

Tutorial - From Model Building to Events (using the full simulation chain).

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Outline

- 1 The FEYNRULES approach.
- 2 Example: the Hidden Abelian Higgs Model
- 3 Implementation in FEYNRULES: the Hidden Abelian Higgs Model
- 4 Model database & validation procedures.
- 5 Summary - outlook.

Monte Carlo tools and discoveries at the LHC (1).

● Matrix element-based event 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 distributions, accurate predictions are required.**

● Best theoretical predictions.

- * **Accurate** theoretical calculations.
 - ◇ Higher order QCD corrections.
 - ◇ Resummation.
 - ◇ Weak corrections.
 - ◇ ...
- * Mandatory for understanding and control of **physics and detector effects**.
- * **Reliable estimate of errors**.

Monte Carlo tools and discoveries at the LHC (2).

- **Establishing of an excess over the SM backgrounds.**
 - * **Difficult task.**
 - * Use of **Monte Carlo generators.**
 - * **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.**
 - * **Sophistication of the analyses** ⇔ **new physics and detector knowledge.**

Monte Carlo tools play a key role!

Monte Carlo tools for BSM (1).

- **New physics theories.**

- * There is a **lot of different** theories.
- * Based on very **different ideas**.
- * **In evolution** (regarding the discoveries).

- **Implementation in Monte Carlo tools.**

- * A model consists in 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.

Monte Carlo tools for BSM (2).

● Validation.

- * **Comparison** with existing analytical and numerical results.
- * **Non systematic and partial.**
 - ◇ **Restricted set** of available results.
 - ◇ **No dedicated framework.**
 - ◇ **Warning: conventions.**

● Distribution.

- * Many models remain **private**.
- * **Exception:** popular models such as the MSSM.
- * Use of **many home-made and hacked versions** of existing models.
⇒ Issues for validation, traceability and maintenance.

An efficient framework is needed:

- * To **develop** new models.
- * To **implement and validate** new models in MC tools.
- * To **test** the models against the future data.

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 L_ANHEP package** [Semenov (1998)].

- * In the context of **CALC_HEP/COMP_HEP**.
- * Allows to run several tests on the Lagrangian (**reducing errors**).
- * Interfaced to **FEYNARTS**.

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.**
 - ◇ ...
- * **New additional functions** can easily be added by users.
 - ◇ **Model spectrum calculator.**
 - ◇ ...

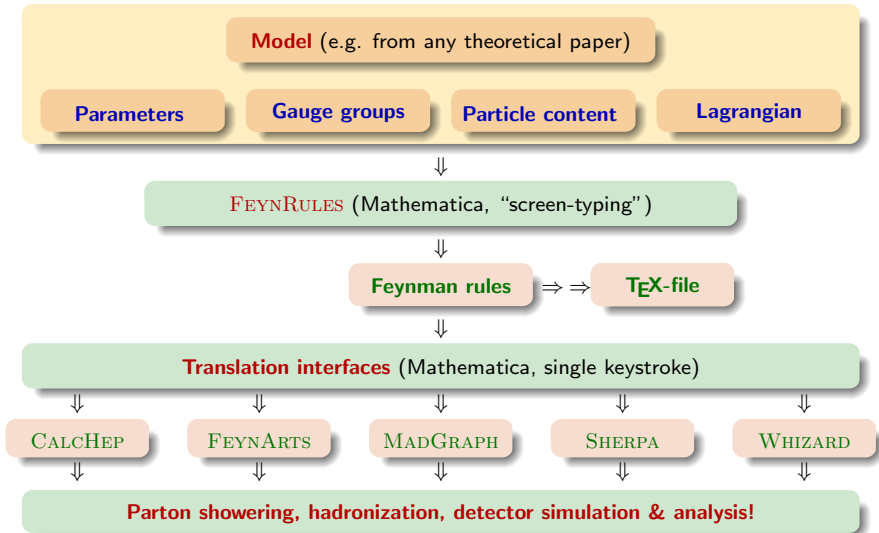
- **Interfaces to Monte Carlo codes.**

- * 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.

Scope and limitations.

- **Supported fields.**
 - * Scalar fields.
 - * Dirac and Majorana fermions [**Weyl fermions: in validation**].
 - * Vector fields.
 - * Ghost fields.
 - * **No spin 3/2.**
 - * Spin two fields.
 - * **No superfields.**
- **The model must fulfil basic quantum field theory requirements.**
 - * Lorentz invariance.
 - * Gauge invariance.
 - * **Higher-dimensional operators are supported.**
- **Interfaces and Monte Carlo tools.**
 - * Only **scalars, Dirac and Majorana fermions, vector** (and ghost) **fields.**
 - * **Higher-dimensional operators** are not all supported.

FEYNRULES.



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- 3 Implementation in FEYNRULES: the Hidden Abelian Higgs Model
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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:

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

- **New gauge sector.**

- * X boson kinetic term.
 - * $X - B$ mixing term.

$$\begin{aligned} \mathcal{L}_{\text{HAH,Gauge}} = & -\frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\ & - \frac{1}{4} \mathbf{X}_{\mu\nu} \mathbf{X}^{\mu\nu} + \frac{\chi}{2} \mathbf{B}_{\mu\nu} \mathbf{X}^{\mu\nu} \end{aligned}$$

- **New Higgs potential.**

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

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}_μ and \tilde{X}_μ** (cf. $\eta = \frac{\chi}{\sqrt{1-\chi^2}}$).
- * The gauge sector Lagrangian is **diagonal**,

$$\mathcal{L}_{\text{HAH,Gauge}} = -\frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4} \tilde{B}_{\mu\nu} \tilde{B}^{\mu\nu} - \frac{1}{4} \tilde{X}_{\mu\nu} \tilde{X}^{\mu\nu}.$$

Model description (4)

- **Symmetry breaking to $U(1)_{EM}$.**

- * Both Higgs fields acquire their vev \mathbf{v} and ξ .

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

- * **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.

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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 $\tilde{X}_\mu, \tilde{B}_\mu, B_\mu, W_\mu^3$ 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.
- * **T_EX-form** (for the T_EX-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]
```

```
WriteW0Output[Lag]
```

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Validation procedure - the four-star system (LH 2009).

- **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, COMPHHEP, MADGRAPH/MADEVENT, SHERPA and WHIZARD results

Process	CalCHEP	CalCHEP	CalCHEP	CompHEP	MadGraph	MadGraph	Sherpa	Whizard	Whizard	Whizard	
	Stock	Feynman	Unitary	Feynman	Stock	Unitary	Stock	Stock	Feynman	Unitary	
gg->gg	116 490.	116 490.	116 490.	116 490.	116 680.	116 120.	116 490	115 031.	116 585.	116 642.	Discrepancy!
uu->gg	199.95	199.95	199.95	199.94	200.21	199.77	199.963	199.693	199.693	199.693	
tE->gg	64.595	64.595	64.595	64.592	64.467	64.537	64.5856	64.623	64.5601	64.5601	
e ⁺ e ⁻ ->μ ⁺ μ ⁻	0.37194	0.37195	0.37195	0.37194	0.37202	0.37148	0.372011	0.372034	0.372028	0.372028	
e ⁺ e ⁻ ->e ⁺ e ⁻	734.15	734.15	734.15	734.16	733.96	734.47	734.314	734.622	734.609	734.609	
e ⁺ e ⁻ ->ν _e ν _e	49.143	49.145	49.145	49.145	results	results	49.1361	49.1139	49.1184	49.1184	
tE->uu	16.018	16.018	16.018	16.018	16.012	16.022	16.0204	16.0214	16.0214	16.0214	
uu->ss	9.7634	9.7634	9.7634	9.7631	9.7631	9.7692	9.76376	9.76348	9.76346	9.76348	
ud->cb	0.3531	0.35311	0.35311	0.35312	0.35274	0.35318	0.353149	0.353212	0.353215	0.353215	
us->cd	0.0010187	0.0010187	0.0010187	0.0010187	0.0010186	0.0010182	0.00101879	0.00101897	0.00101898	0.00101898	
W ⁺ W ⁻ ->tE	44.534	44.535	44.535	44.534	44.647	44.485	44.5503	44.4991	44.4992	44.4992	
tE->ZZ	1.2534	1.2534	1.2534	1.2534	1.254	1.2559	1.25321	1.25431	1.25432	1.25432	
tE->Zγ	1.3119	1.3119	1.3119	1.312	1.3139	1.3113	1.31197	1.31261	1.31202	1.31202	
tE->γγ	0.088486	0.088486	0.088486	0.088485	0.088527	0.088462	0.0884835	0.0884519	0.0884983	0.0884983	
uu->W ⁺ W ⁻	1.7736	1.7737	1.7737	1.7737	1.7698	1.776	1.77424	1.77412	1.77413	1.77413	
uu->ZZ	0.19345	0.19347	0.19347	0.19346	0.19357	0.19318	0.193462	0.192923	0.192927	0.192927	
uu->Zγ	0.33811	0.33812	0.33812	0.33811	0.3381	0.3384	0.334504	0.338125	0.338124	0.338124	Discrepancy!
uu->γγ	0.18322	0.18322	0.18322	0.18323	0.18332	0.18329	0.183224	0.183377	0.183373	0.183373	
z ⁺ z ⁻ ->W ⁺ W ⁻	5.3681	5.3684	5.3684	5.3686	5.3517	5.3637	5.36799	5.36556	5.3656	5.3656	
z ⁺ z ⁻ ->ZZ	0.31816	0.31817	0.31817	0.31816	0.31852	0.31805	0.318256	0.31799	0.317993	0.317993	
z ⁺ z ⁻ ->Zγ	2.0057	2.0057	2.0057	2.0057	2.0083	2.0044	1.98453	1.99948	2.00799	2.00799	Discrepancy!
z ⁺ z ⁻ ->γγ	2.7791	2.7791	2.7791	2.779	2.7773	2.7756	2.77911	2.77248	2.77711	2.77711	
ZZ->ZZ	1.9606	1.9606	1.9606	1.9606	1.9565	1.9555	1.96071	1.96046	1.96046	1.96046	
W ⁺ W ⁻ ->γγ	20.825	20.825	20.825	20.824	20.827	20.804	20.8182	20.8527	20.8171	20.8171	
W ⁺ W ⁻ ->ZZ	272.62	272.63	272.63	272.62	272.36	272.11	272.694	272.422	272.425	272.425	
W ⁺ W ⁻ ->W ⁺ W ⁻	1318.1	1318.2	1318.2	1318.2	1317.2	1318.8	1318.45	1320.05	1320.03	1320.03	
hh->hh	1.8569	1.857	1.857	1.857	-	1.8567	1.85587	1.86179	1.86179	1.86179	
ZZ->hh	6.3027	6.3029	6.3029	6.3029	6.311	6.3137	6.30265	6.29227	6.31003	6.31003	
hh->W ⁺ W ⁻	94.47	94.473	94.473	94.473	94.815	94.833	94.5793	94.5073	94.5077	94.5077	

R-parity violating MSSM

- **Implementation in FEYNRULES** (not public).
 - * **Full superpotential.**
 - * **Full SUSY-breaking Lagrangian.**
 - * **General mixings.**
 - ◇ Neutrinos/neutralinos & charged leptons/charginos.
 - ◇ Neutral Higgses/sneutrinos & charged Higgses/charged sleptons.
 - ◇ **The neutralino/chargino sector will be rewritten.**
 - * **105 + 192 free parameters.**
 - ◇ The **SLHA-FR format** (SLHA2-like format).
 - ◇ C++ translator SLHA1/2 \Leftrightarrow SLHA-FR (**not yet there**).
 - * **One bug found** \Rightarrow being corrected.
- **MADGRAPH model files.**
 - * Created with one single R-parity violating parameter (λ''_{ijk})
[8 hours with a 8GB RAM machine \Rightarrow AAARRGGGHHH?].
 - * **The model files are compiling** [with normal machines].
 - * **To do: validation against (PYTHIA)/HERWIG/SUSYGEN.**
- **CALCHEP, FEYNARTS, SHERPA, WHIZARD model files.**
 - * **On the to-do list.**

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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 \rightarrow FEYNRULES \rightarrow model files for your favourite MC codes.
 - 2) Monte Carlo code \rightarrow 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...

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 - 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 T_EX -file).
- * **Complex/real** parameters.
- * **External/internal** parameters.

Example: QCD - Quark fields (Dirac fermions)

The quark fields

```
F[1] == {
  ClassName      -> q,
  ClassMembers   -> {d, u, s, c, b, t},
  FlavorIndex    -> Flavour,
  SelfConjugate  -> False,
  Indices        -> {Index[Flavour], Index[Colour]},
  WeylComponents -> {qL, qRbar},
  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 - Quark fields (Weyl fermions)

The quark fields

```
W[1] == {
  ClassName      -> qL,
  Chirality      -> Left,
  SelfConjugate  -> False,
  Indices        -> {Index[Flavour], Index[Colour]},
  FlavorIndex    -> Flavour,
  ClassMembers   -> {dL,uL,sL,cL,bL,tL},
  Unphysical     -> True},
W[2] == {
  ClassName      -> qR,
  Chirality      -> Left,
  SelfConjugate  -> False,
  Indices        -> {Index[Flavour], Index[Colour]},
  FlavorIndex    -> Flavour,
  ClassMembers   -> {dR,uR,sR,cR,bR,tR},
  Unphysical     -> True}
```

Example: QCD - Lagrangian

QCD Lagrangian:

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \sum_f \left[\bar{q}_f (i\not{\partial} + g_s \not{G}^a T^a - m_f) q_f \right].$$

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] ;
```

```
LQCDW = -1/4 * FS[G, mu, nu, a] * FS[G, mu, nu, a] +
```

```
I qR.Si[mu].DC[qRbar, mu] + I qLbar.Sibar[mu].DC[qL, mu] -
```

```
MQ[f] * (qR[s,f,c].qL[s,f,c] + qRbar[s,f,c].qLbar[s,f,c]);
```

* **Implicit summations** ⇒ easy debugging.

Example: QCD - Results

Results - let us do (some) phenomenology!

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

Vertex 1

Particle 1 : Vector , G

Particle 2 : Dirac , q†

Particle 3 : Dirac , q

Vertex:

$$i g_s \gamma_{s_2, s_3}^{\mu_1} \delta_{f_2, f_3} T_{m_2, m_3}^a$$

```
WriteFeynArtsOutput[LQCD]
```

```
WriteCHOutput[LQCD]
```

```
WriteMGOutput[LQCD]
```

```
WriteSHOutput[LQCD]
```

```
WriteWOOOutput[LQCD]
```

The (almost) most general MSSM - model

- **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 version 1.2.0.**

$$\left(\tilde{h}_1, \tilde{h}_2, \tilde{h}_3 \right)^T = R^h \left(\sqrt{2} \Re\{H_1^0\}, \sqrt{2} \Re\{H_2^0\}, A_{\text{tree}}^0 \right)^T$$

- * **Gaugino/higgsino sector.**

- ◇ Written in the mass basis (contrary to the rest of the Lagrangian).

- ◇ **Is changed, in version 1.1.4** (present development version).

- **105 free parameters.**

- * The **SLHA-FR format** (SLHA2-like format).

- * C++ translator SLHA1/2 \Leftrightarrow SLHA-FR (**v1.2.0 is coming**).

The (almost) most general MSSM - validation [Duhr, BenjF].

- **Handmade vs. automated implementation.**

- * 2522 vertices, without the four-scalar interactions.
- * **More than 10000 vertices, with the four-scalar interactions !!!**

- **FEYNARTS/FORMCALC.**

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

- **MADGRAPH/MADEVENT** (in the cMSSM limit):

- * MG-Stock was validated by the CATPISS collaboration [Hagiwara *et al.* (2006)].

- ✓ **320 decay widths.**
- ✓ **626 $2 \rightarrow 2$ SUSY processes.**
- ✓ **2708 $2 \rightarrow 3$ SUSY processes.**

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

- **TO DO:** check the general MSSM.

- ◇ With XSUSY [BenjF, Herrmann (in prep.)]
- ◇ With the stock version of WHIZARD [Herrmann].

- **CALCHEP/COMPHEP** (in the cMSSM):

- ✗ **626 $2 \rightarrow 2$ SUSY processes \Rightarrow Bugs found in the stock version!**

The (almost) most general MSSM - validation [Duhr, BenJF].

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

The (almost) most general MSSM - to do list [Duhr, BenjF].

- **From an almost most general model to the most general one.**
 - * Generalization of the **Higgs sector**.
- **MADGRAPH/MADEVENT and CALCHEP/COMPHEP.**
 - * **Check with XSUSY and WHIZARD** for the general model case.
- **SHERPA:**
 - * **Ongoing validation:** one issue related to Majorana particles remaining.
[+ possible hidden stuff].
- **WHIZARD:**
 - * **Starting validation** (the FR-interface must be validated at the same time).
- **We have automatically generated model files for several tools.**
 - * CALCHEP/COMPHEP.
 - * FEYNARTS/FORMCALC.
 - * MADGRAPH/MADEVENT.
 - * SHERPA (?).
 - * WHIZARD (?).
 - * **Can be used for phenomenology.**
 - * Stock versions are working too.