Beyond Minimal Supersymmetric Models
From theory to events.

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Outline

1. Monte Carlo tools and New Physics investigations at the LHC.
2. FeynRules - Beyond the Standard Model Phenomenology made easy.
3. The superspace module of FeynRules - supersymmetry made easy.
4. Phenomenology example: R-parity violating supersymmetry and monotops.
5. Conclusions.

Monte Carlo tools and discoveries at the LHC.

- **One of the goals of the LHC: which New Physics theory is the correct one?**

Confront data and theory.

- **Establishing of an excess over the SM backgrounds**.
  - * **Difficult task**.
  - * Use of **Monte Carlo generators** (backgrounds, signals).
- **Confirmation of the excess**.
  - * **Model building activities**.
    - ◇ Bottom-up and 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 ⇔ new physics and detector knowledge**.

Monte Carlo tools play a key role!
But how is new physics presently investigated in particle physics?

A framework for LHC analyzes (1).

Idea ⇔

Model building

* **Pen&pencil stage.**
* Leading order, loop calculations, ...
* Electroweak, low energy constraints,...

⇒ **Publications**

⇓

Phenomenology

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

⇒ **Publications**

⇓

Experiment

* **Experimental framework.**
* Matrix elements, parton showering, hadronization.
* Realistic detector simulation.
* **Comparison with data**.

⇒ **Publications**

A framework for LHC analyzes (2).

- **New physics theories**.
  - A **lot of different** theories.
  - Based on very **different ideas**.
  - **In evolution** (especially regarding the discoveries).

Implementation in Monte Carlo tools.

- A model consists in:
  - **particles**,
  - **parameters**,
  - **interactions** ($\equiv$ Feynman rules).
- The Feynman rules **have to be derived (from a Lagrangian)**.
  - Must be **translated in a programming language**.
  - **Tedious, time-consuming, error prone**.
  - We need to iterate for each considered model.
  - We need to iterate for each considered MC tool.
  - Beware: **allowed Lorentz and color structures**.
  - Beware: **validation**.

Redundancies of the work.

A framework for LHC analyzes (3).

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

Idea ≡ **Theory**

↘ **Lagrangian**

↘ FeynRules

↘ **Matrix elements (MC generators)**

↘ **Parton showering** ≡ **Phenomenology**

↘ **Hadronization**

↘ **Generic detector**

↘ **Realistic detector**

↘ **Data** ≡ **Experiment**

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The FeynRules approach (1).

- **Starting from physical quantities**.
  - * All the physics is included in the model **Lagrangian**.
    - ◇ The Lagrangian is **absent in the MC implementation**.
  - * **Traceability.**
    - ◇ **Univocal definition of a model**.
    - ◇ **No dependence on the conventions used** by the MC tools.
  - * **Flexibility.**
    - ◇ A modification of a model $\equiv$ change in the Lagrangian.

Aims.

- * 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 FeynRules approach (2).

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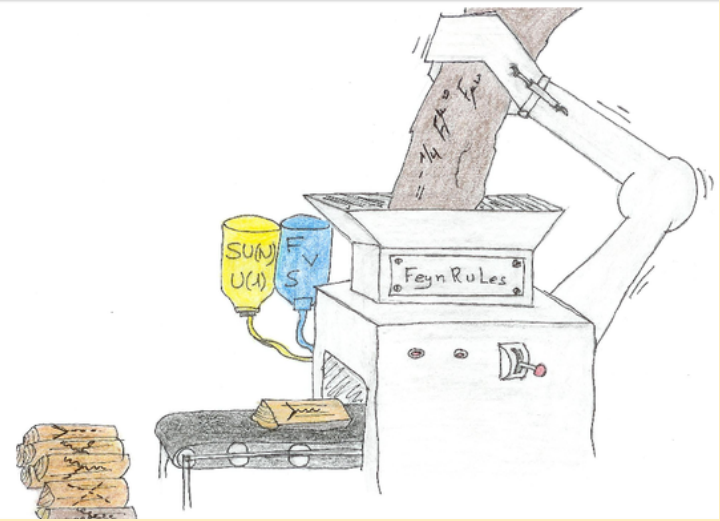
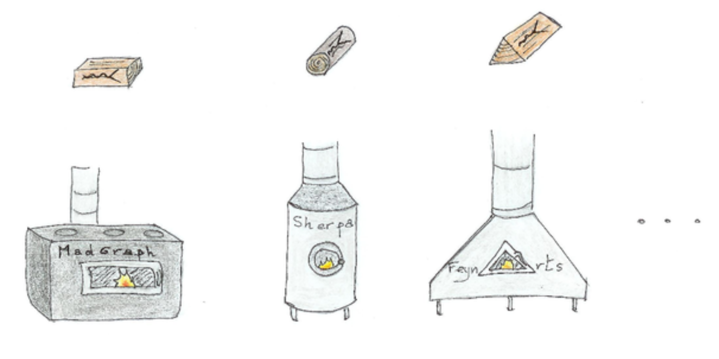
The FeynRules approach (3).



The FeynRules approach (4).



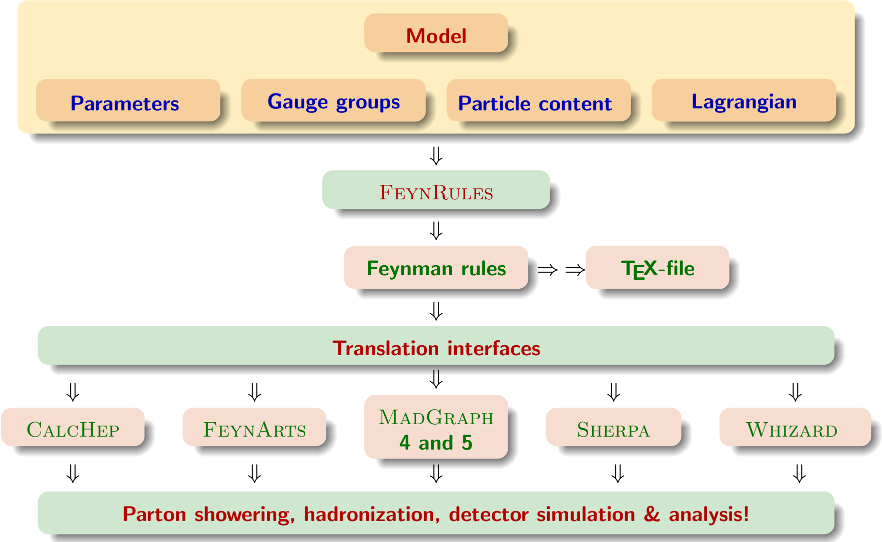
FeynRules in a nutshell.

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

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

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

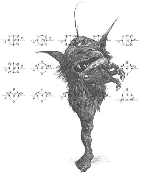
The FeynRules scheme.



Latest developments (1).

- **The UFO** [Degrande, Duhr, BenjF, Grellscheid, Mattelaer, Reiter (2011)].
  - UFO ≡ Universal FeynRules output (**not tied** to any Monte Carlo tool).
  - Allows for **generic** color and Lorentz structures.
  - Used by MadGraph**5**, GoSam **and (in the future by)** Herwig**++**.
  - FeynRules interface: creates a Python **module** to be linked.
  - The module contains **all** the model information.
- **ALOHA** [de Aquino, Link, Maltoni, Mattelaer, Stelzer (2011)].
  - ALOHA ≡ Automatic Libraries Of Helicity Amplitudes.
  - Exports the UFO; **produces the related** Helas **routines** (C++/Python).
    ⇒ to be used for **Feynman diagram computations**.
  - Used by MadGraph**5** / as a standalone package.

Latest developments (2).



- **A superspace module for** FeynRules [Duhr, BenjF (CPC '11)].
  - * Full support for **Weyl fermions and superfields**.
  - * Series expansion in terms of **component fields**.
  - * **Automatic derivation** of supersymmetry-conserving Lagrangians.
  - * **Automatic solution** of the equations of motion for the auxiliaries.
  - * Can be used for **many calculations in superspace**.
- **A new** FeynArts **interface** [Degrande, Duhr].
  - * Allows for **generic** Lorentz structures.
  - * Creates both the **model dependent and independent** FeynArts files.
  - * New version of FormCalc $\Rightarrow$ **multifermion interactions**.

FeynRules-1.6 - status.

- **Current public version: 1.6.0**.
  - * **To be download on http://feynrules.irmp.ucl.ac.be/**.
  - * Contains the **superspace module**.
  - * Contains the **UFO interface** ⇒ MadGraph5, GoSam.
  - * Contains the new FeynArts **interface**.
  - * Interfaced to Whizard. [Christensen, Duhr, BenjF, Reuter, Speckner (2010)]
  - * Supports **color sextets**.
  - * Other interfaces: CalcHep/CompHep, MadGraph4, Sherpa.
  - * **Manual currently being updated** [Christensen, Duhr, BenjF (in prep)].
- **Current online model database**.
  - * **http://feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage/** .
  - * Standard Model and simple extensions (10).
  - * Supersymmetric models (4).
  - * Extra-dimensional models (4).
  - * Strongly coupled and effective field theories (4).

Outline

The Minimal Supersymmetric Standard Model (MSSM).

- **Extension to the Standard Model**: symmetry between fermions and bosons.

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle \ , \quad Q|\text{Fermion}\rangle = |\text{Boson}\rangle \ , \quad Q \text{ being a SUSY generator.}$$

- **The MSSM**: **one** single supersymmetric (SUSY) generator Q.

The MSSM: one SUSY partner for each SM particle.
* Quarks ⇔ squarks; leptons ⇔ sleptons.
* Gauge/Higgs bosons ⇔ gauginos/higgsinos ⇔ charginos/neutralinos.
* Gluon ⇔ gluino.

- **Introduction of the SUSY particles in the theory**.
  * **Solution to the hierarchy problem** (stabilization of the Higgs mass).
  * **Gauge coupling unification** at high energy.
  * **Dark matter candidate** ⇔ lightest SUSY particle stable and neutral. (assuming R-parity conservation).
- **No SUSY discovery until now!** ⇒ **SUSY must be broken.**
  * SUSY masses at a higher scale than Standard Model (SM) masses.
- **The MSSM is more and more constrained ⇒ need to go beyond**.

Motivation for a superspace module.

- **Kinetic terms and gauge interactions for left-handed (s)quarks in the MSSM.**
  - * Not very nicely expressed in terms of **components fields**, i. e. scalars, Weyl fermions, vector fields (**13 terms**):

$$\begin{aligned}\mathcal{L}_{\rm kin} \supset\ & D_\mu \widetilde{Q}_i^\dagger D^\mu \widetilde{Q}^i + \frac{i}{2}\left(\chi_Q^i \sigma^\mu D_\mu \bar\chi_{Qi} - D_\mu \chi_Q^i \sigma^\mu \bar\chi_{Qi}\right) + F_{Qi}^\dagger F_Q^i \\ & + i\sqrt{2}\Big[\frac{1}{6} g' \widetilde{Q}^i \bar{\widetilde{B}} \cdot \bar\chi_{Qi} + g \overline{\widetilde{W}}^k \cdot \bar\chi_{Qi} \frac{\sigma^k}{2} \widetilde{Q}^i + g_s \overline{\widetilde{G}}^a \cdot \bar\chi_{Qi} T^a \widetilde{Q}^i + \text{h. c.}\Big] \\ & - g' D_B \widetilde{Q}_i^\dagger \widetilde{Q}^i - g D_{W^k} \widetilde{Q}_i^\dagger \frac{\sigma^k}{2} \widetilde{Q}^i - g_s D_{G^a} \widetilde{Q}_i^\dagger T^a \widetilde{Q}^i\end{aligned}$$

    $\Rightarrow$ **Need to introduce Dirac and Majorana fermions.**
  - * Naturally expressed in terms of **superfields (1 terms)**:

$$\mathcal{L}_{\rm kin} \supset \left[Q_i^\dagger e^{-2\frac{1}{6}g' \mathbf{V_B}} e^{-2g \mathbf{V_{W^k}} \frac{\sigma^k}{2}} e^{-2g_s \mathbf{V_{G^a}} \frac{T^a}{2}} Q^i \right]\Big|_{\theta\cdot\theta\bar\theta\cdot\bar\theta}$$

- **The module could be a useful tool for model building.**
  (not only a Lagrangian translator).

Superspace basics.

- **Superspace: adapted space to write down SUSY transformations naturally.**
- **Basic objects and their FeynRules (hardcoded) implementation.**
  * The **Majorana spinor** $(\theta, \bar\theta)$ ⇒ a superspace point $\equiv G(x, \theta, \bar\theta)$.
    - ◇ `theta` is defined internally as a regular **Weyl spinor**.
  * SUSY transformation parameters: **Majorana spinors** $(\varepsilon_1, \bar\varepsilon_1)$, $(\varepsilon_2, \bar\varepsilon_2)$, ...
    - ◇ The `epsx` are defined internally as a regular **Weyl spinor**, *e.g.*:
- **The supercharges $(\mathbf{Q}, \bar{\mathbf{Q}})$ and the superderivatives $(\mathbf{D}, \bar{\mathbf{D}})$**

$$Q_\alpha = -i(\partial_\alpha + i\sigma^\mu{}_{\alpha\dot\alpha}\bar\theta^{\dot\alpha}\partial_\mu) \quad \text{and} \quad \bar Q_{\dot\alpha} = i(\bar\partial_{\dot\alpha} + i\theta^\alpha\sigma^\mu{}_{\alpha\dot\alpha}\partial_\mu) \ ,$$

$$D_\alpha = \partial_\alpha - i\sigma^\mu{}_{\alpha\dot\alpha}\bar\theta^{\dot\alpha}\partial_\mu \quad \text{and} \quad \bar D_{\dot\alpha} = \bar\partial_{\dot\alpha} - i\theta^\alpha\sigma^\mu{}_{\alpha\dot\alpha}\partial_\mu \ .$$

[Conventions: BenjF, Rausch de Traubenberg (Ellipses '11)]

$Q_\alpha(\exp)$ and $\bar Q_{\dot\alpha}(\exp)$

```
QSUSY   [exp_, alpha_]
QSUSYBar[exp_, alphadot_]
```

$D_\alpha(\exp)$ and $\bar D_{\dot\alpha}(\exp)$

```
DSUSY   [exp_, alpha_]
DSUSYBar[exp_, alphadot_]
```

* **These operators can be used on any superspace expressions.**

Handling indices: general superfields.

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

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

- **Can be implemented in FeynRules.**
  * **Use of the `nc` environment** (keep the fermion ordering).
  * All the fermions are carrying **lower indices**.
    - ◇ **Metric acting on spin space**: `Ueps` and `Deps`

$$\psi_\alpha = \varepsilon_{\alpha\beta}\psi^\beta\ , \qquad \psi^\alpha = \varepsilon^{\alpha\beta}\psi_\beta\ ,$$
$$\bar\chi_{\dot\alpha} = \varepsilon_{\dot\alpha\dot\beta}\bar\chi^{\dot\beta}\ , \qquad \bar\chi^{\dot\alpha} = \varepsilon^{\dot\alpha\dot\beta}\bar\chi_{\dot\beta}\ .$$

  * Remark: all the components must be declared properly and explicitely.

```
z + nc[theta[sp],xi[sp2]] Ueps[sp2,sp] + ...
```

Chiral superfields.

- **Definition: the most general expansion in $\theta, \bar\theta$ satisfying $\bar D_{\dot\alpha} \Phi(x,\theta,\bar\theta) = 0$.**

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

  * It describes **matter multiplets**.
  * One scalar field ϕ, one Weyl fermion χ, one auxiliary field F.

- **Declaration of the left-handed quark superfield**.

```
CSF[1] == {
  ClassName       -> QL,
  Chirality       -> Left,
  Weyl            -> uqLw,
  Scalar          -> sqL,
  QuantumNumbers -> {Q->2/3},
  Indices         -> {Index[Gen], Index[Colour]}
}
```

  * **Chiral superfield** $\Rightarrow$ the label is `CSF[1]`.
  * The `Scalar` and `Weyl` components must be declared properly.
  * **The auxiliary field are automatically generated (not explicitely present).**

Using some superspace basic objects.

- **Transformation laws for a chiral superfield and its components**:
  - * In terms of **superfields**: $\delta_\varepsilon \Phi(x,\theta,\bar\theta) = i(\varepsilon\cdot Q + \bar Q\cdot\bar\varepsilon)\Phi(x,\theta,\bar\theta)$.
  - * This depends on the **supercharges** `QSUSY` **and** `QSUSYBar`.
  - * The function `DeltaSUSY` is a better option...

```
DeltaPHI = DeltaSUSY[UR, eps1];
```

- **The components of** `DeltaPHI` **read**:

$$\delta_\varepsilon\phi = \sqrt{2}\varepsilon\cdot\psi\ ,\quad \delta_\varepsilon\psi = -i\sqrt{2}\sigma^\mu\bar\varepsilon\partial_\mu\phi - \sqrt{2}F\varepsilon\ ,\quad \delta_\varepsilon F = -i\sqrt{2}\partial_\mu\psi\sigma^\mu\bar\varepsilon\ .$$

```
In[7]:=  DeltaPHI = DeltaSUSY[UR, eps1];

In[8]:=  ScalarComponent[Tonc[DeltaPHI]]

Out[8]=  √2 UQRw_sp$1 . eps1_sp$1

In[10]:= Expand[ThetaComponent[Tonc[DeltaPHI]] / Sqrt[2]]

Out[10]= -√2 FTerm2 eps1_alpha$1783 - i √2 ∂_mu$1[SQR] eps1†_sp$1dot (σ^mu$1)_alpha$1783,sp$1dot

In[12]:= Expand[Theta2Component[Tonc[DeltaPHI]] / (-1)]

Out[12]= -i √2 ∂_mu$1[UQRw_sp$1] . eps1†_sp$1dot (σ^mu$1)_sp$1,sp$1dot
```

  - * `Tonc` **breaks dot products** and restore the `nc` structure (fermion ordering).
  - * This is **mandatory** in order to have `xxxComponent` to work properly.

Matter Lagrangians.

- **Lagrangian associated to the chiral superfield content of the theory.**
  - Contains gauge interactions and kinetic terms for **chiral superfields**.
  - Is entirely **fixed by SUSY and gauge invariance**
  - **Example for** $SU(3)_c \times SU(2)_L \times U(1)_Y$.

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

(Non-abelian vector superfields contains group representation matrices.)

- **Automatic extraction of the matter Lagrangian of a model:**

```
CSFKineticTerms[]
CSFKineticTerms[ UR ] + CSFKineticTerms[ QL ]
```

Superfields: vector superfields (1).

- **We apply the constraint $\Phi = \Phi^\dagger$ on a general superfield**.
- **In the Wess-Zumino gauge, we have**:

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

  * This describes **gauge supermultiplets**: one Majorana fermion $(\lambda,\bar\lambda)$, one (massless) gauge boson v, one auxiliary field D.

- **Declaration of the $SU(3)_c$ vector superfield**.

```
VSF[1] == {
  ClassName          -> GSF,
  GaugeBoson         -> G,
  Gaugino            -> gow,
  Indices            -> {Index[Gluon]}
}
```

  * **Vector superfield** $\Rightarrow$ the label is `VSF[1]`.
  * The `Gaugino` and `GaugeBoson` components must be declared properly.
  * **The auxiliary field are automatically generated (not explicitely present)**.

- **Vector superfields can be associated to a gauge group**.

Superfields: vector superfields (2).

- **Some properties of vector superfields in the Wess-Zumino gauge**:

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

```
In[7]:= GrassmannExpand[GSF[aa] GSF[bb]]

Out[7]= 1/2 θsp$1 . θsp$1 θbar sp$1dot . θbar sp$1dot Gmu$1,aa Gmu$1,bb

In[8]:= GrassmannExpand[GSF[aa] GSF[bb] GSF[cc]]

Out[8]= 0
```

- **The superfield strength tensor is built from associated spinorial superfields**:

$$W_\alpha = -\frac{1}{4}\bar D\cdot\bar D\ e^{2gV} D_\alpha e^{-2gV}, \quad \overline{W}_{\dot\alpha} = -\frac{1}{4} D\cdot D\ e^{-2gV}\bar D_{\dot\alpha} e^{2gV}.$$

W_α, $(W_\alpha)_{ij}$, W^a_α, $\overline{W}_{\dot\alpha}$, $\overline{W}^a_{\dot\alpha}$, $(\overline{W}_{\dot\alpha})_{ij}$

```
SuperfieldStrengthL[ SF, lower spin index ]
SuperfieldStrengthL[ SF, spin index, gauge index/indices ]
SuperfieldStrengthR[ SF, lower spin index ]
SuperfieldStrengthR[ SF, spin index, gauge index/indices ]
```

Vector Lagrangians.

- **Vector superfield interactions: squared superfield strength tensors**.
  - * **Non-abelian groups** (abelian limit easy to obtain).

$$\mathcal{L} = \frac{1}{16g^2\tau_{\mathcal{R}}}\mathrm{Tr}(W^\alpha W_\alpha)_{|_{\theta\theta}} + \frac{1}{16g^2\tau_{\mathcal{R}}}\mathrm{Tr}(\bar{W}_{\dot{\alpha}}\bar{W}^{\dot{\alpha}})_{|_{\bar{\theta}\bar{\theta}}}$$
$$= -\frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + i\,\bar{\lambda}_a\,\bar{\sigma}^\mu\,D_\mu\lambda^a + \frac{1}{2}D_a D^a$$

$\Rightarrow$ Interactions between gauge-bosons and gauginos.

- **Automatic extraction of the vector Lagrangian of a model:**

```
(* all vector superfields *) VSFKineticTerms[]
(* one vector superfield  *) VSFKineticTerms[ GSF ]
```

Full supersymmetric Lagrangians (1).

- **Complete Lagrangian for a model**.

$$\mathcal{L} = \mathbf{\Phi}^\dagger e^{-2gV} \mathbf{\Phi}\big|_{\theta^2\bar\theta^2} + \frac{1}{16g^2\tau_{\mathcal{R}}} \mathrm{Tr}(\mathbf{W}^\alpha \mathbf{W}_\alpha)\big|_{\theta^2} + \frac{1}{16g^2\tau_{\mathcal{R}}} \mathrm{Tr}(\bar{\mathbf{W}}_{\dot\alpha} \bar{\mathbf{W}}^{\dot\alpha})\big|_{\bar\theta^2}$$
$$+ \mathbf{W}(\mathbf{\Phi})\big|_{\theta^2} + \mathbf{W}^\star(\mathbf{\Phi}^\dagger)\big|_{\bar\theta^2} + \mathcal{L}_{\rm soft}$$

  - * **Chiral superfield** kinetic terms: automatic.
  - * **Vector superfield** kinetic terms: automatic.
  - * **Superpotential**: model dependent.
  - * **Soft SUSY-breaking Lagrangian**: model dependent (and often not related to the superspace).

```
Theta2Thetabar2Component[ CSFKineticTerms[] ] +
Theta2Component[ VSFKineticTerms[] + SuperPot ] +
Thetabar2Component[ VSFKineticTerms[] + HC[SuperPot] ] +
LSoft
```

  - * `LSoft` and `SuperPot` are the **only** pieces provided by the user.

Full supersymmetric Lagrangians (2).

- **Solution of the equation of motions**.
  - * Get rid of the auxiliary *D*-fields and *F*-fields through their **eqs. of motion**.

```
lagr = SolveEqMotionD[ lagr ] ;
lagr = SolveEqMotionF[ lagr ] ;
```

- **Back to four-component fermions**.
  - * Usual FeynRules routine (cf. MC code requirements).

```
lagr = WeylToDirac[ lagr ] ;
```

Outline

R-parity violating supersymmetry - the monotop case (1).

- **The model**.
  - * **MSSM chiral superfield content**: H_u, H_d, Q, L, E_R, D_R and U_R.
  - * **MSSM vector superfield content**: V_B, V_W, V_G.
    $\Rightarrow$ **MSSM gauge interactions**: $SU(3)_c \times SU(2)_L \times U(1)_Y$.
  - * **Superpotential**:

$$W = -y_e L \cdot H_d E_R - y_d Q \cdot H_d D_R + y_u Q \cdot H_u U_R + \mu H_d \cdot H_u + \frac{1}{2} \lambda U_R D_R D_R \ .$$

  - ◇ Contains an ϵ in color space.
  - ◇ Not included in any automated MC generator, but MadGraph**5**.

Use of the chain FeynRules $\rightarrow$ **UFO** $\rightarrow$ MadGraph $\rightarrow$ **events.**

R-parity violating supersymmetry - the monotop case (2).

- **Implementation in the superspace module of FeynRules.** [Duhr, BenjF (CPC '11)]

```
yu[ff1,ff2] UR[ff1,cc] (QL[1,ff2,cc] HU[2] - QL[2,ff2,cc] HU[1]) -
yd[ff1,ff2] DR[ff1,cc] (QL[1,ff2,cc] HD[2] - QL[2,ff2,cc] HD[1]) -
ye[ff1,ff2] ER[ff1]    (LL[1,ff2]    HD[2] - LL[2,ff2]    HD[1]) +
MUH (HU[1] HD[2] - HU[2] HD[1]) + 1/2 LUDD[ff1,ff2,ff3] *
  Eps[cc1,cc2,cc3] UR[ff1, cc1] DR[ff2,cc2] DR[ff3,cc3];
```

  * SUSY-breaking Lagrangian not relevant here (but included in the model).

- **Computing the Lagrangian automatically**.

```
lagr =
  Theta2Thetabar2Component[ CSFKineticTerms[] ] +
  Theta2Component[ VSFKineticTerms[] + SuperPot ] +
  Thetabar2Component[ VSFKineticTerms[] + HC[SuperPot] ] +
  LSoft
```

R-parity violating supersymmetry - the monotop case (3).

- **Solution of the equation of motions**.

```
lagr = SolveEqMotionD[ lagr ] ;
lagr = SolveEqMotionF[ lagr ] ;
```

- **Back to four-component fermions**.

```
lagr = WeylToDirac[ lagr ] ;
```

- **Generating an UFO model** [Degrande, Duhr, BenjF, Grellscheid, Mattelaer, Reiter (2011)].

```
lagr = WriteUFO[ lagr, Exclude4Scalars->True ] ;
```

- **Phenomenology with MadGraph5** [Alwall, Herquet, Maltoni, Mattelaer, Stelzer (JHEP '11)].

  * Analysis of the RPV production of monotops.

Monotop production at the LHC [Andrea, BenjF, Maltoni (PRD '11)].

- **Final state signature**: **One top quark in association with missing energy**.
  - * **Hadronic top decays**.
    $\Rightarrow$ Final state: **one b-jet, two light jets, missing energy**.
- **Monotop production in the Standard Model**.
  - * **Loop- and CKM-suppressed**.
- **Observing monotops at the LHC $\Leftrightarrow$ Beyond the Standard Model physics**.
- **R-parity violating SUSY Benchmark: low mass region**.
- **Sources of background**.
  - * **Z ($\rightarrow \nu\bar{\nu}$) + 3 jets**.
    ►Irreducible background.
  - * **QCD multijet**.
    ►Misreconstructed jet $\rightarrow$ fake missing energy.
  - * **W + jets, $t\bar{t}$ and diboson**.
    ►Missing energy: leptonic W decay with nonreconstructed lepton.
  - * **Single top**.
    ►Non- or misreconstructed leptons.

Background rejection (1).

- **A proper analysis requires**:
  - * **Parton showering**.
  - * **Hadronization**.
  - * **A proper detector simulation**.
  - * **Data-driven methods for background estimation.**
- **We rely on existing experimental studies**.
  [Disclaimer: this is a prospective study].
  - * CMS: CERN-PH-EP-2011-065.
  - * ATLAS: PLB **701** (2011) 186.
- **First set of selection cuts.**
  - * Large **missing transverse momentum** ($\not{p}_T > 150$ GeV).
  - * p_T**(jet)** > 50 **GeV** for three high quality jets.
  - * H_T**(jet)** > 300 **GeV**.

$\Rightarrow$ **comparable amount of QCD, $t\bar{t}$, Z and W events**.
$\Rightarrow$ **diboson and single top highly reduced**.

Background rejection (2).

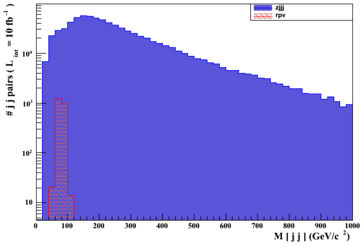
- **Second set of selection cuts: exploiting the presence of a top quark.**
  * Exactly **three jets**.
  * **Lepton veto**.
  * One b-**tagged** jet.
  * Three-jet invariant mass compatible with the **top mass**.
  * Two non-b-jet invariant mass compatible with the W **mass**.

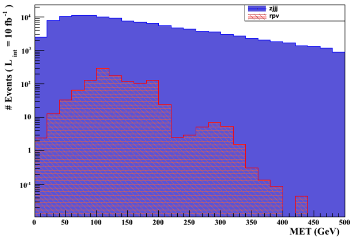
$\Rightarrow$ **all instrumental backgrounds are expected to be highly suppressed**.
$\Rightarrow$ **the only considered source of background consists in** $Z(\to \nu\bar{\nu}) + 3$ **jets**.

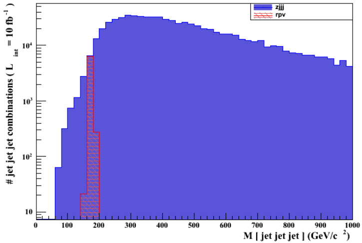
Disclaimer.

- This is a **prospective study**.
- Promising results $\Rightarrow$ **motivation for a more complete study**.
  ►Parton showering & hadronization.
  ►Detector simulation.

Some distributions with MADANALYSIS 5 [Conte, BenjF, Serret (in prep)].

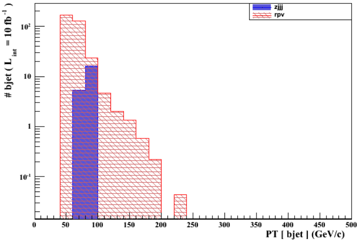






- **Our selection cuts.**
  - ►Exactly **3 parton-level jets**.
  - ►$p_T > 50$ **GeV**; $|\eta| < 2.5$.
  - ►ΔR**(jet,jet)** > 0.5.
- **Additional cuts.**
  - ►MET > 150 GeV.
  - ►$m_{jj} \in [65, 95]$ GeV.
  - ►$m_{bjj} \in [150, 190]$ GeV.

Results.



Excellent (parton-level) background rejection

Outline

Conclusions.

- FeynRules **provides a platform to**:
  - * **Develop** new models.
  - * Investigate their **phenomenology**.

    ⇒ Example of the RPV monotop.

- **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.

Outline

6. One simple example: QCD

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.

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.
* **Weyl fermions** are similar.

Example: QCD - Lagrangian

QCD Lagrangian:

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

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] ;
```

* **Implicit summations** ⇒ easy debugging.

Example: QCD - Results

Results - let us be ready for (some) phenomenology!

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

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

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

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