A comprehensive approach to New Physics simulations.

Benjamin Fuks (IPHC Strasbourg)

In collaboration with N. Christensen (MSU), P. de Aquino (UCL), C. Duhr (UCL), M. Herquet (Nikhef), F. Maltoni (UCL) and S. Schumann (U. Heidelberg).

CMS France Physics Meeting
May 27-28, 2009

Outline

1. Introduction - Monte Carlo generators
2. FeynRules
3. Model database and validation status
4. Summary - outlook

Outline

1. Introduction - Monte Carlo generators
2. FeynRules
3. Model database and validation status
4. Summary - outlook

One simple question.

- **One of the first goals of the LHC: rediscover the Standard Model.**
  - * We need **data** [which are hopefully coming this year].
  - * We need **theoretical predictions** [which is the aim of this talk].

Confront data and theory.

One simple question.

- **One of the first goals of the LHC: rediscover the Standard Model.**
  * We need **data** [which are hopefully coming this year].
  * We need **theoretical predictions** [which is the aim of this talk].

Confront data and theory.

- **Theoretical predictions:**
  * **Handmade calculations** ☹:
    - Easy ... for easy processes!
    - Factorial growth of the number of diagrams.
    - Tedious and error prone task.

One simple question.

- **One of the first goals of the LHC: rediscover the Standard Model.**
  - * We need **data** [which are hopefully coming this year].
  - * We need **theoretical predictions** [which is the aim of this talk].

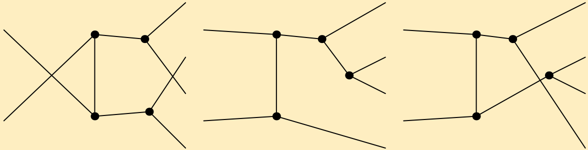
Confront data and theory.

- **Theoretical predictions:**
  - * **Handmade calculations** ☹:
    - ◇ Easy ... for easy processes!
    - ◇ Factorial growth of the number of diagrams.
    - ◇ Tedious and error prone task.
  - * **Automated tools** ☺:
    - ◇ Easy ... for any process!
    - ◇ Can be used to simulate the full collision environment.
    - ◇ There exists a vast zoology of tools.

Working principles of a Monte Carlo generator

1. **Generation of the topologies**.

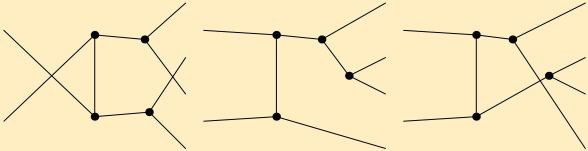
e.g. (some of the possible) $2 \longrightarrow 4$ topologies.



Working principles of a Monte Carlo generator

1. **Generation of the topologies**.

e.g. (some of the possible) $2 \to 4$ topologies.

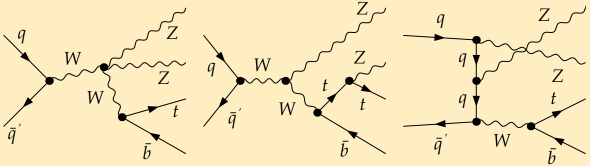


2. **Attach the external and all possible internal particles.**

Working principles of a Monte Carlo generator

1. **Generation of the topologies**.
2. **Attach the external and all possible internal particles.**
3. **Test the existence of the vertices (accept/reject diagrams)**.
   * **Feynman rules table**.

e.g. $ZZtop$ $+b$-jet production (3 among 136 diagrams).



Working principles of a Monte Carlo generator

1. **Generation of the topologies**.
2. **Attach the external and all possible internal particles.**
3. **Test the existence of the vertices (accept/reject diagrams)**.
4. **Squaring amplitudes, phase space integration** ($\Rightarrow$ 0.01 fb).

$$\sigma = \sum_{ab} \int \mathrm{d}x_a \, \mathrm{d}x_b \, \mathrm{d}PS^{(n)} \, f_{a/h_1}(x_a; \mu_F) \, f_{b/h_2}(x_b; \mu_F) \, \frac{\left|M_{ab}\right|^2}{2\hat{s}}$$

* Integration over the momentum fractions of the partons.
* Integration over the n-particle phase space ($n = 4$ here).
* Sum over all subprocesses.
* Parton densities and incident flux.
* Parton-level cuts.

Working principles of a Monte Carlo generator

1. **Generation of the topologies**.
2. **Attach the external and all possible internal particles.**
3. **Test the existence of the vertices (accept/reject diagrams)**.
4. **Squaring amplitudes, phase space integration**.
5. **Event generation** (unweighting).

Working principles of a Monte Carlo generator

1. **Generation of the topologies**.
2. **Attach the external and all possible internal particles.**
3. **Test the existence of the vertices (accept/reject diagrams)**.
4. **Squaring amplitudes, phase space integration**.
5. **Event generation** (unweighting).
6. **Parton showers, hadronization, detector simulation.**

Monte Carlo tools and Beyond the Standard Model Physics

- **Tools zoology**
  - CalcHEP/CompHEP [Pukhov *et al.* (1999); Boss *et al.* (2004)].
  - FeynArts/FormCalc [Hahn (1999,2001)].
  - Herwig [Corcella *et al.* (2001); Bahr *et al.* (2008)].
  - MadGraph/MadEvent [Alwall *et al.* (2007); Maltoni, Stelzer (2003)].
  - Sherpa [Gleisberg *et al.* (2004)].
  - Whizard/Omega [Moretti *et al.* (2001); Kilian *et al.* (2007)].

Monte Carlo tools and Beyond the Standard Model Physics

- **Tools zoology**
  - * CalcHEP/CompHEP [Pukhov *et al.* (1999); Boss *et al.* (2004)].
  - * FeynArts/FormCalc [Hahn (1999,2001)].
  - * Herwig [Corcella *et al.* (2001); Bahr *et al.* (2008)].
  - * MadGraph/MadEvent [Alwall *et al.* (2007); Maltoni, Stelzer (2003)].
  - * Sherpa [Gleisberg *et al.* (2004)].
  - * Whizard/Omega [Moretti *et al.* (2001); Kilian *et al.* (2007)].
- **New Physics theories**:
  - * Which is the correct one [if any]?
  - * LHC $\equiv$ one ring to rule them all out!
  - * **We need theoretical predictions for all models.**

Monte Carlo tools and Beyond the Standard Model Physics

- **Tools zoology**
  - * CalcHEP/CompHEP [Pukhov *et al.* (1999); Boss *et al.* (2004)].
  - * FeynArts/FormCalc [Hahn (1999,2001)].
  - * Herwig [Corcella *et al.* (2001); Bahr *et al.* (2008)].
  - * MadGraph/MadEvent [Alwall *et al.* (2007); Maltoni, Stelzer (2003)].
  - * Sherpa [Gleisberg *et al.* (2004)].
  - * Whizard/Omega [Moretti *et al.* (2001); Kilian *et al.* (2007)].
- **New Physics theories**:
  - * Which is the correct one [if any]?
  - * LHC $\equiv$ one ring to rule them all out!
  - * **We need theoretical predictions for all models.**
- **For a validated tool:**
  - * All the model information is embedded in a **list of Feynman rules**.
  - * Have to be written coupling by coupling, model by model.
  - * Tedious and error prone task.

Monte Carlo tools and Beyond the Standard Model Physics

- **Tools zoology**
  - * CalcHEP/CompHEP [Pukhov *et al.* (1999); Boss *et al.* (2004)].
  - * FeynArts/FormCalc [Hahn (1999,2001)].
  - * Herwig [Corcella *et al.* (2001); Bahr *et al.* (2008)].
  - * MadGraph/MadEvent [Alwall *et al.* (2007); Maltoni, Stelzer (2003)].
  - * Sherpa [Gleisberg *et al.* (2004)].
  - * Whizard/Omega [Moretti *et al.* (2001); Kilian *et al.* (2007)].
- **New Physics theories**:
  - * Which is the correct one [if any]?
  - * LHC $\equiv$ one ring to rule them all out!
  - * **We need theoretical predictions for all models.**
- **For a validated tool:**
  - * All the model information is embedded in a **list of Feynman rules**.
  - * Have to be written coupling by coupling, model by model.
  - * Tedious and error prone task.

FeynRules

More than just automization.

Outline

A roadmap to BSM at the LHC (1)

Models

Theoretical works

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

Phenomenological works

* **Monte Carlo event generation.**
  $\Rightarrow$ **Feynman rules tables!**
* Generic detector simulation, ...
* Signal/background studies.

Experimental works

* **Validated experimental framework (CMSSW).**
  $\Rightarrow$ **Contains Monte Carlo generators!**
* Realistic detector simulation, ...
* Comparison with data.

$\Leftrightarrow$ **Data**

A roadmap to BSM at the LHC (2)

Models ⇒ **FEYNRULES**

Theoretical works

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

Phenomenological works

* **Monte Carlo event generation.**
  ⇒ **Feynman rules tables!**
* Generic detector simulation, ...
* Signal/background studies.

Experimental works

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

⇔ **Data**

FeynRules.

- Communicates with MadGraph, Sherpa, ...
- ✔ No new MC validation.
- ✔ MC validated for exp. software.
- ✔ Mathematica based.
- ✔ Portable, documented.

FeynRules

Model (e.g. from any theoretical paper)

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

$\Downarrow$

FEYNRULES (Mathematica, "screen-typing")

$\Downarrow$

Feynman rules $\Rightarrow \Rightarrow$ **TEX-file**

$\Downarrow$

Translation interfaces (Mathematica, single keystroke)

$\Downarrow$ $\Downarrow$ $\Downarrow$ $\Downarrow$ $\Downarrow$

CalcHEP | **FeynArts** | **MadGraph** | **Sherpa** | **...**

$\Downarrow$ $\Downarrow$

CMSSW & analysis! (simple copy paste)

Outline

Model database

- **Publicly available (FeynRules v1.2.5)**:
  - * **The Standard Model** [N. Christensen, C. Duhr].
  - * **Higgs effective theory (large m_{top} approximation)** [C. Duhr].
  - * **The Three-Site Model** [N. Christensen].
    - 5D $SU(2) \times SU(2) \times U(1)$ theory in a slice of Anti-deSitter space.
    - Gauge invariant higgsless model.
    - Heavy extra gauge bosons and new fermionic states.
  - * **The Hill Model** [P. Aquino, C. Duhr].
    - SM plus an additional scalar sector coupling only to the Higgs.
    - Two Higgs fields after mass matrix diagonalization.
- **Soon available (within 2-3 weeks)**:
  - * **The most general two-Higgs-doublet model** [M. Herquet].
  - * **The most general MSSM** [BenjF].
  - * **Extra dimensional models** [P. Aquino].
- **Soon available (within 2-3 weeks, but not interfaced to Monte Carlo codes)**:
  - * **Chiral pertubation theory** [C. Degrande].
  - * **Strongly interacting Light Higgs models** [C. Degrande].

Validation sheet

- **FeynArts/FormCalc:**
  * Use of the **FeynRules** version of the FeynArts model files.
  * **Check of the FormCalc-produced formulas with litterature.**
  * Used versions: **FormCalc-5.4** and **FormCalc-6.0**.
- **MadGraph/MadEvent**:
  * Comparison between (existing) **stock** and **FeynRules** model files.
  * Test of various $2 \to 2$ and $2 \to 3$ processes.
  * Used version: **MadGraph-4.4.21**.
- **CalcHEP/CompHEP:**
  * Comparison between (existing) **stock** and **FeynRules** model files.
  * **Test of both Feynman and unitary gauges.**
  * Test of various $2 \to 2$ and $2 \to 3$ processes.
  * Used version: **CalcHEP-2.5**.
- **Sherpa:** on the to-do list...
- **Comparison:** different generators, gauges, ...

Example: validation of the most general MSSM (1)

- **Handmade vs. automated implementation.**
  - * 2522 vertices, without the four-scalar interactions.
  - * **More that 10000 vertices, with the four-scalar interactions !!!**
  - * R-parity violation: add $\approx$ 100 free parameters...

Example: validation of the most general MSSM (1)

- **Handmade vs. automated implementation.**
  - 2522 vertices, without the four-scalar interactions.
  - **More that 10000 vertices, with the four-scalar interactions !!!**
  - R-parity violation: add ≈ 100 free parameters...

- **FeynArts/FormCalc:** most general R-parity-conserving MSSM.
  - ✔ All $2 \to 2$ SUSY hadroproduction processes checked with litterature. [Bozzi, BenjF, Herrmann, Klasen (2007); BenjF, Herrmann, Klasen (2009; in preparation)].

Example: validation of the most general MSSM (1)

- **Handmade vs. automated implementation.**
  - 2522 vertices, without the four-scalar interactions.
  - **More that 10000 vertices, with the four-scalar interactions !!!**
  - R-parity violation: add ≈ 100 free parameters...
- **FeynArts/FormCalc:** most general R-parity-conserving MSSM.
  - ✔ All $2 \to 2$ SUSY hadroproduction processes checked with litterature. [Bozzi, BenjF, Herrmann, Klasen (2007); BenjF, Herrmann, Klasen (2009; in preparation)].
- **MadGraph/MadEvent** (in the cMSSM limit):
  - MG-Stock was validated by the CATPISS collaboration [Hagiwara *et al.* (2006)].
  - ✔ **320 decay widths.**
  - ✔ **626** $2 \to 2$ **SUSY processes.**
  - ✔ **2708** $2 \to 3$ **SUSY processes.**

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

Example: validation of the most general MSSM (1)

- **Handmade vs. automated implementation.**
  - * 2522 vertices, without the four-scalar interactions.
  - * **More that 10000 vertices, with the four-scalar interactions !!!**
  - * R-parity violation: add ≈ 100 free parameters...
- **FeynArts/FormCalc:** most general R-parity-conserving MSSM.
  - ✔ All $2 \to 2$ SUSY hadroproduction processes checked with litterature. [Bozzi, BenjF, Herrmann, Klasen (2007); BenjF, Herrmann, Klasen (2009; in preparation)].
- **MadGraph/MadEvent** (in the cMSSM limit):
  - * MG-Stock was validated by the CATPISS collaboration [Hagiwara *et al.* (2006)].
  - ✔ **320 decay widths.**
  - ✔ **626** $2 \to 2$ **SUSY processes.**
  - ✔ **2708** $2 \to 3$ **SUSY processes.**

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

- **CalcHEP/CompHEP** (in the cMSSM):
  - ✔ **626** $2 \to 2$ **SUSY processes.**
  - ✘ **Some bugs found in the stock version!**

Example: validation of the most general MSSM (2)

Some MadGraph and CalcHEP results

Process	MG-FR	MG-Stock	CH-FR	CH-Stock	Result
e+,e->e+,e-	7.5203×10^{2}	7.5216×10^{2}	7.5137×10^{2}	7.5137×10^{2}	OK: 0.105086%
e+,e->vm,vm~	1.5268×10^{-3}	1.5285×10^{-3}	1.5261×10^{-3}	1.5262×10^{-3}	OK: 0.15714%
e+,e->t,t~	1.1098×10^{-2}	1.1101×10^{-2}	1.1108×10^{-2}	1.1114×10^{-2}	OK: 0.144066%
e+,e->d,d~	5.6391×10^{-3}	5.6597×10^{-3}	5.6465×10^{-3}	5.6465×10^{-3}	OK: 0.36464%
e+,e->W+,W-	2.8014×10^{-1}	2.801×10^{-1}	2.8008×10^{-1}	2.8009×10^{-1}	OK: 0.0214202%
e+,e->Z,Z	1.535×10^{-2}	1.5347×10^{-2}	1.5347×10^{-2}	1.5347×10^{-2}	OK: 0.0195459%
e+,e->Z,a	6.2902×10^{-2}	6.2901×10^{-2}	6.292×10^{-2}	6.292×10^{-2}	OK: 0.0302016%
e+,e->sl5-,sl5+	3.2044×10^{-2}	3.2002×10^{-2}	3.2039×10^{-2}	3.2039×10^{-2}	OK: 0.131156%
e+,e->sl2-,sl2+	3.6401×10^{-2}	3.641×10^{-2}	3.64×10^{-2}	3.64×10^{-2}	OK: 0.0274688%
e+,e->sl5-,sl2+	2.0292×10^{-3}	2.0269×10^{-3}	2.0291×10^{-3}	2.0291×10^{-3}	OK: 0.113409%
e+,e->sl1-,sl1+	1.6061×10^{-3}	1.6061×10^{-3}	1.6054×10^{-3}	1.6054×10^{-3}	OK: 0.0435933%
e+,e->sv3,sv3~	9.5578×10^{-2}	9.5567×10^{-2}	9.554×10^{-2}	9.5542×10^{-2}	OK: 0.039766%
e+,e->su4,su4~	2.9679×10^{-3}	2.9676×10^{-3}	2.9692×10^{-3}	2.9692×10^{-3}	OK: 0.0539011%
e+,e->su1,su1~	1.9518×10^{-3}	1.9486×10^{-3}	1.9517×10^{-3}	1.9517×10^{-3}	OK: 0.164086%
e+,e->su6,su6~	2.2021×10^{-3}	2.2041×10^{-3}	2.202×10^{-3}	2.202×10^{-3}	OK: 0.0953224%
e+,e->su1,su6~	4.4196×10^{-4}	4.4134×10^{-4}	4.4155×10^{-4}	4.4155×10^{-4}	OK: 0.140383%
e+,e->sd4,sd4~	4.9197×10^{-4}	4.926×10^{-4}	4.9192×10^{-4}	4.9192×10^{-4}	OK: 0.138138%
e+,e->sd6,sd6~	2.0014×10^{-3}	2.0012×10^{-3}	2.0016×10^{-3}	2.0016×10^{-3}	OK: 0.019986%
e+,e->sd1,sd2~	2.1502×10^{-4}	2.149×10^{-4}	2.1494×10^{-4}	2.1494×10^{-4}	OK: 0.0558243%
e+,e->n1,n1	7.6112×10^{-3}	7.6075×10^{-3}	7.6077×10^{-3}	7.6076×10^{-3}	OK: 0.0486244%
e+,e->n1,n2	2.7949×10^{-3}	2.792×10^{-3}	2.7942×10^{-3}	2.7943×10^{-3}	OK: 0.103814%
e+,e->n2,n3	4.1779×10^{-4}	4.1709×10^{-4}	4.17×10^{-4}	4.1701×10^{-4}	OK: 0.189269%
e+,e->n2,n4	7.5931×10^{-4}	7.5959×10^{-4}	7.5912×10^{-4}	7.5914×10^{-4}	OK: 0.0618946%
e+,e->n4,n4	3.5319×10^{-5}	3.531×10^{-5}	3.5317×10^{-5}	3.5317×10^{-5}	OK: 0.0254853%
e+,e->x1+,x1-	1.204×10^{-2}	1.2038×10^{-2}	1.2039×10^{-2}	1.2039×10^{-2}	OK: 0.0166127%
e+,e->x2+,x2-	7.0411×10^{-3}	7.0479×10^{-3}	7.0494×10^{-3}	7.0494×10^{-3}	OK: 0.11781%
e+,e->Z,h1	7.6379×10^{-4}	7.6496×10^{-4}	7.6477×10^{-4}	7.6478×10^{-4}	OK: 0.153066%
e+,e->Z,h2	1.0024×10^{-7}	1.0007×10^{-7}	1.0017×10^{-7}	1.0017×10^{-7}	OK: 0.169737%
e+,e->h3,h1	9.9472×10^{-8}	9.9485×10^{-8}	9.9461×10^{-8}	9.9466×10^{-8}	OK: 0.0241272%
e+,e->h3,h2	7.172×10^{-4}	7.1771×10^{-4}	7.177×10^{-4}	7.1771×10^{-4}	OK: 0.0710846%
e+,e->H+,H-	1.7338×10^{-3}	1.7338×10^{-3}	1.7355×10^{-3}	1.7355×10^{-3}	OK: 0.0980025%

Example: validation of the most general MSSM (3)

Some MadGraph and CalcHEP results

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

Outline

Summary: the philosophy of FeynRules

* **Theorist-friendly environment to develop new models**.
  Mathematica-based.

* **Filling the gap between model building and collider phenomenology.**
  1) Lagrangian $\longrightarrow$ FeynRules $\longrightarrow$ model files for your favourite Monte Carlo codes.
  2) Monte Carlo code $\longrightarrow$ phenomenology (e.g. cf. CMSSW).

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

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

* **The validation of the existing models is ongoing.**
  Different generators, gauges, etc...

* Contact us to add your favourite **model**.
* Contact us to add your favourite **Monte Carlo tool**.
* Website: **http://feynrules.phys.ucl.ac.be** .

Backup slides - one short 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.

Example: QCD - Lagrangian

QCD Lagrangian:

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

The QCD Lagrangian

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

* **Implicit summations** ⇒ easy debugging.

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]
```