FeynRules - status and plans.

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Outline.

1. General features of FeynRules.
2. A simple example: QCD.
3. From FeynRules-1.4 to FeynRules-1.6.
4. On the road to FeynRules-1.8.
   - FeynRules @ NLO.
   - Extension of the superspace module and Rarita-Schwinger fields.
   - Web validation of the FeynRules models.
5. Conclusion.

Beyond the Standard model theories & Monte Carlo tools.

- **New physics theories**.
  - * There are a **lot of different** theories.
  - * Based on very **different ideas**.
  - * **In evolution** (especially regarding the discoveries [or exclusions!]).
- **Implementation in Monte Carlo tools**.
  - * A model consists in particles, parameters and vertices.
    - ◇ The Feynman rules have to **be derived**.
    - ◇ Each rule has to be translated into a **programming language**.
  - * **Tedious, time-consuming, error prone task**.
  - * We need to iterate for each considered model.
  - * We need to iterate for each considered Monte Carlo tool.
  - * This needs to be **validated**.

State-of-the-art in reinventing the wheel.
Redundancies in the work.

A FeynRules-based framework for LHC analyzes.

- **A framework for LHC analyzes based on FeynRules to**:

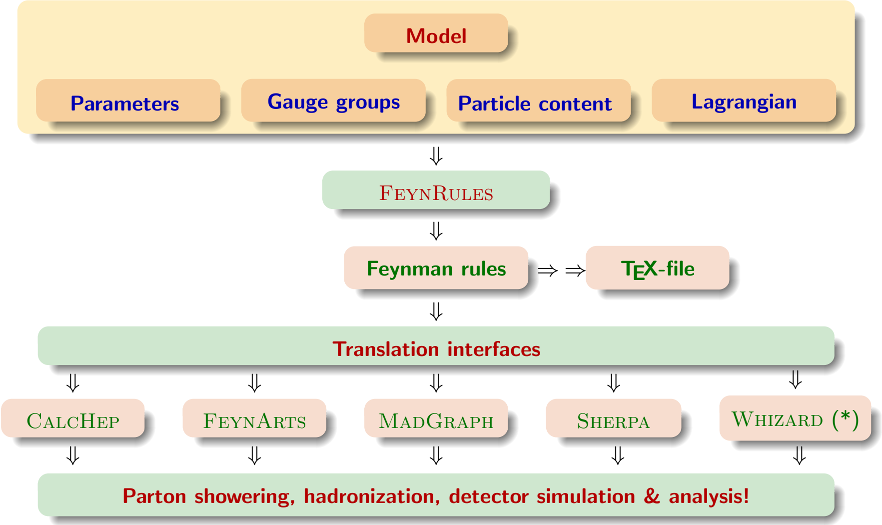
  [Christensen, de Aquino, Duhr, BenjF, Herquet, Maltoni, Schumann (EPJC '11)].

  * **Develop new models**.
  * **Implement (and validate)** new models in Monte Carlo tools.
  * Facilitate **phenomenological** investigations of the models.
  * **Test** the models against data.

- FeynRules **(version 1.4) in a nutshell** [Christensen, Duhr (CPC' 09)].

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

FeynRules in a nutshell.



(*) [Christensen, Duhr, BenjF, Reuter, Speckner (arXiv:1010.3251)]

Outline.

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 bosons.

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.

Example: QCD - Lagrangian.

QCD Lagrangian:

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_f \Big[\bar{q}_f \big(i \not{D} - m_f \big) q_f \Big].$$

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.
- **Field strengths** ⇒ automatic.
- **Covariant derivatives** ⇒ automatic.

Example: QCD - Results.

Results - let us do (some) phenomenology!

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

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

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

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

* How to use the output files?
  ⇒ a simple **copy & paste**.

Outline.

The Sainte-Odile workshop: achieved projects.

The Sainte-Odile workshop (March '10): in the Vosgian mountains.

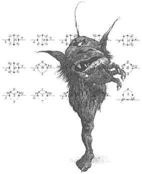
The Sainte-Odile workshop: achieved projects.

The Sainte-Odile workshop (March '10): in the monastery.

The Sainte-Odile workshop: achieved projects.

- **The UFO** [Degrande, Duhr, BenjF, Grellscheid, Mattelaer, Reiter (arXiv:1108.2040)].
  * UFO ≡ Universal FeynRules output (**not tied** to any Monte Carlo tool).
  * Allows for **generic** color and Lorentz structures.
  * Used by MadGraph**5,** Golem **and** Herwig**++**.
  * FeynRules interface: creates a Python **module** to be linked.
  * Still an issue with **multifermion interactions** [cf. working group 2].
- **ALOHA** [de Aquino, Link, Maltoni, Mattelaer, Stelzer (arXiv:1108.2041)].
  * 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**.

The Sainte-Odile workshop: achieved projects.



- **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.
  * Contains the new FeynArts **interface**.
  * Supports **color sextets**.
  * Other interfaces: CalcHep/CompHep, MadGraph4, Sherpa, Whizard.
  * The **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).

Model database - status.

- **Simple extensions of the Standard Model**.
  * Standard Model + additional scalar, vector, tensor fields.
  * Triplet and sextet diquarks, monotops.
  * Higgs effective theories.
  * Four generations.
  * Two-Higgs-Doublet model.
  * Type III See-Saw.
- **Supersymmetric models**.
  * MSSM, NMSSM, RPV-MSSM, R-MSSM.
- **Extra-dimensional models**.
  * Three-Site model.
  * Universal Extra-Dimensions, Large Extra Dimensions, Compact Heidi.
- **Strongly coupled and effective field theories**.
  * Three-Site model.
  * Chiral perturbation theory.
  * Strongly Interacting Light Higgs.
  * Technicolor.

Outline.

NLO calculations in the context of MadGraph.

- **Real emission**.
  - * Must include the appropriate **subtraction terms**.
    ⇒ MadFKS [Frederix, Frixione, Maltoni, Stelzer (JHEP '09)].
  - * The tree-level Feynman rules are the **only required components**.

☺ **No problem ⇒ problem solved.** ☺

- **One-loop virtual amplitudes**.
  - * Several algorithms have been proposed in the last few years.
    ⇒ MadLoop [Hirshi, Frederix, Frixione, Garzelli, Maltoni, Pittau (JHEP '11)].
    ⇒ based on OPP reduction [Ossola, Papadopolous, Pittau (NPB '07)].
  - * Requirements:
    - ◇ **Tree-level Feynman rules**.
    - ◇ **UV renormalization counterterms**.
    - ◇ **Rational R_2 terms**.

☹ **The two latter must be included by hand.** ☹

NLO calculations in the context of FeynRules.

- **Counterterms and R_2 terms.**
  - * **Non-automatic steps.**
  - * **Can be derived from the tree-level Lagrangian.**

All the information is already there at the FeynRules-level.

- **Automatic renormalization in the $\overline{\text{MS}}$-scheme with FeynRules** [BenjF, Serret].
  1. **Automated extraction of the renormalized Lagrangian** ✓.
  2. **Modification of the FeynArts interface to include counterterms** .
  3. **Calculation of the renormalization constants with FormCalc** ✗.
  4. **Re-injection in FeynRules** ✗.
- **Automatic R_2 terms** ✗.
- **The UFO at NLO**

To be discussed here (working groups 1/2).

- **One-loop amplitudes with MadLoop (and MadGolem?).**

Automatic field renormalization.

- **Field renormalization with FeynRules.**

```
FieldRenormalization[uq[s,f,c]]
```

$$\blacktriangleright u_{sfc} \to u_{sfc} + \frac{1}{2}\Big[(\delta Z^L_{uu})_{ff'cc'}\ (P_L)_{ss'} + (\delta Z^R_{uu})_{ff'cc'}\ (P_R)_{ss'}\Big]\ u_{s'f'c'}$$

```
FieldRenormalization[H]
```

$$\blacktriangleright H \to H + \frac{1}{2}\Big[\delta Z_{HH}\ H + \delta Z_{H\varphi}\ \varphi\Big]$$

```
FieldRenormalization[Z[mu]]
```

$$\blacktriangleright Z_\mu \to Z_\mu + \frac{1}{2}\Big[\delta Z_{ZZ}\ Z_\mu + \delta Z_{ZA}\ A_\mu\Big]$$

  * **Multiplicative renormalization** is performed: $\Phi \to \sqrt{Z}\Phi \approx (1 + \frac{1}{2}\delta Z)\Phi$.
  * Includes all possible **mixings** at the loop-level.
  * Discards **unphysical** fields (but keeps the ghosts).

- **Complete renormalization of the field content with FeynRules.**

```
FieldRenormalization[]
```

Automatic renormalization of the model parameters.

- **Parameter renormalization with FeynRules.**

```
ParameterRenormalization[aS]
```
► $\alpha_s \to \alpha_s + \delta\alpha_s$

```
ParameterRenormalization[gs]
```
► $g_s \to g_s + \delta g_s$

```
ParameterRenormalization[CKM[i,j]]
```
► $V_{ij} \to V_{ij} + \delta V_{ij}$

  * Similar treatment for the external and internal parameters.
  * Similar treatment for scalar, vector, matrices etc...

- **Complete renormalization of the model parameters with FeynRules.**

```
ParameterRenormalization[]
```

Automatic expansion of the renormalization constants.

- **Expansion of the renormalization constants (works with full Lagrangians)**.
  - * The **type of the interactions** in the loops can be specified.
  - * The **loop-level** can be specified.

```
ExtractCounterterms[l[s,f],{aS,1}]
```

$$\blacktriangleright l_{sf} \to l_{sf} + \frac{\alpha_s}{4\pi}\Big[(\delta Z_{ll}^{L(1)})_{ff'}\ (P_L)_{ss'} + (\delta Z_{ll}^{R(1)})_{ff'}\ (P_R)_{ss'}\Big]\ l_{s'f'}$$

```
ExtractCounterterms[ydo,{{aS,2},{aEW,1}}]
```

$$\blacktriangleright y_d \to y_d + \frac{\alpha_s}{2\pi}\delta y_d^{(1,0)} + \frac{\alpha}{2\pi}\delta y_d^{(0,1)} + \frac{\alpha_s^2}{4\pi^2}\delta y_d^{(2,0)} + \frac{\alpha_s\alpha}{4\pi^2}\delta y_d^{(1,1)} + \frac{\alpha_s^2\alpha}{8\pi^3}\delta y_d^{(2,1)}$$

- **Treatment of the internal parameters**.
  - * Automatic computation of the **relations** among renormalization constants.
  - * **Only** the ren. cnsts of the **external parameters** will have to be computed.

g_s and α_s at first order in QCD.

$$g_s = 2\sqrt{\pi\alpha_s} \qquad \Rightarrow \qquad \delta g_s^{(1)} = \frac{\sqrt{\alpha_s}}{2\sqrt{\pi}}\delta\alpha_s^{(1)}$$

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The superspace module of FeynRules.

- **Current developments**.
  - * **Automated spectrum generator**.
    [Alloul, Djouadi, BenjF, Kneur, Moultaka, Rausch de Traubenberg, Ughetto, Zerwas].
  - * **Gravitino/goldstino** in FeynRules.
    [Christensen, Duhr, BenjF]

Supersymmetric renormalization group equations.

- **SUSY Lagrangians at low energy**.
  * Contains **a huge number** of free parameters.
  * Example: 105 for the MSSM.
  * Loss of **predictivity**.

- **SUSY Lagrangians at high energy**.
  * **Universal boundary conditions** ⇒ reduced number of parameters.
  * Must be **evolved to low energy**.
  * Examples: gauge coupling constant and Yukawa interactions.

$$Q\frac{\mathrm{d}g}{\mathrm{d}Q} = -\frac{g^3}{16\pi^2}\Big[3C(G) - T(R)\Big] ,$$

$$Q\frac{\mathrm{d}f_{abc}}{\mathrm{d}Q} = -\frac{1}{32\pi^2}\Big[4g^2[C(A)+C(B)+C(C)]f_{abc} - (X_a^{a'} f_{a'bc} + X_b^{b'} f_{ab'c} + X_c^{c'} f_{abc'})\Big]$$

☺ **The RGEs can be extracted automatically for any model.** ☺
☺ **Automated spectrum generator for supersymmetric theories.** ☺

On the way to an automated SuSpect 3 program.

- **Ingredients for an automated spectrum generator**.
  1. Automatic analytic **derivation of the RGEs at one loop** in FeynRules ✔.
  2. **Validation for the (RPV or not) MSSM and the NMSSM** ✔.
  3. Extension at the **two-loop level**.
  4. **Interfacing** to the RGE module of SuSpect.
  5. Extraction of the **mass matrices**.
  6. Minimization of the **scalar potential** ✗.
- **Example of FeynRules output for the RGEs**.

Short selection of RGEs of the *R*-parity conserving MSSM.

```
rge=RGE[Lsoft,Superpotential]; rge[[1]]
```

► $\frac{\mathrm{d}g'}{\mathrm{d}t} = \frac{33g'^3}{80\pi^2}$

```
rge=RGE[Lsoft,Superpotential]; rge[[9]]
```

► $\frac{\mathrm{d}(y_e)_{ij}}{\mathrm{d}t} = \frac{1}{16\pi^2}\Big[3(y_e y_e^\dagger y_e)_{ij} + (y_e)_{ij}\Big(-\frac{9}{5}g'^2 - 3g_w^2 + 3\mathrm{Tr}\{y_d^\dagger y_d\} + \mathrm{Tr}\{y_e^\dagger y_e\}\Big)\Big]$

Spin 3/2 Rarita-Schwinger fields.

- **Spin 3/2 fields.**
  - * **Four-component fields** are now fully supported ✔.

Gravitino implementation.

```
R[1] == {
  ClassName          -> Gvno,
  SelfConjugate      -> True,
  Mass               -> {MGvno,500},
  Width              -> {WGvno, 10},
  ParticleName       -> "Gvno",
  PDG                -> 1000039,
  PropagatorLabel    -> "Gvno",
  PropagatorType     -> Straight,
  PropagatorArrow    -> None}
```

  - * Analytical **validation** with the literature ✔.
  - * Extension to **two-component fermions** ✗.
  - * Inclusion in the **UFO** ✗.

Goldstino interactions.

- **Extraction of the Goldstino couplings with the superspace module.**
  - **Variation** of the SUSY Lagrangian:

$$\delta_\varepsilon \mathcal{L} = \partial_\mu K^\mu \quad \text{using the (predefined) supercharges,}$$

$$\delta_\varepsilon \mathcal{L} = \partial_\mu \left[\frac{\partial \mathcal{L}}{\partial(\partial_\mu X)} \delta_\varepsilon X \right] \quad \text{Nœther theorem} \ .$$

  - Extraction of the **conserved supercurrent**.

$$\varepsilon \cdot J^\mu + \overline{J}^\mu \cdot \overline{\varepsilon} = \frac{\partial \mathcal{L}}{\partial(\partial_\mu X)} \delta_\varepsilon X - K^\mu \ .$$

  - **One of the auxiliary field gets a vev** (*e.g.*, F^1)

$$J^\mu_\alpha = i\sqrt{2}(\sigma^\mu \overline{\psi}_1)_\alpha F^1 + \widetilde{J}^\mu_\alpha$$

  - Supercurrent conservation ⇒**Goldstino (ψ_1) interaction Lagrangian**:

$$\mathcal{L} = \frac{1}{2\sqrt{2}} \frac{1}{\langle F^1 \rangle} \psi^1 \cdot \partial_\mu \widetilde{J} + \frac{1}{2\sqrt{2}} \frac{1}{\langle F_1^\dagger \rangle} \overline{\psi}_1 \cdot \partial_\mu \widetilde{\overline{J}} \ .$$

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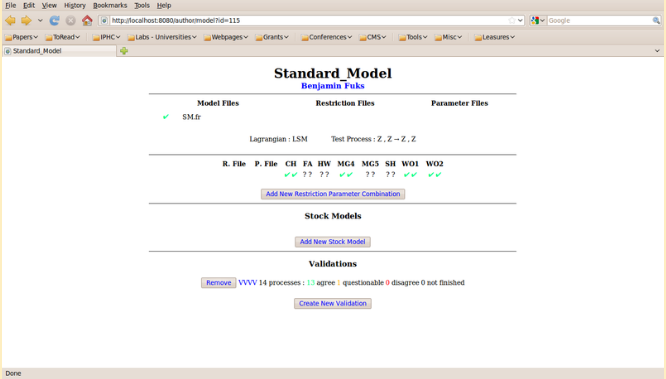
Validation of new models.

- FeynRules **provides a platform to**:
  - * **Develop** Beyond the Standard Model theories.
  - * **Validate** them to an unprecendented level.
- **Using the different interfaces, we can compare different Monte Carlos**:
  - * Using **different conventions**.
  - * Using **different gauges**.
  - * Using **different way of handling large cancellations**.
- **This can be fully automated**.
- **This can be stored on the Internet**.

Web validation.



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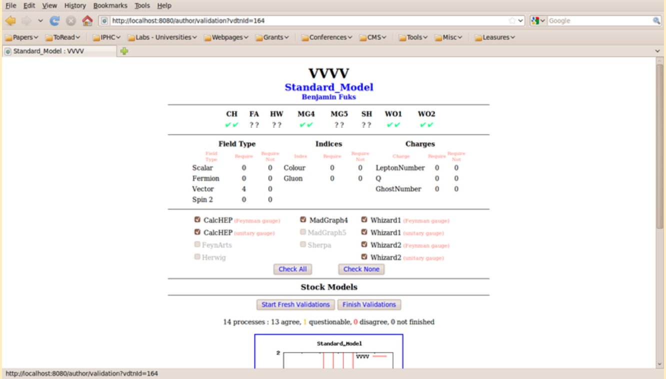

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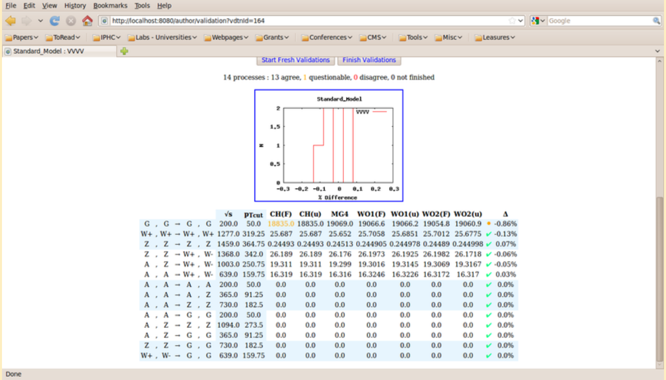

	√s	PTcut	CH(F)	CH(u)	MG4	WO1(F)	WO1(u)	WO2(F)	WO2(u)	Δ
G , G → G , G	200.0	50.0	18835.0	18835.0	19069.0	19066.6	19066.2	19054.8	19060.9	-0.86%
W+ , W+ → W+ , W+	1277.0	319.25	25.687	25.687	25.652	25.7058	25.6851	25.7012	25.6775	-0.13%
Z , Z → Z , Z	1459.0	364.75	0.24493	0.24493	0.24513	0.244905	0.244978	0.24489	0.244998	0.07%
Z , Z → W+ , W-	1368.0	342.0	26.189	26.189	26.176	26.1973	26.1925	26.1982	26.1718	-0.06%
A , Z → W+ , W-	1003.0	250.75	19.311	19.311	19.299	19.3016	19.3145	19.3069	19.3167	-0.05%
A , A → W+ , W-	639.0	159.75	16.319	16.319	16.316	16.3246	16.3226	16.3172	16.317	0.03%
A , A → A , A	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0%
A , A → A , Z	365.0	91.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0%
A , A → Z , Z	730.0	182.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0%
A , A → G , G	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0%
A , Z → Z , Z	1094.0	273.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0%
A , Z → G , G	365.0	91.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0%
Z , Z → G , G	730.0	182.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0%
W+ , W- → G , G	639.0	159.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0%

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Conclusions.

- **FeynRules-1.6 is now public and includes**:
  - * A **superspace** module.
  - * A **UFO interface**.
  - * A new FeynArts interface.
  - * **Color sextets**.
- **FeynRules-1.8 is being developed**.
  - * Towards **NLO** [cf. working group 1/2].
  - * **Spin 3/2** fields [cf. working group 2].
  - * Towards an automated **SUSY spectrum generator**.
  - * Les Houches 2011: **automatic decay calculator**.
    (with A. Arbey and N. Mahmoudi) [cf. working group 3].
  - * Les Houches 2011: **automatic computation of Wilson coefficients**.
    $\Rightarrow$ SuperISO $\Rightarrow$ flavor physics (with A. Arbey and N. Mahmoudi).
  - * Development of the **web platform**.
- **Missing stuff**?

To be discussed here.