From FeynRules to CMSSW
A comprehensive approach to New Physics simulations.

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Outline

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Theoretical calculations for the LHC.

- **One of the goals of the LHC: which New Physics theory is the correct one?**
  [if any, LHC might be one ring to rule them all out!]
  - We need **data** [which are hopefully coming this (next?) year].
  - We need **theoretical predictions for all models** [which is the aim of this talk].

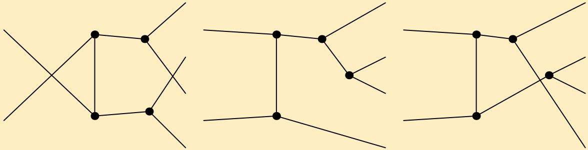
Confront data and theory.

- **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)

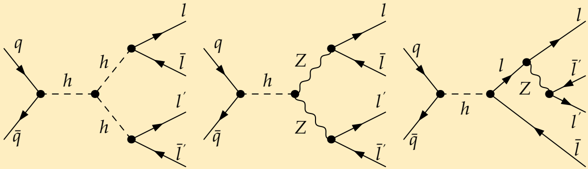
1. **Generation of the topologies**.

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



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

e.g. 4 leptons production in the SM (3 among 960 diagrams, SM).



Working principles of a Monte Carlo generator (2)

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

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

* 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.

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 [Maltoni, Stelzer (2003); Alwall *et al.* (2007)].
  - Sherpa [Gleisberg *et al.* (2004)].
  - Whizard/Omega [Moretti *et al.* (2001); Kilian *et al.* (2007)].
- **Model implementation**:
  - List of particles.
  - List of external and internal parameters.
  - List of vertices ($\equiv$ Feynman rules).
- **Assuming a validated tool:**
  - **The Feynman rules have to be written coupling by coupling**.
  - Tedious and error prone task.
  - **The validation may be long ☹**.
  - We need to iterate for each considered model.

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.**
  ⇒ **Model implementation!**
* Generic detector simulation, ...
* Signal/background studies.

Experimental works - CMSSW

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

⇔ **Data**

A roadmap to BSM at the LHC (2)

Models

F E Y N R U L E S

Theoretical works

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

Phenomenological works

* **Monte Carlo event generation.**
  ⇒ **Automatized model implementation!**
* Generic detector simulation, ...
* Signal/background studies.

Experimental works - CMSSW

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

⇔ Data

FeynRules.

- ✔ Mathematica based.
- ✔ Linked to MC's.
- ✔ No MC modification (validated).
- ✔ 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 | Whizard

⇓ (MadGraph) ⇓ (Sherpa)

CMSSW **& analysis!** (simple copy paste)

Outline

Model database

- **Publicly available (FeynRules v1.4.0)**:
  * **The Standard Model** [N. Christensen, C. Duhr].
  * **The most general two-Higgs-doublet model** [M. Herquet].
  * **The most general MSSM** [BenjF].
  * **Universal extra dimensional models** [P. Aquino].
  * **The Minimal Higgsless Model** [N. Christensen].
  * **Higgs effective theory (large m_{top} approximation)** [C. Duhr].
  * **Hidden Abelian Higgs Model** [C. Duhr].
  * **The Hill Model** [P. Aquino, C. Duhr].
- **Not interfaced to Monte Carlo codes**:
  * **Large extra dimensional models** [P. Aquino].
  * **Chiral pertubation theory** [C. Degrande].
  * **Strongly interacting Light Higgs models** [C. Degrande].
- **Missing models: tell us!** ☺

Validation procedure - the four-star system

- **Any model can be put on the FeynRules website.**
- **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 Standard Model

CalcHep, CompHep, MadGraph/MadEvent, Sherpa and Whizard results

Process	CalcHEP Stock	CalcHEP Feynman	CalcHEP Unitary	CompHEP Feynman	MadGraph Stock	MadGraph Unitary	Sherpa Unitary	Whizard Stock	Whizard Feynman	Whizard Unitary	
$gg \to gg$	116490.	116490.	116490.	116490.	116680.	116120.	116490	115031.	116585.	116642.	Discrpency!
$u\bar{u} \to gg$	199.95	199.95	199.95	199.94	200.21	199.77	199.963	199.693	199.693	199.693	
$t\bar{t} \to gg$	64.595	64.595	64.595	64.592	64.467	64.537	64.5856	64.623	64.5601	64.5601	
$e^+e^- \to \mu^+\mu^-$	0.37194	0.37195	0.37195	0.37194	0.37202	0.37148	0.372011	0.372034	0.372028	0.372028	
$e^+e^- \to e^+e^-$	734.15	734.15	734.15	734.16	733.96	734.47	734.314	734.622	734.609	734.609	
$e^+e^- \to \nu_e\bar{\nu}_e$	49.143	49.145	49.145	49.145	results	results	49.1361	49.1139	49.1184	49.1184	
$t\bar{t} \to u\bar{u}$	16.018	16.018	16.018	16.018	16.012	16.022	16.0204	16.0214	16.0214	16.0214	
$u\bar{u} \to s\bar{s}$	9.7634	9.7634	9.7634	9.7631	9.7631	9.7692	9.76376	9.76348	9.76346	9.76348	
$u\bar{d} \to c\bar{s}$	0.3531	0.35311	0.35311	0.35312	0.35274	0.35318	0.353149	0.353212	0.353215	0.353215	
$u\bar{s} \to c\bar{d}$	0.0010187	0.0010187	0.0010187	0.0010187	0.0010186	0.0010182	0.00101879	0.00101897	0.00101898	0.00101898	
$W^+W^- \to t\bar{t}$	44.534	44.535	44.535	44.534	44.647	44.485	44.5503	44.4991	44.4992	44.4992	
$t\bar{t} \to ZZ$	1.2534	1.2534	1.2534	1.2534	1.254	1.2559	1.25321	1.25431	1.25432	1.25432	
$t\bar{t} \to Z\gamma$	1.3119	1.3119	1.3119	1.312	1.3139	1.3113	1.31197	1.31261	1.31202	1.31202	
$t\bar{t} \to \gamma\gamma$	0.088486	0.088486	0.088486	0.088485	0.088527	0.088462	0.0884835	0.0884519	0.0884983	0.0884983	
$u\bar{u} \to W^+W^-$	1.7736	1.7737	1.7737	1.7737	1.7698	1.776	1.77424	1.77412	1.77413	1.77413	
$u\bar{u} \to ZZ$	0.19345	0.19347	0.19347	0.19346	0.19357	0.19318	0.193462	0.192923	0.192927	0.192927	
$u\bar{u} \to Z\gamma$	0.33811	0.33812	0.33812	0.33811	0.3381	0.3384	0.334504	0.338125	0.338124	0.338124	Discrpency!
$u\bar{u} \to \gamma\gamma$	0.18322	0.18322	0.18322	0.18323	0.18332	0.18329	0.183224	0.183377	0.183373	0.183373	
$\tau^+\tau^- \to W^+W^-$	5.3681	5.3684	5.3684	5.3686	5.3517	5.3637	5.36799	5.36556	5.3656	5.3656	
$\tau^+\tau^- \to ZZ$	0.31816	0.31817	0.31817	0.31816	0.31852	0.31805	0.318256	0.31799	0.317993	0.317993	
$\tau^+\tau^- \to Z\gamma$	2.0057	2.0057	2.0057	2.0057	2.0083	2.0044	1.98453	1.99948	2.00799	2.00799	Discrpency!
$\tau^+\tau^- \to \gamma\gamma$	2.7791	2.7791	2.7791	2.779	2.7773	2.7756	2.77911	2.77248	2.77711	2.77711	
$ZZ \to ZZ$	1.9606	1.9606	1.9606	1.9606	1.9565	1.9555	1.96071	1.96046	1.96046	1.96046	
$W^+W^- \to \gamma\gamma$	20.825	20.825	20.825	20.824	20.827	20.804	20.8182	20.8527	20.8171	20.8171	
$W^+W^- \to ZZ$	272.62	272.63	272.63	272.62	272.36	272.11	272.694	272.422	272.425	272.425	
$W^+W^- \to W^+W^-$	1318.1	1318.2	1318.2	1318.2	1317.2	1318.8	1318.45	1320.05	1320.03	1320.03	
$hh \to hh$	1.8569	1.857	1.857	1.857	-	1.8567	1.85587	1.86179	1.86179	1.86179	
$ZZ \to hh$	6.3027	6.3029	6.3029	6.3029	6.311	6.3137	6.30265	6.29227	6.31003	6.31003	
$hh \to W^+W^-$	94.47	94.473	94.473	94.473	94.815	94.833	94.5793	94.5073	94.5077	94.5077	

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 !!!**
- 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, using two gauges):
  - ✔ **626** $2 \to 2$ **SUSY processes.**
  - ✘ **Some bugs found in the stock version!**

Example: validation of the most general MSSM (2)

Some MadGraph/MadEvent 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 %

From FeynRules to CMSSW

- **A powerful prospecting chain**:
  - * **Model implementation**: FeynRules
  - * **Events**: CalcHep, MadGraph/MadEvent, Sherpa, ...
  - * **Parton showering**: Pythia, Herwig, ...
  - * **Hadronization**: Pythia, ...
  - * **Detector effects**: Delphes, PGS,...
- **A tutorial could be presented at a further meeting**.
- CMSSW
  - * Contains CompHep, MadGraph/MadEvent and Sherpa.
  - * FeynRules is supported by the MC people (if an interface exists).
  - * **No CMSSW modification required to include FeynRules models.** ☺

    [One single copy paste is the only thing to do!]
- **Implementation and validation of new models**.
  - * Is any important/interesting model missing?
  - * **Which validation criteria should we require?** [A CMS fifth star?]

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 MC codes.
  2) Monte Carlo code → phenomenology (*e.g.* 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 models is not neglected!**
  Different generators, gauges, etc...

* Contact us to add your favourite **model**.
* Contact us to add your favourite **Monte Carlo tool**.
* Contact us for a **detailed tutorial**.
* 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]
```