A comprehensive approach to New Physics simulations.

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CMS France Physics Meeting
May 27-28, 2009

Outline

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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].

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

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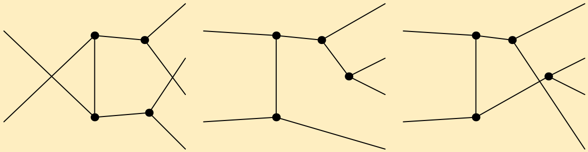
    - ◇ Tedious and error prone task.
  * **Automated tools** ☺:
    - ◇ Easy ... for any process!
    - ◇ Can be used to simulate the full collision environment.
    - ◇ There exists a vast zoology of tools.

Working principles of a Monte Carlo generator

1. **Generation of the topologies**.

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



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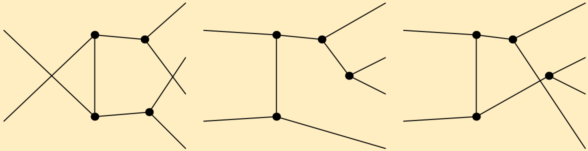
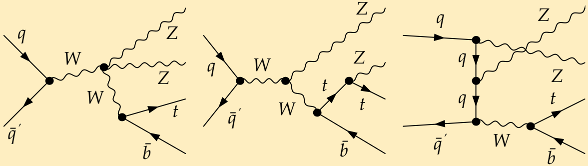


2. **Attach the external and all possible internal particles.**

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.

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5. **Event generation** (unweighting).

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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)].
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  - * Which is the correct one [if any]?
  - * LHC $\equiv$ one ring to rule them all out!
  - * **We need theoretical predictions for all models.**

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  * 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.

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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**

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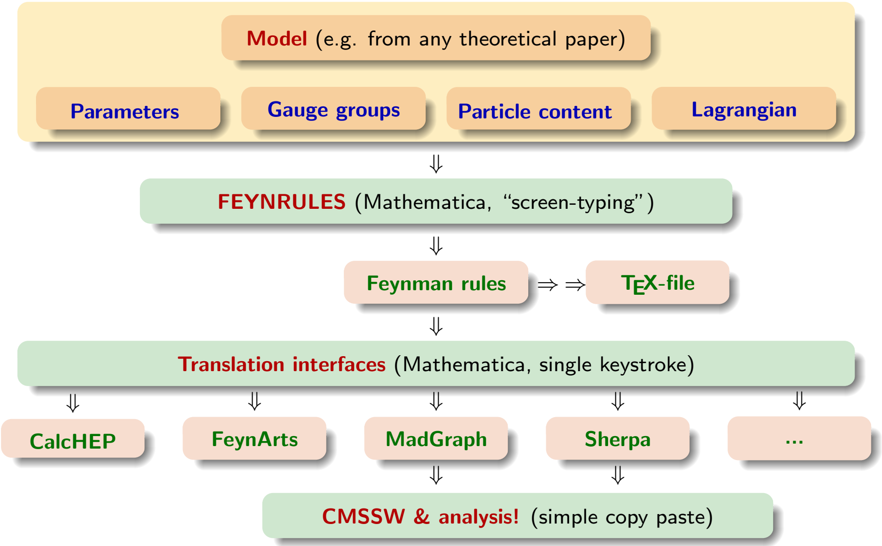
⇔ **Data**

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
FEYNRULES (Mathematica, “screen-typing”)
Feynman rules
TEX-file
Translation interfaces (Mathematica, single keystroke)
CalcHEP
FeynArts
MadGraph
Sherpa
...
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 $2 \longrightarrow 2$ and $2 \longrightarrow 3$ 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 $2 \longrightarrow 2$ and $2 \longrightarrow 3$ 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...

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  - ✔ All $2 \rightarrow 2$ SUSY hadroproduction processes checked with litterature. [Bozzi, BenjF, Herrmann, Klasen (2007); BenjF, Herrmann, Klasen (2009; in preparation)].

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- **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.

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- **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 → FeynRules → model files for your favourite Monte Carlo codes.
  2) Monte Carlo code → 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:

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

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]
```