Recent developments of FeynRules
Investigations of (non-)minimal supersymmetric models at the LHC.

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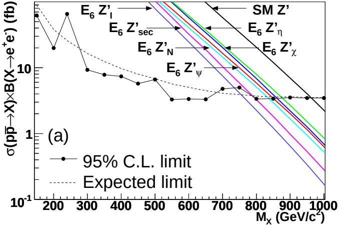
In collaboration with N. Christensen, C. Duhr + Monte Carlo collaborators
+ CMS Strasbourg + master students.

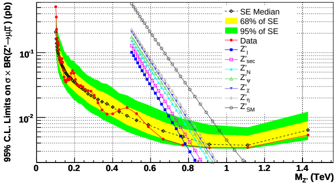
CMS Physics France 2010 meeting @ IRFU Saclay
April 1, 2010

Outline

1. The FeynRules approach for new physics investigations.
2. Ongoing phenomenological analyses at the IPHC Strasbourg.
    - Model database & validation procedure.
    - The Minimal Supersymmetric Standard Model.
    - The Minimal Supersymmetric Standard Model with *R*-parity violation.
    - The Next-to-Minimal Supersymmetric Standard Model
3. Summary - outlook.

To get started: a (maybe not so) funny story.





[CDF Collaboration, PRL 102 (2009) 031801 & 081805]

- **Mandatory**: it is **April 1st** and I am **Belgian**.
- **Why should theorists and experimentalists talk [more] together?**
- **One simple [counter-]example**.
  - Two PRL papers on Z' **searches** from CDF [even the same issue of PRL].
  - Di-electron channel (left panel) and di-muon channel (right panel).
  - Different theoretical predictions for the same benchmark: **a factor of 2!!!**
  - **Two different definitions of the signal**:
    - $\sigma\left[p\bar{p} \to Z' \to \mu^+\mu^-\right] - \sigma\left[p\bar{p} \to \gamma, Z \to \mu^+\mu^-\right]$.
    - $\sigma\left[p\bar{p} \to \gamma, Z, Z' \to e^+e^-\right] - \sigma\left[p\bar{p} \to \gamma, Z \to e^+e^-\right]$.

Monte Carlo tools and discoveries at the LHC.

- **Establishing of an excess over the SM backgrounds** **[Difficult task]**.
  - * Use of **Monte Carlo 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 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** (*e.g.*, NLO MC generators, resummation, ...).
  - * **Sophistication of the analyses** $\Leftrightarrow$ **new physics and detector knowledge**.

Monte Carlo tools play a key role!

Monte Carlo tools for BSM physics.

- **New physics theories**: a lot of theories, based on different ideas, in evolution.
- **Implementation in Monte Carlo tools**.
  - A model $\Leftrightarrow$ **particles, parameters and vertices** ($\equiv$ Feynman rules).
    - ◇ The Feynman rules **have to be derived**.
    - ◇ Each rule **has to be translated in a 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.
- **Validation**.
  - **Comparison** with existing analytical and numerical results.
  - **Non-systematic and partial** (set of available results, conventions,...).
  - **No dedicated framework**.
- **Distribution**.
  - Many models remain **private** (**some exceptions**, *e.g.*, 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.

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.

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**.

Main features of FeynRules.

[Christensen, Duhr (2009); Christensen, Duhr, BenjF (*in prep.*)]

- **The working environment is** Mathematica.
  - * **Flexibility** for symbolic manipulations.
    - ◇ **Routines** to check a Lagrangian.
    - ◇ ...
  - * Various **built-in features.**
    - ◇ **Matrix diagonalization**.
    - ◇ **Pattern recognition functions**.
    - ◇ ...
  - * **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!

Scope and limitations.

- **Supported fields**.
  - * Scalar fields.
  - * Dirac and Majorana fermions [**Weyl fermions: in validation**].
  - * Vector and ghost fields.
  - * **No spin 3/2**.
  - * Spin two fields.
  - * Superfields [**being implemented**].
- **The model must fulfil basic quantum field theory requirements**.
  - * Lorentz invariance.
  - * Gauge invariance.
  - * **Higher-dimensional operators are supported** [**but not at the MC level**].

Current developments.

[BenjF *et al.*, FR-2010 Workshop on automatization for BSM physics - proceeding (*in prep.*)].

- **Quantum field theory functionalities**.
  - * Superfields.
  - * Automatized mass matrix diagonalization from the Lagrangian.
  - * Automatized treatment of higher-order operators.
- **New interface between** FeynRules **and the Monte Carlo tools**.
  - * Python interface (Herwig, MadGraph).
  - * Automatized generation of the Helas routines .
  - * New FeynArts interface.
- **Development of a web-based** FeynRules **BSM model database**.

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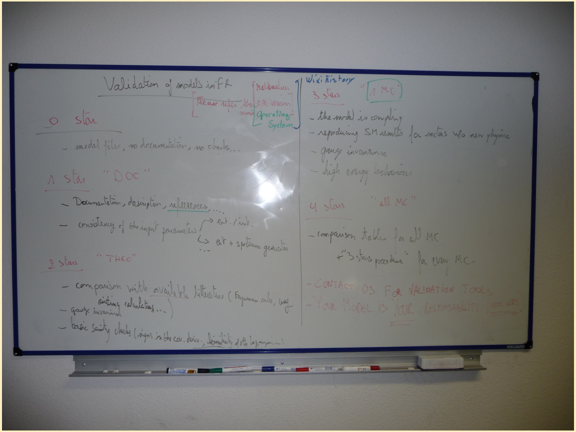
Validation procedure - the four-star system (LH2009)

On the road to the FeynRules validation system (at Les Houches '09)

Validation procedure - the four-star system (LH2009)

On the road to the FEYNRULES validation system (at Les Houches '09)



Validation procedure - the four-star system [LH 2009].

- **Any model can be put on the FeynRules web-based model database.**
- **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**.

Example: validation of the MSSM.

CalcHep, MadGraph, Sherpa and Whizard results.

Process	MG-FR	MG-ST	CH-FR	SH-FR	SH-ST	WO-FR	WO-ST	Comparison
tau+,tau->mu+,mu-	7.79717×10^{-2}	7.79636×10^{-2}	7.7953×10^{-2}	7.79517×10^{-2}	7.79517×10^{-2}	7.79726×10^{-2}	7.79726×10^{-2}	δ = 0.02682 %
tau+,tau->tau+,tau-	7.47198×10^{2}	7.47372×10^{2}	7.4687×10^{2}	7.46917×10^{2}	7.46916×10^{2}	7.46874×10^{2}	7.46874×10^{2}	δ = 0.06725 %
tau+,tau->tau+,tau-	7.4775×10^{2}	7.45526×10^{2}	7.4687×10^{2}	7.46917×10^{2}	7.46916×10^{2}	7.46874×10^{2}	7.46874×10^{2}	δ = 0.2979 %
tau+,tau->ve,ve~	1.71188×10^{-2}	1.7162×10^{-2}	1.7137×10^{-2}	1.71363×10^{-2}	1.71363×10^{-2}	1.71364×10^{-2}	1.71364×10^{-2}	δ = 0.2522 %
tau+,tau->vm,vm~	1.71228×10^{-2}	1.71143×10^{-2}	1.7137×10^{-2}	1.71363×10^{-2}	1.71363×10^{-2}	1.71364×10^{-2}	1.71364×10^{-2}	δ = 0.1325 %
tau+,tau->vt,vt~	5.22862×10^{1}	5.22451×10^{1}	5.2287×10^{1}	5.22911×10^{1}	5.22911×10^{1}	5.22673×10^{1}	5.22673×10^{1}	δ = 0.08809 %
tau+,tau->u,u~	1.23918×10^{-1}	1.23829×10^{-1}	1.2393×10^{-1}	1.23928×10^{-1}	1.23928×10^{-1}	1.23941×10^{-1}	1.23941×10^{-1}	δ = 0.09047 %
tau+,tau->t,t~	1.20537×10^{-1}	1.20517×10^{-1}	1.2055×10^{-1}	1.20555×10^{-1}	1.20555×10^{-1}	1.20546×10^{-1}	1.20546×10^{-1}	δ = 0.03159 %
tau+,tau->d,d~	6.31517×10^{-2}	6.30846×10^{-2}	6.31×10^{-2}	6.30984×10^{-2}	6.30984×10^{-2}	6.31049×10^{-2}	6.31049×10^{-2}	δ = 0.1063 %
tau+,tau->b,b~	6.50114×10^{-2}	6.51088×10^{-2}	6.5112×10^{-2}	6.51065×10^{-2}	6.51065×10^{-2}	6.51171×10^{-2}	6.51171×10^{-2}	δ = 0.1624 %
tau+,tau->W+,W-	1.98242	1.98701	1.9876	1.98836	1.98836	1.98761	1.98761	δ = 0.2991 %
tau+,tau->Z,Z	1.09732×10^{-1}	1.09381×10^{-1}	1.0952×10^{-1}	1.09567×10^{-1}	1.09567×10^{-1}	1.09527×10^{-1}	1.09527×10^{-1}	δ = 0.3202 %
tau+,tau->Z,a	5.25298×10^{-1}	5.2566×10^{-1}	5.2606×10^{-1}	5.26164×10^{-1}	5.26164×10^{-1}	5.25994×10^{-1}	5.25994×10^{-1}	δ = 0.1647 %
tau+,tau->sl1+,sl1-	1.68958×10^{-1}	1.68905×10^{-1}	1.6894×10^{-1}	1.68965×10^{-1}	1.6896×10^{-1}	1.68984×10^{-1}	1.68954×10^{-1}	δ = 0.04709 %
tau+,tau->sl6+,sl6-	1.08456×10^{-1}	1.08482×10^{-1}	1.0844×10^{-1}	1.08466×10^{-1}	1.08464×10^{-1}	1.08462×10^{-1}	1.08465×10^{-1}	δ = 0.03828 %
tau+,tau->sl1+,sl6-	4.331×10^{-2}	4.32897×10^{-2}	4.3292×10^{-2}	4.32956×10^{-2}	4.32994×10^{-2}	4.32977×10^{-2}	4.33259×10^{-2}	δ = 0.08351 %
tau+,tau->sv1,sv1~	4.86058×10^{-1}	4.86097×10^{-1}	4.8605×10^{-1}	4.86095×10^{-1}	4.86095×10^{-1}	4.86133×10^{-1}	4.86142×10^{-1}	δ = 0.01897 %
tau+,tau->n1,n1	7.52127×10^{-2}	7.52249×10^{-2}	7.5229×10^{-2}	7.52178×10^{-2}	7.52178×10^{-2}	7.52232×10^{-2}	7.52206×10^{-2}	δ = 0.02161 %
tau+,tau->n1,n2	2.56445×10^{-2}	2.56203×10^{-2}	2.5624×10^{-2}	2.56212×10^{-2}	2.56212×10^{-2}	2.56206×10^{-2}	2.56215×10^{-2}	δ = 0.09431 %
tau+,tau->n1,n3	3.10904×10^{-3}	3.1058×10^{-3}	3.1067×10^{-3}	3.10674×10^{-3}	3.10674×10^{-3}	3.10725×10^{-3}	3.08907×10^{-3}	δ = 0.6442 %
tau+,tau->n1,n4	4.61264×10^{-3}	4.61504×10^{-3}	4.6164×10^{-3}	4.61617×10^{-3}	4.61617×10^{-3}	4.6163×10^{-3}	4.59955×10^{-3}	δ = 0.3657 %
tau+,tau->n2,n2	4.39512×10^{-2}	4.39575×10^{-2}	4.3953×10^{-2}	4.39454×10^{-2}	4.39454×10^{-2}	4.39481×10^{-2}	4.39427×10^{-2}	δ = 0.03356 %
tau+,tau->n2,n3	4.87387×10^{-3}	4.86117×10^{-3}	4.867×10^{-3}	4.86689×10^{-3}	4.86689×10^{-3}	4.86744×10^{-3}	4.86902×10^{-3}	δ = 0.2608 %
tau+,tau->n2,n4	6.44698×10^{-3}	6.45983×10^{-3}	6.4664×10^{-3}	6.46598×10^{-3}	6.46598×10^{-3}	6.46596×10^{-3}	6.46334×10^{-3}	δ = 0.3008 %
tau+,tau->n3,n3	9.28002×10^{-5}	9.2623×10^{-5}	9.2716×10^{-5}	9.27123×10^{-5}	9.27123×10^{-5}	9.27189×10^{-5}	9.27202×10^{-5}	δ = 0.1911 %
tau+,tau->n3,n4	2.14878×10^{-2}	2.1484×10^{-2}	2.1493×10^{-2}	2.14921×10^{-2}	2.14921×10^{-2}	2.14931×10^{-2}	2.1493×10^{-2}	δ = 0.04203 %
tau+,tau->n4,n4	4.9133×10^{-4}	4.91839×10^{-4}	4.9184×10^{-4}	4.91841×10^{-4}	4.91841×10^{-4}	4.91851×10^{-4}	4.91854×10^{-4}	δ = 0.1064 %
tau+,tau->x1+,x1-	1.0258×10^{-1}	1.02574×10^{-1}	1.0263×10^{-1}	1.02618×10^{-1}	1.02618×10^{-1}	1.02611×10^{-1}	1.02611×10^{-1}	δ = 0.05481 %
tau+,tau->x2+,x2-	6.70443×10^{-2}	6.69276×10^{-2}	6.6912×10^{-2}	6.69091×10^{-2}	6.69091×10^{-2}	6.69131×10^{-2}	6.69368×10^{-2}	δ = 0.2019 %
tau+,tau->x1+,x2-	1.16966×10^{-2}	1.17145×10^{-2}	1.17×10^{-2}	1.16998×10^{-2}	1.16997×10^{-2}	1.17004×10^{-2}	1.16851×10^{-2}	δ = 0.2513 %
tau+,tau->h1,h1	9.27951×10^{-7}	9.27981×10^{-7}	9.2778×10^{-7}	9.27789×10^{-7}	9.27789×10^{-7}	9.27761×10^{-7}	9.27771×10^{-7}	δ = 0.02368 %
tau+,tau->h1,h2	1.61028×10^{-5}	1.60933×10^{-5}	1.6097×10^{-5}	1.60975×10^{-5}	1.60975×10^{-5}	1.61073×10^{-5}	1.61075×10^{-5}	δ = 0.08804 %
tau+,tau->h3,h3	6.04309×10^{-5}	6.03865×10^{-5}	6.0407×10^{-5}	6.0413×10^{-5}	6.0413×10^{-5}	6.04515×10^{-5}	6.04527×10^{-5}	δ = 0.1096 %
tau+,tau->Z,h1	8.90511×10^{-3}	8.91065×10^{-3}	8.9097×10^{-3}	8.91135×10^{-3}	8.91135×10^{-3}	8.90772×10^{-3}	8.90772×10^{-3}	δ = 0.07004 %
tau+,tau->Z,h2	9.18474×10^{-3}	9.17875×10^{-3}	9.1742×10^{-3}	9.17437×10^{-3}	9.17437×10^{-3}	9.18049×10^{-3}	9.18058×10^{-3}	δ = 0.1149 %
tau+,tau->Z,h3	9.19797×10^{-3}	9.19166×10^{-3}	9.1912×10^{-3}	9.19128×10^{-3}	9.19128×10^{-3}	9.19754×10^{-3}	9.19764×10^{-3}	δ = 0.07368 %
tau+,tau->h3,h1	1.74141×10^{-5}	1.74135×10^{-5}	1.7414×10^{-5}	1.74136×10^{-5}	1.74136×10^{-5}	1.74234×10^{-5}	1.74237×10^{-5}	δ = 0.05854 %
tau+,tau->h3,h2	2.03081×10^{-3}	2.031×10^{-3}	2.0313×10^{-3}	2.0317×10^{-3}	2.0317×10^{-3}	2.0308×10^{-3}	2.03079×10^{-3}	δ = 0.04483 %
tau+,tau->H+,H-	7.50756×10^{-3}	7.50766×10^{-3}	7.5092×10^{-3}	7.50967×10^{-3}	7.50967×10^{-3}	7.50797×10^{-3}	7.50797×10^{-3}	δ = 0.02808 %

The (almost) most general MSSM.

[Christensen, de Aquino, Degrande, Duhr, BenjF, Herquet, Maltoni, Schumann (2009)]

- **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.*
$$\left(\tilde u_1, \tilde u_2, \tilde u_3, \tilde u_4, \tilde u_5, \tilde u_6\right)^T = R^{\tilde u}\left(\tilde u_L, \tilde c_L, \tilde t_L, \tilde u_R, \tilde c_R, \tilde t_R\right)^T,$$
$$\left(\tilde d_1, \tilde d_2, \tilde d_3, \tilde d_4, \tilde d_5, \tilde d_6\right)^T = R^{\tilde d}\left(\tilde d_L, \tilde s_L, \tilde b_L, \tilde d_R, \tilde s_R, \tilde b_R\right)^T.$$
  - * **Higgs sector.**
    - ◇ Only 2×2 mixing considered for the moment.
    - ◇ **To be generalized in forthcoming versions**.
$$\left(\tilde h_1, \tilde h_2, \tilde h_3\right)^T = R^h\left(\sqrt{2}\Re\{H_1^0\}, \sqrt{2}\Re\{H_2^0\}, A^0_{\rm tree}\right)^T$$
  - * Written in terms of **Weyls, scalars, vectors.**
    - ◇ **To be generalized in forthcoming versions** (superfields).
- **105 free parameters.**
  - * The **SLHA-FR format** (SLHA2-like format).
  - * C++ translator SLHA1/2 ⇔ SLHA-FR.

MSSM phenomenology @ Strasbourg.

- **Squark/gluino production decaying to tau leptons** [D. Bodin, U. Goerlach, Y. Mikami].
  - **See Yoshi's talk** for details.
  - Strong process ⇒ **large cross section** at the LHC.
  - Cascade decays to LSP ⇒ **missing transverse energy**.
  - Multileptons, multijets ⇒ **large final state multiplicity**.
- **Slepton pair production** [BenjF, D. Gelé, G. Serret].
  - Weak process ⇒ **challenging**.
  - Direct decays to LSP & **not so much missing transverse energy**.
  - **Clean final state**.
  - **Is this channel reachable at the LHC**?
    - ◇ If yes: at which energy, for which luminosity?
    - ◇ **Prospective work using the FEYNRULES framework**.
      ⇒ from the model to the simulation of the detector.
    - ◇ Up to now: hardly at 7 TeV; **life is more confortable at 10/14 TeV**.
  - **Work in progress...**

R-parity violating MSSM

- **Implementation in FeynRules** (soon public).
  - **Full superpotential.**
  - **Full SUSY-breaking Lagrangian.**
  - **General mixings.**
  - **105 + 192 free parameters.**
    - The **SLHA-FR format** (SLHA2-like format).
    - C++ translator SLHA1/2 ⇔ SLHA-FR.

- **Monte Carlo model files**.
  - Created with one single *R*-parity violating parameter.
    [8 hours with a 8GB RAM machine ⇒ AAARRGGGHHH?].
  - **Implementation of restrictions, new FeynRules algorithm**.
    [10-15 minutes on my laptop ⇒ better!].
  - **To do: full validation against Pythia/Herwig/SusyGen**.
    (only partial now).

RPV-MSSM phenomenology @ Strasbourg.

- **Series of mini-workshop on *R*-parity violating supersymmetry**.
  - Supported by the **CNRS-IN2P3 Théorie-LHC France initiative**.
  - Theorists: J.M. Bessot (M1), BenjF, C. Lorentzen (PhD), I. Schienbein.
  - **CMS** experimentalists: J. Andrea, A. Besson, E. Conte, J. Guigue (M2).

- **Resonant slepton production** [E. Conte, BenjF, J. Guigue].
  - Slepton $\rightarrow$ lepton + neutralino $\rightarrow$ two leptons & two jets.
  - **No missing transverse energy**.
  - Investigation of **displaced vertices**.
  - **This channel is probably reachable at the LHC, at 7 TeV, for 1 fb^{-1}**.
    - ◇ Is this competing with the present RPV bounds?
    - ◇ Regions of the parameter space reachable by the LHC?

- **Resonant squark production** [J. Andrea, BenjF].
  - RPV contributions to single top production.
  - **This channel is reachable at the LHC, both at 7/14 TeV**.
    - ◇ **This is competing with the present RPV bounds**!
    - ◇ Preliminary results ... soon available... [in one or two weeks]

- **Implementation of new precision theoretical tools** [BenjF, C. Lorentzen, I. Schienbein].

RPV-MSSM phenomenology @ 7 TeV with 1 fb^{-1}.

Things are going on!

Results [hopefully] **soon available!**
⇒ Two analyses almost over!

Next RPV workshop (probably @ Strasbourg) in July!
⇒ Interested? Contact Eric Conte or myself!

The Next-to-Minimal Supersymmetric Standard Model

- **Implementation in FeynRules** (soon 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 ⇔ SLHA-FR.
- **Validated against the stock version of Whizard** [Braam, BenjF, Reuter].
- **Tau lepton production in the NMSSM** [BenjF, U. Goerlach, M. Kraft].
  - * **Copiously produced**.
    - ◇ If the lightest pseudoscalar Higgs is lighter than the $b\bar{b}$ threshold.
  - * Realistic scenario (cf. LEP, etc...) in large parts of the parameter space.
  - * Investigation of the τ **multiplicity** (7/10/14 TeV).

Outline

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...

Supersymmetric models investigations with FEYNRULES

* **MSSM**: prospective work for non standard channels.
  ◇ Master2 internship of G. Serret (with BenjF, D. Gelé): **slepton pair production**.

* **RPV-MSSM**: various ongoing different studies.
  ◇ Master1 internship of J.M. Bessot (with E. Conte, BenjF): **constraints, benchmarks**.
  ◇ Master2 internship of J. Guigue (with E. Conte, BenjF): **single slepton**.
  ◇ Andrea & BenjF: **single squark**.
  ◇ BenjF, Lorentzen, Schienbein: **development of new theoretical tools**.

* **NMSSM.**
  ◇ Master2 internship of M. Kraft (with BenjF, U. Goerlach): τ **lepton production**.

* **New models**: Left-Right MSSM, hybrid $N = 1/N = 2$ supersymmetry, etc...
  ◇ ANR *Jeunes chercheurs et jeunes chercheuses* proposal: **AutoLHC**.
  ◇ **Feel free to join our effort** [even for non-SUSY models]!

Backup slides

Backup slides

Model description (1)

[J. Wells (2008)]

- **Simple extension of the Standard Model gauge groups**.
  - Additional **$U(1)_X$** symmetry.
  - **No coupling to the SM fermions**.
  - The full gauge group G is

$$G = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X .$$

- **New particles**.
  - One **X** boson associated to the new $U(1)_X$.
  - One Higgs field ϕ.
    - Breaking the new $U(1)_X$.
    - Singlet under the SM gauge groups.

Model description (2)

- **New interactions**.
  - The Lagrangian is given by:

$$\mathcal{L}_{\rm HAH} = \mathcal{L}_{\rm HAH,Gauge} + \mathcal{L}_{\rm HAH,Fermions} + \mathcal{L}_{\rm HAH,Higgs} + \mathcal{L}_{\rm HAH,Yukawa}.$$

- **New gauge sector**.
  - X boson kinetic term.
  - $X - B$ mixing term.

$$\mathcal{L}_{\rm HAH,Gauge} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \mathbf{X}_{\mu\nu} \mathbf{X}^{\mu\nu} + \frac{\chi}{2} \mathbf{B}_{\mu\nu} \mathbf{X}^{\mu\nu}$$

- **New Higgs potential**.

$$\mathcal{L}_{\rm HAH,Higgs} = D_\mu \Phi^\dagger D^\mu \Phi + \mathbf{D}_\mu \phi^\dagger \mathbf{D}^\mu \phi + \mu_\Phi^2 \Phi^\dagger \Phi + \mu_\phi^2 \phi^\dagger \phi - \lambda (\Phi^\dagger \Phi)^2 - \rho (\phi^\dagger \phi)^2 - \kappa (\mathbf{\Phi}^\dagger \mathbf{\Phi}) (\phi^\dagger \phi).$$

Model description (3)

- **Particle mixing in the gauge sector**.
  - * **Rotation** in the (X_μ, B_μ) basis:

$$\begin{pmatrix} \tilde{X}_\mu \\ \tilde{B}_\mu \end{pmatrix} = \begin{pmatrix} \sqrt{1-\chi^2} & 0 \\ -\chi & 1 \end{pmatrix} \begin{pmatrix} X_\mu \\ B_\mu \end{pmatrix} .$$

  - * **The SM fermions couple both to $\tilde{B}_\mu$ and $\tilde{X}_\mu$** $\left(\text{cf. } \eta = \frac{\chi}{\sqrt{1-\chi^2}}\right)$.
  - * The gauge sector Lagrangian is **diagonal**,

$$\mathcal{L}_{\rm HAH,Gauge} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} \tilde{B}_{\mu\nu} \tilde{B}^{\mu\nu} - \frac{1}{4} \tilde{X}_{\mu\nu} \tilde{X}^{\mu\nu} .$$

Model description (4)

- **Symmetry breaking to $U(1)_{EM}$.**
  - * Both Higgs fields acquire their vev **v** and ξ.

$$\Phi \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix} \quad \text{and} \quad \phi \to \frac{1}{\sqrt{2}} (h + \xi).$$

  - * **Neutral gauge boson mixing.**

$$\begin{pmatrix} \tilde{B} \\ W^3 \\ \tilde{X} \end{pmatrix} = \begin{pmatrix} c_W & -s_W\, c_\alpha & s_W\, s_\alpha \\ s_W & c_W\, c_\alpha & -c_W\, s_\alpha \\ 0 & s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} A \\ Z \\ Z' \end{pmatrix}.$$

  - * **Higgs boson mixing.**

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_h & s_h \\ -s_h & c_h \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}.$$

Implementation in a Monte Carlo code

- **Starting from the SM implementation**.
- **Couplings**.
  - * Full rewriting of the **Higgs** sector.
  - * New Z' **couplings**.
  - * Modification of the Z **couplings**.
  - * **More than half** of the SM implementation will be modified.
- **New particles and parameters**.

Hard and tedious job.

Implementation of the new model in FeynRules (1)

1. **Download the SM implementation.**
2. **Define the new gauge group and gauge boson.**

The $U(1)_X$ gauge group

```
U1X == {
  Abelian            -> True,
  GaugeBoson         -> X,
  Charge             -> QX,
  CouplingConstant -> gX}
```

X field definition

```
V[61] == {
  ClassName      -> X,
  SelfConjugate -> True,
  Definitions    -> {X[mu_] -> chi eta Xp[mu]},
  Unphysical     -> True}
```

- **Gauge boson and gauge group** definition.
- Association of a **coupling constant**.
- The $\tilde{\mathbf{X}}_\mu, \tilde{\mathbf{B}}_\mu, \mathbf{B}_\mu, \mathbf{W}^3_\mu$ field definitions must be modified.

Implementation of the new model in FeynRules (2)

1. **Download the SM implementation.**
2. **Define the new gauge group and gauge boson.**
3. **Define the new (internal and external) parameters.**

Parameters of the model

```
eta == {
  TeX               -> \[Eta],
  ParameterType     -> External,
  BlockName         -> HIDDEN,
  OrderBlock        -> 2,
  Value             -> 0.01,
  Description       -> "U(1)X - U(1)Y mixing parameter"},
MH2 == {
  ComplexParameter -> False,
  ParameterType     -> Internal,
  Value             -> Sqrt[lam v^2+rho xi^2+Sqrt[(lam v^2
                         -rho xi^2)^2+kap^2 v^2 xi^2]],
  Description       -> "Mass of H2"}
```

* **All the information** needed by the MC codes.
* **TeX-form** (for the TeX-file).
* **Complex/real** parameters.
* **External/internal** parameters.
* **Same for the other model parameters.**

Implementation of the new model in FeynRules (3)

1. **Download the SM implementation**.
2. **Define the new gauge group and gauge boson**.
3. **Define the new (internal and external) parameters**.
4. **Add the new fields**.

Some Higgs fields

```
S[12] == {
  ClassName          -> h2,
  SelfConjugate      -> True,
  Mass               -> {MH2, Internal},
  Width              -> {WH2, 5.23795},
  PropagatorLabel    -> "h2",
  PropagatorType     -> ScalarDash,
  PropagatorArrow    -> None,
  PDG                -> 35},
S[110] == {
  ClassName          -> H,
  SelfConjugate      -> True,
  Unphysical         -> True,
  Definitions        -> {H -> ch h1 + sh h2}}
```

* The same holds for the other Higgses.
* **All the information** is needed by the MC codes.

Implementation of the new model in FeynRules (4)

1. **Download the SM implementation**.
2. **Define the new gauge group and gauge boson**.
3. **Define the new (internal and external) parameters**.
4. **Add the new fields**.
5. **Modify the Lagrangian**.

The gauge Lagrangian

```
LGauge = -1/4*FS[B, mu,nu]*FS[B, mu,nu]
          -1/4*FS[X, mu,nu]*FS[X, mu,nu]
          +chi/2*FS[B, mu,nu]*FS[X, mu,nu]
          -1/4*FS[Wi, mu, nu, i1]*FS[Wi, mu, nu, i1]
          -1/4*FS[G, mu, nu, a]*FS[G, mu, nu, a];
```

- **Implicit summations** $\Rightarrow$ easy debugging.
- Fermionic Lagrangian in gauge basis $\Rightarrow$ **not modified**.
- Higgs sector modified.

Implementation of the new model in FeynRules (4)

1. **Download the SM implementation**.
2. **Define the new gauge group and gauge boson**.
3. **Define the new (internal and external) parameters**.
4. **Add the new fields**.
5. **Modify the Lagrangian**.
6. **Let us phenomenologize!**

```
FeynmanRules[Lag, FlavorExpand->SU2W]
    Particle 1 : Vector , W
    Particle 2 : Vector, W†
    Particle 3 : Vector , Z
    Particle 4 : Vector , Zp
    Vertex:
```

$$-i\, c_\alpha c_w^2 g_w^2 s_\alpha \left(\eta_{\mu_1,\mu_4}\, \eta_{\mu_2,\mu_3} + \eta_{\mu_1,\mu_3}\, \eta_{\mu_2,\mu_4} - 2\eta_{\mu_1,\mu_2}\, \eta_{\mu_3,\mu_4} \right)$$

```
    WriteFeynArtsOutput[Lag]
    WriteCHOutput[Lag]
    WriteMGOutput[Lag]
    WriteSHOutput[Lag]
    WriteWOOutput[Lag]
```