chi}_{Q}^{i} - D_{\mu} \chi_{Q}^{i} \sigma^{\mu} \tilde{\chi}_{Q}^{i}) + F_{Q}^{i} F_{Q}^{i} \\
    + i \sqrt{2} \left[ \frac{1}{6} g' \tilde{Q}_{i}^{\dagger} \tilde{B} \cdot \tilde{\chi}_{Q}^{i} + g \tilde{W}^{k} \cdot \tilde{\chi}_{Q}^{i} \frac{\sigma^{k}}{2} \tilde{Q}^{i} + g_{s} \tilde{G}^{a} \cdot \tilde{\chi}_{Q}^{i} \frac{T^{a}}{2} \tilde{Q}^{i} + \text{h. c.} \right] \\
    - g' D_{B} \tilde{Q}_{i}^{\dagger} \tilde{Q}^{i} - g D_{W} \tilde{Q}_{i}^{\dagger} \frac{\sigma^{k}}{2} \tilde{Q}^{i} - g_{s} D_{G} \tilde{Q}_{i}^{\dagger} \frac{T^{a}}{2} \tilde{Q}^{i}
    \]

  - Naturally expressed in terms of superfields (1 terms):
    
    \[
    \mathcal{L}_{\text{kin}} = \left[ Q_{i}^{\dagger} e^{-\frac{1}{6} g' V_{B}} e^{-2 g V_{W}} e^{\frac{\sigma^{k}}{2}} e^{-2 g_{s} V_{G}} \frac{T^{a}}{2} Q^{i} \right] \left| \theta \cdot \bar{\theta} \cdot \bar{\theta} \right|
    \]
Why superfields (4)?

Example 2: kinetic and gauge interactions terms for left-handed (s)quarks.

* Not very nicely expressed in terms of components fields, i.e., scalars, Weyl fermions, vector fields:

\[ L_{\text{kin}} = D_{\mu}Q_{i}^{\dagger}D^{\mu}Q_{i} + \frac{i}{2}(\chi_{Q}^{i}\sigma_{\mu}D_{\mu}\bar{\chi}Q_{i} - D_{\mu}\chi_{Q}^{i}\sigma_{\mu}\bar{\chi}Q_{i}) + F_{Q}^{i}\bar{F}_{Q}^{i} \]

\[ + i\sqrt{2}\left[ \frac{1}{6}g'e_{i}^{j}B\cdot\bar{\chi}Q_{i} + gW^{k}\cdot\bar{\chi}Q_{i} \right] + \frac{g}{2}\bar{\chi}Q_{i} + \frac{s}{2}\bar{\chi}Q_{i} \]

\[ - g'D_{B}Q_{i}^{\dagger}\bar{Q}_{i} - gD_{W}^{k}\bar{Q}_{i}^{\dagger} + \frac{g_{s}G_{a}}{2}Q_{i} + \frac{g_{s}G_{a}}{2}\bar{Q}_{i} \]

* Are all relative signs and factors of \( i \) correct (especially in the non-gauge-like interactions)?

* Four-component fermions... (They are painful, but required for MCs).

* The superfield formalism seems more convenient...

\[ L_{\text{kin}} = \left[ Q_{i}^{\dagger}e^{-2\frac{1}{6}g'B}e^{-2gW^{k}}\frac{\sigma^{k}}{2}e^{-2g_{s}G_{a}}\frac{T^{a}}{2}Q_{i} \right] \]
Why superfields (5)?

Motivation for a superfield module in **FeynRules**

- **Natural** to implement any supersymmetric theory.
- **Zero probability** to introduce wrong signs, $i$ factors,...
- Could be a **useful tool** for model building.
  (not only a Lagrangian translator).
- **Convenient** for many possible extensions.
Why superfields (5)?

Motivation for a superfield module in FeynRules

* **Natural** to implement any supersymmetric theory.

* **Zero probability** to introduce wrong signs, $i$ factors,...

* Could be a **useful tool** for model building.
  (not only a Lagrangian translator).

* **Convenient** for many possible extensions.

* **Available** as a $\beta$-version for a month.

* **Validated vs. an exercise textbook.**

* Will be publicly available in early 2011.
  Manual (BenjF) + first pheno applications (Alwall, Duhr, BenjF).
Superspace and superfields: the superspace.

- **Conventions:** à la Fuks-Rausch de Traubenberg.
- Superspace: adapted space to write down SUSY transformations naturally.
Superspace and superfields: the superspace.

- **Conventions:** à la Fuks-Rausch de Traubenberg.
- **Superspace:** adapted space to write down SUSY transformations naturally.

**Basic objects and their FeynRules (hardcoded) implementation.**

* The **Majorana spinor** $(\theta, \bar{\theta}) \Rightarrow$ a superspace point $\equiv G(x, \theta, \bar{\theta})$.

* The transformation parameters, the **Majorana spinor** $(\varepsilon_{\text{SUSY}}, \bar{\varepsilon}_{\text{SUSY}})$.

\[
\begin{align*}
W[1000] &= \{ \\
     \text{ClassName} &\rightarrow \text{theta}, \\
     \text{Chirality} &\rightarrow \text{Left}, \\
     \text{SelfConjugate} &\rightarrow \text{False} \}
\end{align*}
\]

\[
\begin{align*}
W[2000] &= \{ \\
     \text{ClassName} &\rightarrow \text{epsSUSY}, \\
     \text{Chirality} &\rightarrow \text{Left}, \\
     \text{SelfConjugate} &\rightarrow \text{False} \}
\end{align*}
\]
Superspace and superfields: the superspace.

- **Conventions**: \textit{à la} Fuks-Rausch de Traubenberg.
- **Superspace**: adapted space to write down SUSY transformations naturally.
- **Basic objects and their FeynRules (hardcoded) implementation.**
  * The **Majorana spinor** \((\theta, \bar{\theta})\) \(\Rightarrow\) a superspace point \(\equiv G(x, \theta, \bar{\theta})\).
  * The transformation parameters, the **Majorana spinor** \((\varepsilon_{\text{SUSY}}, \bar{\varepsilon}_{\text{SUSY}})\).

\[
W[1000] == \{ \\
\text{ClassName} \rightarrow \text{theta}, \text{Chirality} \rightarrow \text{Left}, \text{SelfConjugate} \rightarrow \text{False}\}
\]

\[
W[2000] == \{ \\
\text{ClassName} \rightarrow \text{epsSUSY}, \text{Chirality} \rightarrow \text{Left}, \text{SelfConjugate} \rightarrow \text{False}\}
\]

- **The supercharges** \((Q, \bar{Q})\): action to the left \(\equiv G(0, \varepsilon, \bar{\varepsilon})G(x, \theta, \bar{\theta})\).
- **The superderivatives** \((D, \bar{D})\): action to the right \(\equiv G(x, \theta, \bar{\theta})G(0, \varepsilon, \bar{\varepsilon})\).

\[
Q_\alpha = -i(\partial_\alpha + i\sigma^\mu \gamma_\alpha \bar{\theta} \gamma^\alpha \partial_\mu) \quad \text{and} \quad \bar{Q}_{\dot{\alpha}} = i(\bar{\partial}_{\dot{\alpha}} + i\theta^\alpha \sigma^\mu \gamma_\alpha \partial_\mu) ,
\]
\[
D_\alpha = \partial_\alpha - i\sigma^\mu \gamma_\alpha \bar{\theta} \gamma^\alpha \partial_\mu \quad \text{and} \quad \bar{D}_{\dot{\alpha}} = \bar{\partial}_{\dot{\alpha}} - i\theta^\alpha \sigma^\mu \gamma_\alpha \partial_\mu .
\]

\[Q_\alpha(\exp) \text{ and } \bar{Q}_{\dot{\alpha}}(\exp)\]

\[Q_{\text{SUSY}}[\exp_, \alpha_] \quad Q_{\text{SUSYBar}}[\exp_, \alpha_\dot{\_}]
\]

\[D_\alpha(\exp) \text{ and } \bar{D}_{\dot{\alpha}}(\exp)\]

\[D_{\text{theta}}[\exp_, \alpha_] \quad D_{\text{thetabar}}[\exp_, \alpha_\dot{\_}]
\]
Superspace and superfields: the general superfield.

- **Definition of a generic superfield.**
  - Most general (reducible) expansion in the $\theta, \bar{\theta}$ variables.
Superspace and superfields: the general superfield.

**Definition of a generic superfield.**

* Most general (reducible) **expansion in the \( \theta, \bar{\theta} \) variables.**

* Can be expressed as,

\[
\Phi(x, \theta, \bar{\theta}) = z(x) + \theta \cdot \xi(x) + \bar{\theta} \cdot \bar{\zeta}(x) + \theta \cdot \theta f(x) + \bar{\theta} \cdot \bar{\theta} g(x) + \theta \sigma^\mu \bar{\theta} \nu_\mu(x) + \bar{\theta} \cdot \bar{\theta} \theta \cdot \omega(x) + \theta \cdot \theta \cdot \bar{\theta} \cdot \bar{\bar{\rho}}(x) + \theta \cdot \theta \bar{\theta} \cdot \bar{\bar{\theta}} d(x).
\]
Superspace and superfields: the general superfield.

- **Definition of a generic superfield.**
  - Most general (reducible) **expansion in the \( \theta, \bar{\theta} \) variables.**
  - Can be expressed as,

\[
\Phi(x, \theta, \bar{\theta}) = z(x) + \theta \cdot \xi(x) + \bar{\theta} \cdot \zeta(x) + \theta \cdot \theta f(x) + \bar{\theta} \cdot \bar{\theta} g(x) + \theta \sigma^\mu \bar{\theta} \, \nu_\mu(x) + \bar{\theta} \cdot \theta \omega(x) + \theta \cdot \theta \cdot \bar{\theta} \cdot \bar{\theta} d(x).
\]

- **16 bosonic degrees of freedom.**
  - Four complex scalar fields \( z, f, g, d \).
  - One complex vector field \( \nu_\mu \).
- **16 fermionic degrees of freedom.**
  - Four Weyl fermions \( \xi, \zeta, \omega, \rho \).
Superspace and superfields: the general superfield.

**Definition of a generic superfield.**

* Most general (reducible) expansion in the $\theta, \bar{\theta}$ variables.

Can be expressed as,

$$
\Phi(x, \theta, \bar{\theta}) = z(x) + \theta \cdot \xi(x) + \bar{\theta} \cdot \bar{\zeta}(x) + \theta \cdot \theta f(x) + \bar{\theta} \cdot \bar{\theta} g(x) + \\
\theta \sigma^\mu \bar{\theta} v_\mu(x) + \bar{\theta} \cdot \bar{\theta} \theta \cdot \omega(x) + \theta \cdot \theta \cdot \bar{\theta} \cdot \bar{\rho}(x) + \theta \cdot \theta \bar{\theta} \cdot \bar{\theta} d(x).
$$

* 16 bosonic degrees of freedom.
  ◦ Four complex scalar fields $z, f, g, d$.
  ◦ One complex vector field $v_\mu$.

* 16 fermionic degrees of freedom.
  ◦ Four Weyl fermions $\xi, \zeta, \omega, \rho$.

**Can be implemented in FeynRules-superfields.**

* Use of the NC environment (keep the fermion ordering).

* All the components must be declared properly and explicitly.

* In the model file:

$$
z + \text{NC}[	ext{theta}, \text{xi}] \text{ Ueps} \text{ + ...}
$$
Superspace and superfields: the chiral superfield (1).

- Most general expansion in the $\theta, \bar{\theta}$ variables satisfying $\bar{D}_\dot{\alpha} \Phi(x, \theta, \bar{\theta}) = 0$.

\[
\Phi(x, \theta, \bar{\theta}) = \phi(y) + \sqrt{2} \theta \cdot \psi(y) - \theta \cdot \theta F(y) \text{ where } y^\mu = x^\mu - i \theta \sigma^\mu \bar{\theta}.
\]
Superspace and superfields: the chiral superfield (1).

- Most general expansion in the $\theta, \bar{\theta}$ variables satisfying $\bar{D}_\alpha \Phi(x, \theta, \bar{\theta}) = 0$.

$$\Phi(x, \theta, \bar{\theta}) = \phi(y) + \sqrt{2} \theta \cdot \psi(y) - \theta \cdot \theta F(y) \text{ where } y^\mu = x^\mu - i \theta \sigma^\mu \bar{\theta}.$$ 

* Suitable to describe the **matter supermultiplet**.
* One scalar field $\phi$, one Weyl fermion $\chi$, one auxiliary field $F$. 

---

**Supersymmetry with FeynRules**

Benjamin Fuks - Theory Seminar @ DESY Hamburg - 09.11.2010 - 44
Superspace and superfields: the chiral superfield (1).

- **Most general expansion in the** $\theta, \bar{\theta}$ **variables satisfying** $\bar{D}_\alpha \Phi(x, \theta, \bar{\theta}) = 0$.

\[
\Phi(x, \theta, \bar{\theta}) = \phi(y) + \sqrt{2} \theta \cdot \psi(y) - \theta \cdot \theta F(y) \quad \text{where} \quad y^\mu = x^\mu - i\theta \sigma^\mu \bar{\theta}.
\]

* Suitable to describe the **matter supermultiplet**.
* One scalar field $\phi$, one Weyl fermion $\chi$, one auxiliary field $F$.

**Can be implemented in FeynRules-superfields.**

### Chiral superfield - up-type Higgs doublet

```
CSF[1] == {
  ClassName -> HU,
  Chirality -> Left,
  Weyl -> huw,
  Scalar -> hus,
  QuantumNumbers -> {Y->1/2},
  Indices -> {Index[SU2D]},
  FlavorIndex -> SU2D
}
```

* The scalar and Weyl fermionic fields must be declared properly.
* The auxiliary field will be automatically generated, if not explicit.
Superspace and superfields: the chiral superfield (2).

- **Expansion in superspace with FeynRules**: \( \Phi(y, \theta) = \phi(y) + \sqrt{2} \theta \cdot \psi(y) - \theta \cdot \theta F(y) \).

\[
\begin{align*}
\text{In}[12]:= & \text{SF2Components}[\text{HU}][[1]] \\
\text{Out}[12]= & \text{hus} + \sqrt{2} \, \theta_{\text{sp}}[1] \cdot \text{huw}_{\text{sp}}[1] - \text{FTerm4} \, \theta_{\text{sp}}[1] \cdot \overline{\theta}_{\text{sp}}[1] - \frac{1}{4} \theta_{\mu}[1] \cdot \theta_{\mu}[1] \cdot \text{hus} + i \, \theta_{\mu}[1] \cdot \overline{\theta}_{\mu}[1] \cdot \theta_{\mu}[1] \cdot \overline{\theta}_{\mu}[1] \\
\text{In}[18]:= & \text{Do}[\text{If} [\text{SF2Components}[\text{HU}][[2, i]] =!= 0, \text{Print}[i, "::", \text{SF2Components}[\text{HU}][[2, i]]]], \{i, 1, 9\}] \\
1:: & \text{hus} \\
2:: & \sqrt{2} \, \text{huw}_{\alpha}[14236] \\
4:: & -i \, \theta_{\mu}[14875] \cdot \text{hus} \\
5:: & -\text{FTerm4} \\
7:: & i \, \theta_{\mu}[1] \cdot \overline{\theta}_{\mu}[1] \cdot \theta_{\mu}[1] \cdot \overline{\theta}_{\mu}[1] + \frac{1}{\sqrt{2}} \\
9:: & -\frac{1}{4} \theta_{\mu}[1] \cdot \theta_{\mu}[1] \cdot \text{hus} \\
\end{align*}
\]

* `FTerm4` was automatically generated.
* Automatic `y`-expansion.
Superspace and superfields: the chiral superfield (3).

- **SUSY transformation laws:**
  * In terms of superfields: \( \delta_\varepsilon \Phi(x, \theta, \bar{\theta}) = i(\varepsilon \cdot Q + \bar{Q} \cdot \bar{\varepsilon}) \cdot \Phi(x, \theta, \bar{\theta}) \).
  * In terms of component fields (depending on \( y \), not \( x \)): \[
    \delta_\varepsilon \phi = \sqrt{2}\varepsilon \cdot \psi, \quad \delta_\varepsilon \psi = -i\sqrt{2}\sigma^\mu \bar{\varepsilon} \partial_\mu \phi - \sqrt{2}F\varepsilon, \quad \delta_\varepsilon F = -i\sqrt{2}\partial_\mu \psi \sigma^\mu \bar{\varepsilon}.
  \]
Superspace and superfields: the chiral superfield (3).

**SUSY transformation laws:**

* In terms of **superfields**: 
  \[ \delta_\epsilon \Phi(x, \theta, \bar{\theta}) = i(\epsilon \cdot Q + \bar{Q} \cdot \bar{\epsilon}) \cdot \Phi(x, \theta, \bar{\theta}). \]

* In terms of **component fields** (depending on \( y \), not \( x \)):
  \[
  \begin{align*}
  &\delta_\epsilon \phi = \sqrt{2} \epsilon \cdot \psi, \\
  &\delta_\epsilon \psi = -i \sqrt{2} \sigma^\mu \bar{\epsilon} \partial_\mu \phi - \sqrt{2} F \epsilon, \\
  &\delta_\epsilon F = -i \sqrt{2} \partial_\mu \psi \sigma^\mu \bar{\epsilon}.
  \end{align*}
  \]

* With **FeynRules**:

```plaintext
In[6]:= tmp = SF2Components[HU][[1]];
  tmp2 = Expand[I * NC[epssusy[sp3b], Expand[QSUSY[ToNC[tmp], sp3]]] Ueps[sp3, sp3b]];
  SF2Components[tmp2][[2, 1]]
  SF2Components[tmp2][[2, 2]] / Sqrt[2]
  SF2Components[tmp2][[2, 5]] / (-1)

Out[8]= \(\sqrt{2} \) huw[sp$1].epssusy[sp$1]

Out[9]= -\(\sqrt{2} \) FTerm4.epssusy[alpha$2251]

Out[10]= 0
```

* ToNC breaks dot products and the NC structure keeps fermion ordering.
* Ueps corresponds to the antisymmetric tensor with upper indices.
Superspace and superfields: the chiral superfield (3).

● **SUSY transformation laws:**
  * In terms of **superfields:**  \( \delta_\epsilon \Phi(x, \theta, \bar{\theta}) = i(\epsilon \cdot Q + \bar{Q} \cdot \bar{\epsilon}) \cdot \Phi(x, \theta, \bar{\theta}) \).
  * In terms of **component fields** (depending on \( y \), not \( x \)):  
    \[
    \delta_\epsilon \phi = \sqrt{2} \epsilon \cdot \psi , \quad \delta_\epsilon \psi = -i \sqrt{2} \sigma^\mu \bar{\epsilon} \partial_\mu \phi - \sqrt{2} F \epsilon , \quad \delta_\epsilon F = -i \sqrt{2} \partial_\mu \psi \sigma^\mu \bar{\epsilon} .
    \]
  * With **FeynRules:**

```plaintext
In[15]:= tmp = SF2Components[HU][[1]]; tmp2 = Expand[I * NC[Expand[QSUSYBar[ToNC[tmp], adot]], epssusybar[bdot]] Ueps[adot, bdot]]; SF2Components[tmp2][[2, 1]]; SF2Components[tmp2][[2, 2]] / Sqrt[2]; SF2Components[tmp2][[2, 5]] / (-1)

Out[17]= 0

Out[18]= -i \sqrt{2} \partial_{\mu_1} [hus] epssusy^{\dagger}_{sp$1dot} (\sigma^{\mu_1})_{alpha$4408,sp$1dot}

Out[19]= -i \sqrt{2} \partial_{\mu_1} [huw_{sp$1}] . epssusy^{\dagger}_{sp$1dot} (\sigma^{\mu_1})_{sp$1,sp$1dot}
```

* ToNC breaks dot products and the NC structure keeps fermion ordering.
* Ueps corresponds to the antisymmetric tensor with upper indices.
Superspace and superfields: the vector superfield (1).

- Expansion in the $\theta, \bar{\theta}$ variables satisfying $\Phi = \Phi^\dagger$ in the Wess-Zumino gauge.

$$\Phi_{W,Z}(x, \theta, \bar{\theta}) = \theta \sigma^\mu \bar{\theta} v_\mu + i \theta \cdot \theta \bar{\theta} \cdot \bar{\lambda} - i \bar{\theta} \cdot \bar{\theta} \theta \cdot \lambda + \frac{1}{2} \theta \cdot \theta \bar{\theta} \cdot \bar{\theta} D$$
Superspace and superfields: the vector superfield (1).

- **Expansion in the** $\theta, \bar{\theta}$ **variables satisfying** $\Phi = \Phi^\dagger$ **in the Wess-Zumino gauge.**

\[
\Phi_{\text{W.Z.}}(x, \theta, \bar{\theta}) = \theta \sigma^\mu \bar{\theta} v_\mu + i \theta \cdot \theta \bar{\theta} \cdot \bar{\lambda} - i \bar{\theta} \cdot \bar{\theta} \theta \cdot \lambda + \frac{1}{2} \theta \cdot \theta \bar{\theta} \cdot \bar{\theta} D .
\]

- Suitable to describe the **gauge supermultiplet.**
- One Majorana fermion $(\lambda, \bar{\lambda})$, one gauge boson $v$, one auxiliary field $D$. 
Superspace and superfields: the vector superfield (1).

- Expansion in the $\theta, \bar{\theta}$ variables satisfying $\Phi = \Phi^\dagger$ in the Wess-Zumino gauge.

$$\Phi_{W.Z.}(x, \theta, \bar{\theta}) = \theta \sigma^\mu \bar{\theta} v_\mu + i \theta \cdot \theta \bar{\theta} \cdot \bar{\lambda} - i \bar{\theta} \cdot \bar{\theta} \theta \cdot \lambda + \frac{1}{2} \theta \cdot \theta \bar{\theta} \cdot \bar{\theta} D.$$ 

- Suitable to describe the gauge supermultiplet.
- One Majorana fermion ($\lambda, \bar{\lambda}$), one gauge boson $v$, one auxiliary field $D$.
- Can be implemented in FeynRules-superfields.

**Vector superfield for $SU(2)_L$**

```
VSF[1] == {
    ClassName -> WSF,
    GaugeBoson -> Wi,
    Gaugino -> wow,
    Indices -> {Index[SU2W]},
    FlavorIndex -> SU2W
}
```

**Associated gauge group**

```
SU2L == {
    Abelian -> False,
    GaugeBoson -> Wi,
    CouplingConstant -> gw,
    SF -> WSF,
    StructureConstant -> ep,
    Representations -> {...},
    Definitions -> {...}
}
```

- The Weyl fermionic and vectorial fields must be declared properly.
- The auxiliary field will be automatically generated, if not explicit.
Superspace and superfields: the vector superfield (2).

Expansion in superspace with FeynRules:

\[ \Phi = \theta \sigma^\mu \bar{\theta} v_\mu + i \theta \cdot \theta \bar{\theta} \cdot \bar{\lambda} - i \bar{\theta} \cdot \bar{\theta} \cdot \lambda + \frac{1}{2} \theta \cdot \theta \bar{\theta} \cdot \bar{\theta} D . \]

* $D\text{Term}_2$ was automatically generated.
* The index naming scheme is optimized, for readability.
Superspace and superfields: the vector superfield (3).

Properties of the vector superfield:

\[ \Phi^2_{W.Z.} = \frac{1}{2} \theta \cdot \bar{\theta} \cdot \bar{v}^{\mu} v_{\mu}, \]  
\[ \Phi^3_{W.Z.} = 0. \]
Superspace and superfields: the vector superfield (3).

- Properties of the vector superfield:

\[ \Phi^2_{W,Z.} = \frac{1}{2} \theta \cdot \theta \overline{\theta} \cdot \overline{v}^{\mu} v_{\mu}, \quad \Phi^3_{W,Z.} = 0. \]

```math
SF2Components[WSF[ii] WSF[jj]][[1]]
```

```
Out[23]=
\[ \frac{1}{2} \theta_{sp1} \cdot \theta_{sp1} \overline{\theta}_{sp1dot} \cdot \overline{\theta}_{sp1dot} \rightdot \rightdot Wi_{mu1, SU2W1001} Wi_{mu1, SU2W1002} \]
```

```
In[24]:= SF2Components[WSF[ii] WSF[jj] WSF[kk]][[1]]
```

```
Out[24]= 0
```
Superspace and superfields: the vector superfield (3).

- **Properties of the vector superfield:**
  \[ \Phi^2_{W.Z.} = \frac{1}{2} \theta \cdot \theta \bar{\theta} \cdot \bar{\theta} v^\mu v_\mu, \quad \Phi^3_{W.Z.} = 0. \]

  ```math
  SF2Components[WSF[ii] WSF[jj]][[1]]
  ```

  ```math
  Out[23]= \frac{1}{2} \theta_{sp$1} \cdot \theta_{sp$1} \bar{\theta}_{sp$1dot} \cdot \bar{\theta}_{sp$1dot} W_{i\mu$1},SU2W$1001 W_{i\mu$1},SU2W$1002
  ```

  ```math
  ```

  ```math
  Out[24]= 0
  ```

- **The superfield strength tensor is built from associated spinorial superfields:**
  \[ W_\alpha = -\frac{1}{4} \bar{D} \cdot D e^{2gV} D_\alpha e^{-2gV}, \quad \bar{W}_{\dot{\alpha}} = -\frac{1}{4} D \cdot D e^{-2gV} \bar{D}_{\dot{\alpha}} e^{2gV}. \]

  \[ W_\alpha, (W_\alpha)_{ij}, \bar{W}_{\dot{\alpha}} \text{ and } (\bar{W}_{\dot{\alpha}})_{ij} \]

  - `Sca2SpinL[ superfield, lower spin index ]`
  - `Sca2SpinL[ superfield, spin index, gauge index, gauge index ]`
  - `Sca2SpinR[ superfield, lower spin index ]`
  - `Sca2SpinR[ superfield, spin index, gauge index, gauge index ]`
Superspace and superfields: the vector superfield (4).

- **Spinorial superfields:**

\[
W_\alpha(y, \theta) = -2g \left( -i \lambda_\alpha + \left[ -\frac{i}{2}(\sigma^\mu \bar{\sigma}^\nu \theta)F_{\mu\nu} + \theta_\alpha D \right] - \theta \cdot \theta (\sigma^\mu D_\mu \bar{\lambda})_\alpha \right).
\]

FeynRules has performed the \( y \)-expansion.

- Spinors with non-lower spin index are embedded in a TensDot2 structure.
- Tadj matrices automatically added: \( D = D^a T_a, \ldots \)
Each vector superfield is attached to one gauge group.
Lagrangians: superfield strength tensors - SFSTs (1).

- Each vector superfield is attached to one gauge group.
- Vector superfield interactions are obtained by calculating SFSTs.
  * Abelian groups.
    \[
    \mathcal{L} = \frac{1}{4} W^\alpha W_\alpha |_{\theta\theta} + \frac{1}{4} \bar{W}^{\dot{\alpha}} \bar{W}_{\dot{\alpha}} |_{\bar{\theta}\bar{\theta}} \\
    = - \frac{1}{4} \mathbf{F}_{\mu\nu} \mathbf{F}^{\mu\nu} + i \bar{\lambda} \sigma^\mu D_\mu \lambda + \frac{1}{2} D^2 .
    \]
  * Non-abelian groups.
    \[
    \mathcal{L} = \frac{1}{16g^2 \tau_R} \text{Tr}(W^\alpha W_\alpha) |_{\theta\theta} + \frac{1}{16g^2 \tau_R} \text{Tr}(\bar{W}^{\dot{\alpha}} \bar{W}^\dot{\alpha}) |_{\bar{\theta}\bar{\theta}} \\
    = - \frac{1}{4} \mathbf{F}^a_{\mu\nu} \mathbf{F}^{\mu\nu}_a + i \bar{\lambda}_a \bar{\sigma}^\mu D_\mu \lambda^a + \frac{1}{2} D_a D^a \\
    \Rightarrow \text{Interactions between gauge-bosons and gauginos.}
    \]
Lagrangians: superfield strength tensors - SFSTs (1).

- Each vector superfield is attached to one gauge group.
- Vector superfield interactions are obtained by calculating SFSTs.
  * Abelian groups.

\[
\mathcal{L} = \frac{1}{4} W^\alpha W_\alpha \mid_{\theta \theta} + \frac{1}{4} \bar{W}^\dot{\alpha} \bar{W}^\dot{\alpha} \mid_{\bar{\theta} \bar{\theta}} \\
= - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i \bar{\lambda} \bar{\sigma}^\mu \partial_\mu \lambda + \frac{1}{2} D^2 .
\]

* Non-abelian groups.

\[
\mathcal{L} = \frac{1}{16 g^2 \tau_R} \text{Tr}(W^\alpha W_\alpha) \mid_{\theta \theta} + \frac{1}{16 g^2 \tau_R} \text{Tr}(\bar{W}^\dot{\alpha} \bar{W}^\dot{\alpha}) \mid_{\bar{\theta} \bar{\theta}} \\
= - \frac{1}{4} F^a_{\mu \nu} F_a^{\mu \nu} + i \bar{\lambda}_a \bar{\sigma}^\mu D_\mu \lambda^a + \frac{1}{2} D_a D^a \\
\Rightarrow \text{Interactions between gauge-bosons and gauginos.}
\]

- Automatic extraction of the SFSTs of a model:
Lagrangians: superfield strength tensors - SFSTs (2).

**Abelian superfield strengths:**

\[ \mathcal{L} = - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i \bar{\lambda} \sigma^\mu \partial_\mu \lambda + \frac{1}{2} D^2 . \]
Lagrangians: superfield strength tensors - SFSTs (2).

- **Abelian superfield strengths:**

\[
\mathcal{L} = - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\lambda} \sigma^\mu \partial_\mu \lambda + \frac{1}{2} D^2 .
\]

- **Case of the MSSM in FeynRules.**

```math
\begin{align*}
\text{In}[7] := & \quad \text{GetSuperFS[]} \\
\text{Out}[7] = & \quad \frac{1}{4} \text{SuperFS}[\text{BSF, True}] + \frac{\text{SuperFS}[\text{WSF, False}]}{16 g_w^2 \tau_{\text{SU2L}}} + \frac{\text{SuperFS}[\text{GSF, False}]}{16 g_s^2 \tau_{\text{SU3C}}} \\
\text{In}[18] := & \quad \text{tmp} = \text{SF2Components}[\%[7[[1]]]]; \\
& \quad \text{tmp}[[2, 5]] + \text{tmp}[[2, 6]] \\
\text{Out}[19] = & \quad \frac{\text{DTerm1}^2}{2} - \frac{1}{2} \partial_{\mu_s2} [B_{\mu_s1}]^2 + \frac{1}{2} \partial_{\mu_s2} [B_{\mu_s1}] \partial_{\mu_s1} [B_{\mu_s2}] + \\
& \quad \frac{1}{2} i \text{bow}_{sp$1$} \cdot \partial_{\mu_s1} [\text{bow}^\dagger_{sp$1$dot}] (\sigma^{\mu_s1})_{sp$1$, sp$1$dot} - \frac{1}{2} i \partial_{\mu_s1} [\text{bow}_{sp$1$}] \cdot \text{bow}^\dagger_{sp$1$dot} (\sigma^{\mu_s1})_{sp$1$, sp$1$dot}
\end{align*}
```
Lagrangians: superfield strength tensors - SFSTs (3).

- **Non-abelian superfield strengths:**

\[ \mathcal{L} = - \frac{1}{4} F^a_{\mu \nu} F_a^{\mu \nu} + i \bar{\lambda}_a \bar{\sigma}^\mu D_\mu \lambda^a + \frac{1}{2} D_a D^a. \]
Lagrangians: superfield strength tensors - SFSTs (3).

- **Non-abelian superfield strengths:**

\[
\mathcal{L} = - \frac{1}{4} F_{\mu \nu}^a F_{\mu \nu}^a + i \bar{\lambda}_a \sigma^\mu D_\mu \lambda^a + \frac{1}{2} D_a D^a .
\]

- **Case of the MSSM in **FeynRules**.

In[16]:= tmp = SF2Components[%7[[2]]];
    tmp[[2, 5]] + tmp[[2, 6]]
Out[17]= 
\(-\frac{1}{2} \partial_{\mu 2} [W1_{\mu 1}, SU2W1]^2 + \frac{1}{2} \partial_{\mu 2} [W1_{\mu 1}, SU2W1] \partial_{\mu 1} [W1_{\mu 2}, SU2W1] + \\
\frac{DTerm2_{SU2W1}}{2} - \frac{1}{2} i \partial_{\mu 1} [\omega sp1, SU2W1] . \omega sp1dot, SU2W1 \left(\sigma^{\mu 1}\right) sp1, sp1dot^+ + \\
\frac{1}{2} i \omega sp2, SU2W1 . \partial_{\mu 1} [\omega^+ sp1dot, SU2W1] \left(\sigma^{\mu 1}\right) sp2, sp1dot - \\
\frac{1}{2} i g_w \omega sp1, SU2W1 . \omega^+ sp2dot, SU2W2 ep sp1, sp2sp2dot, SU2W3 \left(\sigma^{\mu 1}\right) sp1, sp2sp2dot, SU2W3 - \\
\frac{1}{2} i g_w \omega sp2, SU2W1 . \omega^+ sp1dot, SU2W2 ep sp1, sp2sp2dot, SU2W3 \left(\sigma^{\mu 1}\right) sp2, sp1sp1dot, SU2W3 + \\
g_w \partial_{\mu 2} [W1_{\mu 1}, SU2W1] ep sp1, SU2W3, SP2W2, SU2W3, SU2W3 \left(\sigma^{\mu 1}\right) sp1, SU2W1, SP2W1, SU2W2 SU2W3 - \\
\frac{1}{4} g_w^2 ep sp1, SU2W1, SU2W2, SU2W3 ep sp2, SU2W4, SU2W5 SU2W3 W1_{\mu 1}, SU2W1 W1_{\mu 1}, SU2W4 W1_{\mu 2}, SU2W2 W1_{\mu 2}, SU2W5\)
Lagrangians: chiral superfield kinetic terms (1).

The kinetic terms for chiral superfields are given by,

$$\mathcal{L} = \left[ \Phi^\dagger(x, \theta, \bar{\theta}) e^{-2y\phi} g' V_B e^{-2g} V_W e^{-2g_s} V_G (x, \theta, \bar{\theta}) \right] \theta \cdot \bar{\theta} \cdot \bar{\theta}$$

⇒ Gauge interactions.

* The vector superfields contains the proper representation matrices.
Lagrangians: chiral superfield kinetic terms (1).

- The kinetic terms for chiral superfields are given by,

\[ \mathcal{L} = \left[ \Phi^\dagger(x, \theta, \bar{\theta}) e^{-2y \Phi^g B} e^{-2g^W W} e^{-2g^S S} \Phi(x, \theta, \bar{\theta}) \right] \theta \cdot \theta \bar{\theta} \cdot \bar{\theta} \]

⇒ Gauge interactions.

* The vector superfields contains the proper representation matrices.

- Automatic extraction with FeynRules: case of the MSSM.

In[20]:= Getkins[]

Lagrangians: chiral superfield kinetic terms (2).

- **Right electron kinetic Lagrangian:**

\[
\mathcal{L} = D_\mu \phi^\dagger D^\mu \phi - \frac{i}{2} (D_\mu \bar{\psi} \bar{\sigma}^\mu \psi - \bar{\psi} \bar{\sigma}_\mu D_\mu \psi) + i \sqrt{2} g \bar{\lambda}^a \cdot \bar{\psi} T_\alpha \phi - i \sqrt{2} g \phi^\dagger T_\alpha \psi \cdot \lambda^a \\
+ FF^\dagger - g D^a \phi^\dagger T^a \phi .
\]
Lagrangians: chiral superfield kinetic terms (2).

- **Right electron kinetic Lagrangian:**
  \[ \mathcal{L} = D_\mu \phi^\dagger D^\mu \phi - \frac{i}{2} \left( D_\mu \bar{\psi} \sigma^\mu \psi - \bar{\psi} \sigma^\mu D_\mu \psi \right) + i \sqrt{2} g \bar{\lambda}^a \cdot \bar{\psi} T_a \phi - i \sqrt{2} g \phi^\dagger T_a \psi \cdot \lambda^a \]
  \[ + \overline{F}^\dagger - g D^a \phi^\dagger T^a \phi. \]

- **In FeynRules:**
  
  ```math
  \text{In[20]} = \text{Getkins[]} \\
  \text{Out[20]} = \text{GetSFKineticTerms[DR]} + \text{GetSFKineticTerms[ER]} + \text{GetSFKineticTerms[HD]} + \text{GetSFKineticTerms[HU]} + \text{GetSFKineticTerms[LL]} + \text{GetSFKineticTerms[QL]} + \text{GetSFKineticTerms[UR]} + \text{GetSFKineticTerms[VR]}
  
  \text{In[23]} = \text{SF2Components[Getkins[][[2]]][[2, -1]]} \\
  \text{Out[23]} = \frac{1}{2} \partial_\mu [\overline{\text{ERsGEN1}}] \partial_\mu [\text{ERs}_{\text{GEN1}}^\dagger] - \frac{1}{4} \partial_\mu [\partial_\mu [\text{ERs}_{\text{GEN1}}^\dagger]] \overline{\text{ERsGEN1}} - \\
  i g' B_{\mu\mu_1} \partial_\mu_1 [\text{ERs}_{\text{GEN1}}^\dagger] \overline{\text{ERsGEN1}} + \frac{i}{2} \sqrt{2} g' \text{bow}_{sp1dot} \cdot \text{ERw}_{sp1dot, GEN1} \overline{\text{ERsGEN1}} - \\
  \frac{1}{4} \partial_\mu [\partial_\mu [\text{ERsGEN1}]] \text{ERs}_{\text{GEN1}}^\dagger + i g' B_{\mu\mu_1} \partial_\mu_1 [\text{ERsGEN1}] \text{ERs}_{\text{GEN1}}^\dagger - \\
  i \sqrt{2} g' \text{ERw}_{sp1, GEN1} \cdot \text{bow}_{sp1} \text{ERs}_{\text{GEN1}}^\dagger - \text{DTerm1} g' \text{ERsGEN1} \text{ERs}_{\text{GEN1}}^\dagger + (g')^2 B_{\mu\mu_1} \text{ERsGEN1} \text{ERs}_{\text{GEN1}}^\dagger + \\
  \text{FTerm7GEN1 FTerm7}_{\text{GEN1}}^\dagger - \frac{1}{2} i \partial_\mu [\text{ERw}_{sp1, GEN1}] \cdot \text{ERw}_{sp1dot, GEN1} (\sigma_{\mu_1}^1)_{sp1, sp1dot} + \\
  \frac{1}{2} i \text{ERw}_{sp1, GEN1} \cdot \partial_\mu [\text{ERw}_{sp1dot, GEN1}] (\sigma_{\mu_1}^1)_{sp1, sp1dot} - \\
  \frac{1}{2} g' B_{\mu\mu_1} \text{ERw}_{sp1, GEN1} \cdot \text{ERw}_{sp1dot, GEN1} (\sigma_{\mu_1}^1)_{sp1, sp1dot}
  ```
Supersymmetric Lagrangians.

\[ \mathcal{L} = \Phi^\dagger e^{-2gV} \Phi |_{\theta^2 \bar{\theta}^2} + \frac{1}{16g^2 \tau_R} \text{Tr}(W^\alpha W_\alpha) |_{\theta^2} + \frac{1}{16g^2 \tau_R} \text{Tr}(\bar{W}_\dot{\alpha} \bar{W}^{\dot{\alpha}}) |_{\bar{\theta}^2} \]

\[ + W(\Phi) |_{\theta^2} + W^*(\Phi^\dagger) |_{\bar{\theta}^2} + \mathcal{L}_{\text{soft}} \]
**Supersymmetric Lagrangians.**

\[ \mathcal{L} = \Phi^\dagger e^{-2gV} \Phi |_{\bar{\theta}^2 \bar{\theta}^2} + \frac{1}{16g^2 \tau_R} \text{Tr}(W^\alpha W_\alpha) |_{\bar{\theta}^2} + \frac{1}{16g^2 \tau_R} \text{Tr}(\bar{W}_\dot{\alpha} \bar{W}^\dot{\alpha}) |_{\bar{\theta}^2} \\
+ W(\Phi) |_{\bar{\theta}^2} + W^*(\Phi^\dagger) |_{\bar{\theta}^2} + \mathcal{L}_{\text{soft}} \]

- **Chiral superfields kinetic terms:** automatic.
- **Vector superfield strengths:** automatic.
- **Superpotential:** model dependent.
- **Soft SUSY-breaking Lagrangian:** model dependent.
Supersymmetric Lagrangians.

\[ \mathcal{L} = \Phi^\dagger e^{-2gV} \Phi |_{\theta^2 \bar{\theta}^2} + \frac{1}{16g^2\tau \mathcal{R}} \text{Tr}(\mathcal{W}^\alpha \mathcal{W}_\alpha)|_{\theta^2} + \frac{1}{16g^2\tau \mathcal{R}} \text{Tr}(\bar{\mathcal{W}}^\dot{\alpha} \bar{\mathcal{W}}^{\dot{\alpha}})|_{\bar{\theta}^2} + \mathcal{W}(\Phi)|_{\theta^2} + \mathcal{W}^*(\Phi^\dagger)|_{\bar{\theta}^2} + \mathcal{L}_{\text{soft}} \]

- **Chiral superfields kinetic terms**: automatic.
- **Vector superfield strengths**: automatic.
- **Superpotential**: model dependent.
- **Soft SUSY-breaking Lagrangian**: model dependent.

**SUSY Lagrangian**

\[
\text{LSoft} + \text{SF2Components[GetKins[]][2,9]} + \text{SF2Components[GetSuperFS[] + SuperPot][2,5]} + \text{SF2Components[GetSuperFS[] + HC[SuperPot]][2,6]};
\]
Supersymmetric Lagrangians.

\[ \mathcal{L} = \phi^\dagger e^{-2gV} \phi \big|_{\theta^2 \bar{\theta}^2} + \frac{1}{16g^2 \tau_R} \text{Tr} (W^\alpha W_\alpha) \big|_{\bar{\theta}^2} + \frac{1}{16g^2 \tau_R} \text{Tr} (\tilde{W}_\dot{\alpha} \tilde{W}^{\dot{\alpha}}) \big|_{\bar{\theta}^2} \\
\quad + W(\Phi) \big|_{\theta^2} + W^*(\Phi^\dagger) \big|_{\bar{\theta}^2} + \mathcal{L}_{\text{soft}} \]

- **Chiral superfields kinetic terms**: automatic.
- **Vector superfield strengths**: automatic.
- **Superpotential**: model dependent.
- **Soft SUSY-breaking Lagrangian**: model dependent.

**SUSY Lagrangian**

\[
\text{LSoft + SF2Components[GetKins[]][[2,9]] + } \\
\text{SF2Components[GetSuperFS[] + SuperPot][[2,5]] + } \\
\text{SF2Components[GetSuperFS[] + HC[SuperPot]][[2,6]] ;}
\]

- **Solution of the equations of motion for the auxiliary fields.**

\[
\text{lagr = SolveEqMotionD[ lagr ] ; lagr = SolveEqMotionF[ lagr ] ;}
\]
Supersymmetric Lagrangians.

\[ \mathcal{L} = \Phi^\dagger e^{-2gV} \Phi |_{\bar{\theta}^2 \theta^2} + \frac{1}{16g^2} \text{Tr}(W^\alpha W_\alpha) |_{\bar{\theta}^2} + \frac{1}{16g^2} \text{Tr}(\bar{W}_\dot{\alpha} \bar{W}^{\dot{\alpha}}) |_{\bar{\theta}^2} + \mathcal{W}(\Phi) |_{\theta^2} + \mathcal{W}^*(\Phi^\dagger) |_{\bar{\theta}^2} + \mathcal{L}_{\text{soft}} \]

- **Chiral superfields kinetic terms**: automatic.
- **Vector superfield strengths**: automatic.
- **Superpotential**: model dependent.
- **Soft SUSY-breaking Lagrangian**: model dependent.

**SUSY Lagrangian**

\[
\text{LSoft} + \text{SF2Components[GetKins[]][[2,9]] + SF2Components[GetSuperFS[] + SuperPot][[2,5]] + SF2Components[GetSuperFS[] + HC[SuperPot]][[2,6]] ;}
\]

- **Solution of the equations of motion for the auxiliary fields**.

\[
\text{lagr} = \text{SolveEqMotionD[ lagr ] ; lagr} = \text{SolveEqMotionF[ lagr ] ;}
\]

- **Back to four-component fermions** (needed for Monte Carlo generators).

\[
\text{lagr} = \text{WeylToDirac[ lagr ] ;}
\]
Lagrangians - example: the MSSM.

In[6]:= \text{lagr} = \text{Lag};

Generation of the superfield strengths...
++ BSF superfield strength generated in 3.91 s.
++ WSF superfield strength generated in 41.06 s.
++ GSF superfield strength generated in 38.46 s.
... Achieved!

Generation of the Kaehler potential...
++ DR kinetic terms generated in 5.11 s.
++ ER kinetic terms generated in 2.17 s.
++ HD kinetic terms generated in 5.07 s.
++ HU kinetic terms generated in 5.06 s.
++ LL kinetic terms generated in 5.18 s.
++ QL kinetic terms generated in 9.83 s.
++ UR kinetic terms generated in 5.36 s.
++ VR kinetic terms generated in 0.45 s.
... Achieved!

Generation of the superpotential achieved in 15.43 s.

Generation of the soft SUSY-breaking Lagrangian achieved in 0 s.
D-equations of motion solved in 2.48 s.
F-equations of motion solved in 65.09 s.

Transformation to Dirac fermions...
++ Removal of color antifundamentals in 0 s.
++ First optimization of the index naming scheme done in 0.87 s.
++ Expansion of the SU2L indices done in 93.6 s.
++ Second optimization of the index naming scheme done in 8.88 s.
++ Transforming Weyls into Diracs done in 285.72 s.
++ Final optimization of the index naming scheme done in 9.59 s.
... Achieved!
# Outline

1. Monte Carlo tools and New Physics investigations at the LHC.

2. Status of **FeynRules**.

3. New developments in **FeynRules**.

4. Supersymmetric model building with **FeynRules** - the superfield module.

5. Web validation and model database.

6. Conclusions.
Validation of new models.

**FeynRules** provides a platform to:

- develop BSM theories.
- validate them to an unprecedented level.

Using the different interfaces, we can compare results for different MCs:

- Using different conventions.
- Using different gauges.
- Using different way of handling large cancellations.

This can be fully automatized.

This can be stored on the Internet.
Web validation (1) [Christensen].
Web validation (2) [Christensen].
Web validation (3) [Christensen].
Outline

1. Monte Carlo tools and New Physics investigations at the LHC.
4. Supersymmetric model building with FeynRules - the superfield module.
5. Web validation and model database.
6. Conclusions.
Conclusions.

- **FeynRules** provides a platform to:
  * Develop new models.
  * Investigate their phenomenology.
  * Validate their implementation in commonly used tools.

- The LHC is now running.
  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.
Communication between theorists and experimentalists.

- How to communicate the models between theorists and experimentalists?
  
  * Theory paper on the arXiv are not enough.
  * A model database would be useful.

In a future, not too far far away from now...
Communication between theorists and experimentalists.

Supersymmetry with FeynRules

Benjamin Fuks - Theory Seminar @ DESY Hamburg - 09.11.2010 - 66