Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

BSM phenomenology with FeynRules

Claude Duhr

in collaboration with N. Christensen and B. Fuks

SLAC, 16/11/2011

BSM @ LHC

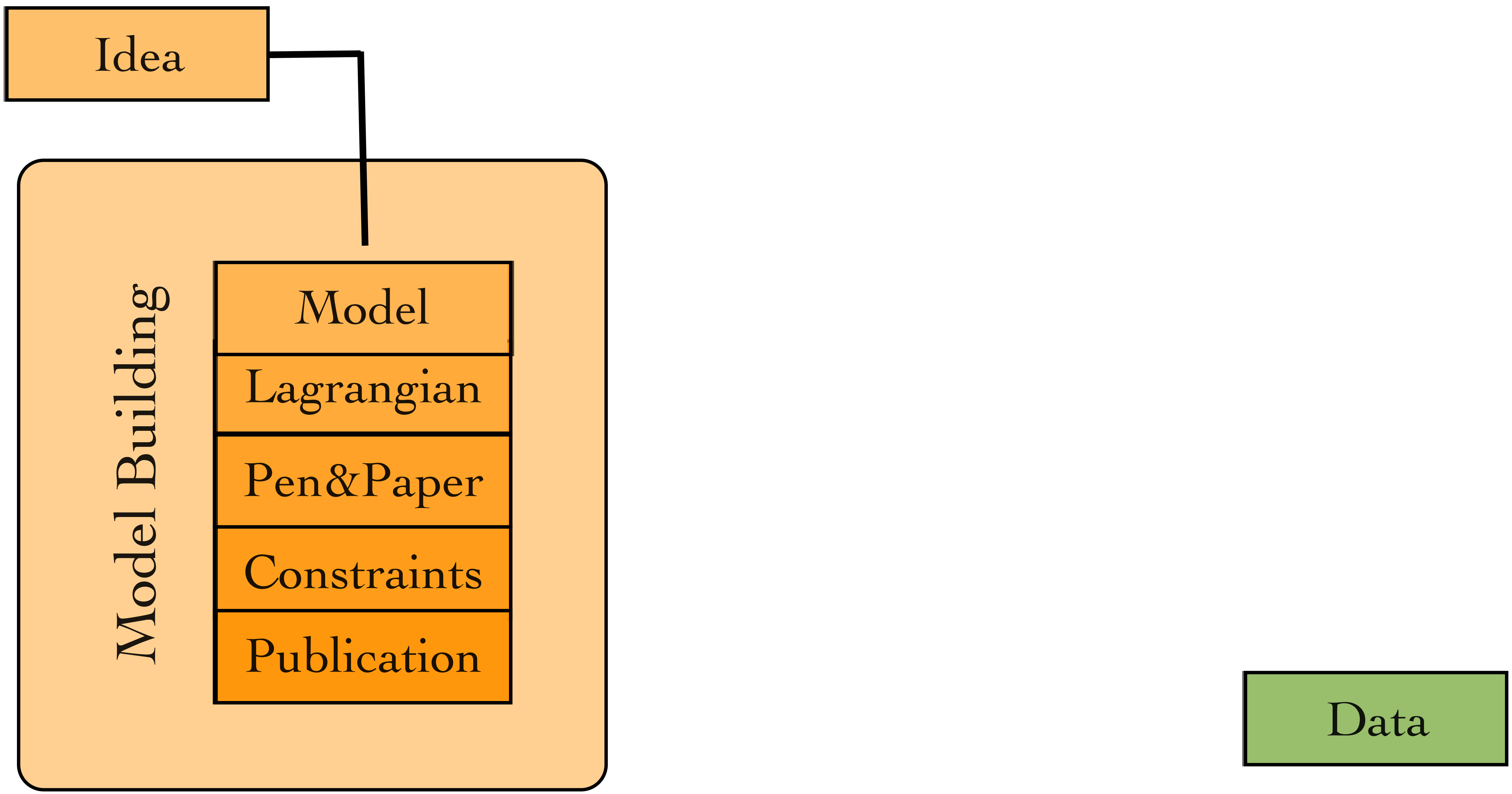
- So far, the LHC has found no signal of Physics Beyond the SM.
- As the MSSM parameter space gets more and more constraint, we have to start thinking about new BSM models.
- Already now, the number of proposed BSM scenarios is huge!
- Even more are to come when an excess of the SM will be observed at the LHC.

BSM @ LHC

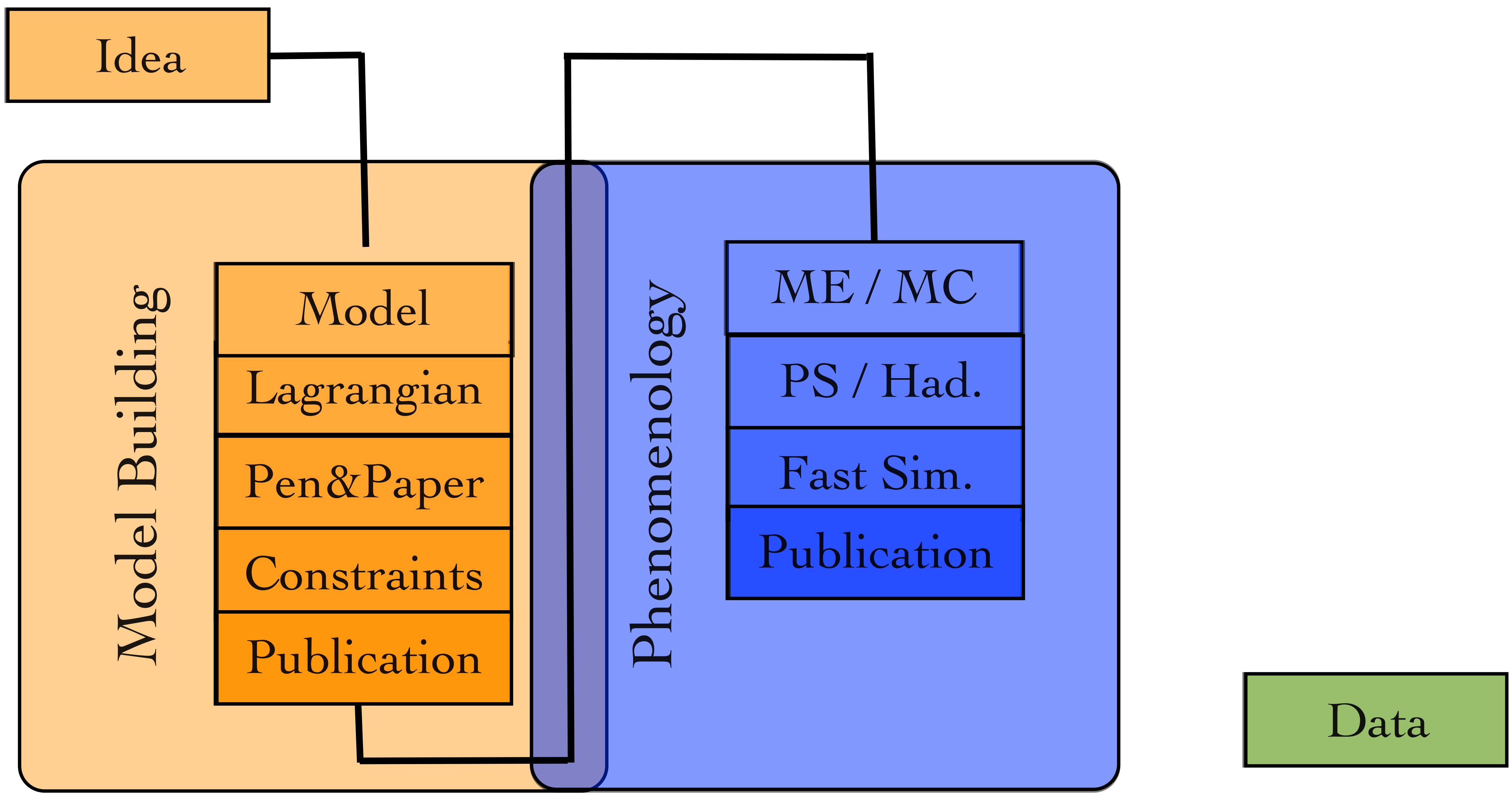
Idea

Data

BSM @ LHC


Idea
Model Building
Model
Lagrangian
Pen&Paper
Constraints
Publication
Data

BSM @ LHC



Idea
Model Building
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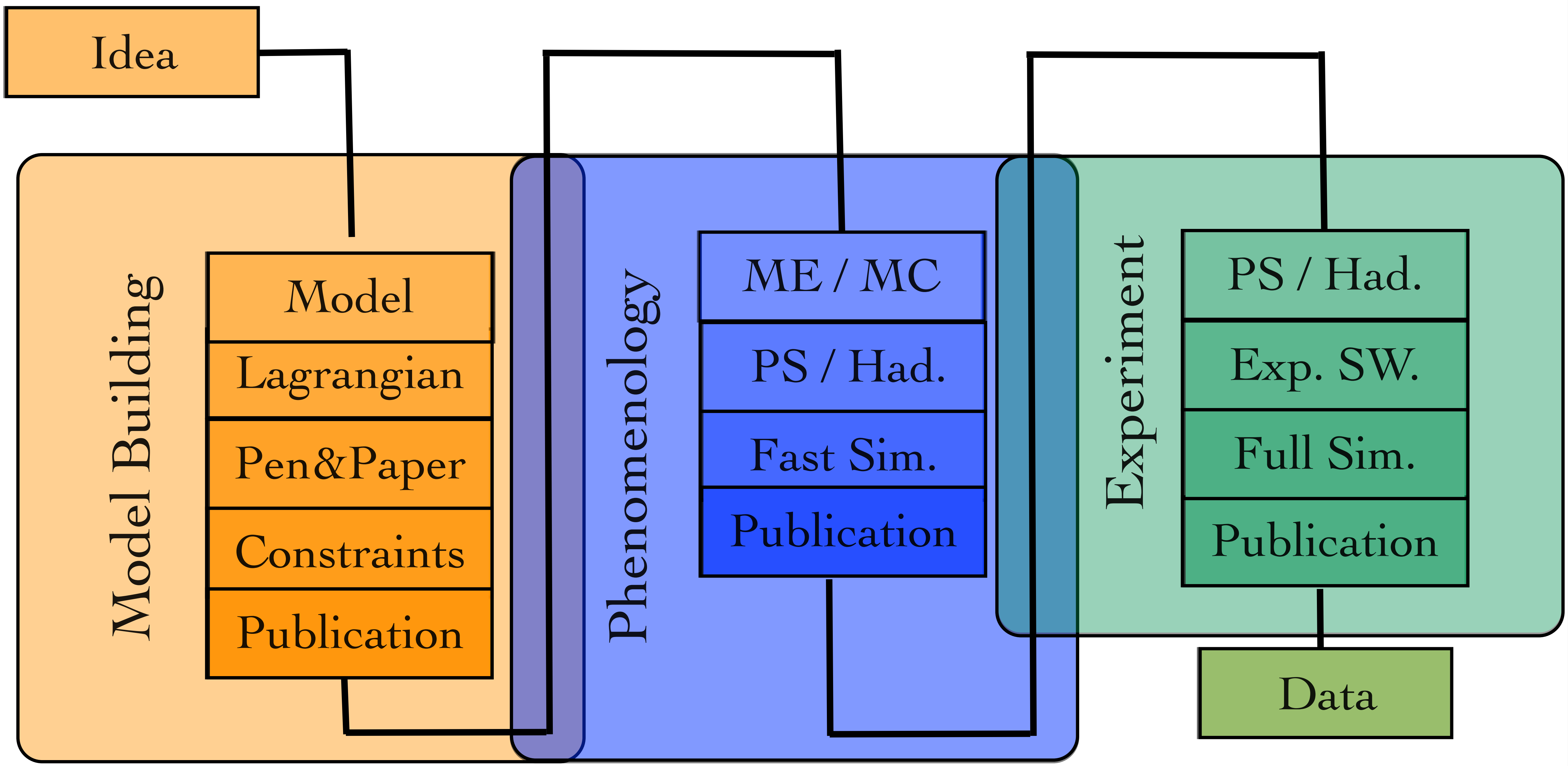
Phenomenology
ME / MC
PS / Had.
Fast Sim.
Publication
Data

BSM @ LHC



Idea
Model Building
Model
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Publication
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ME / MC
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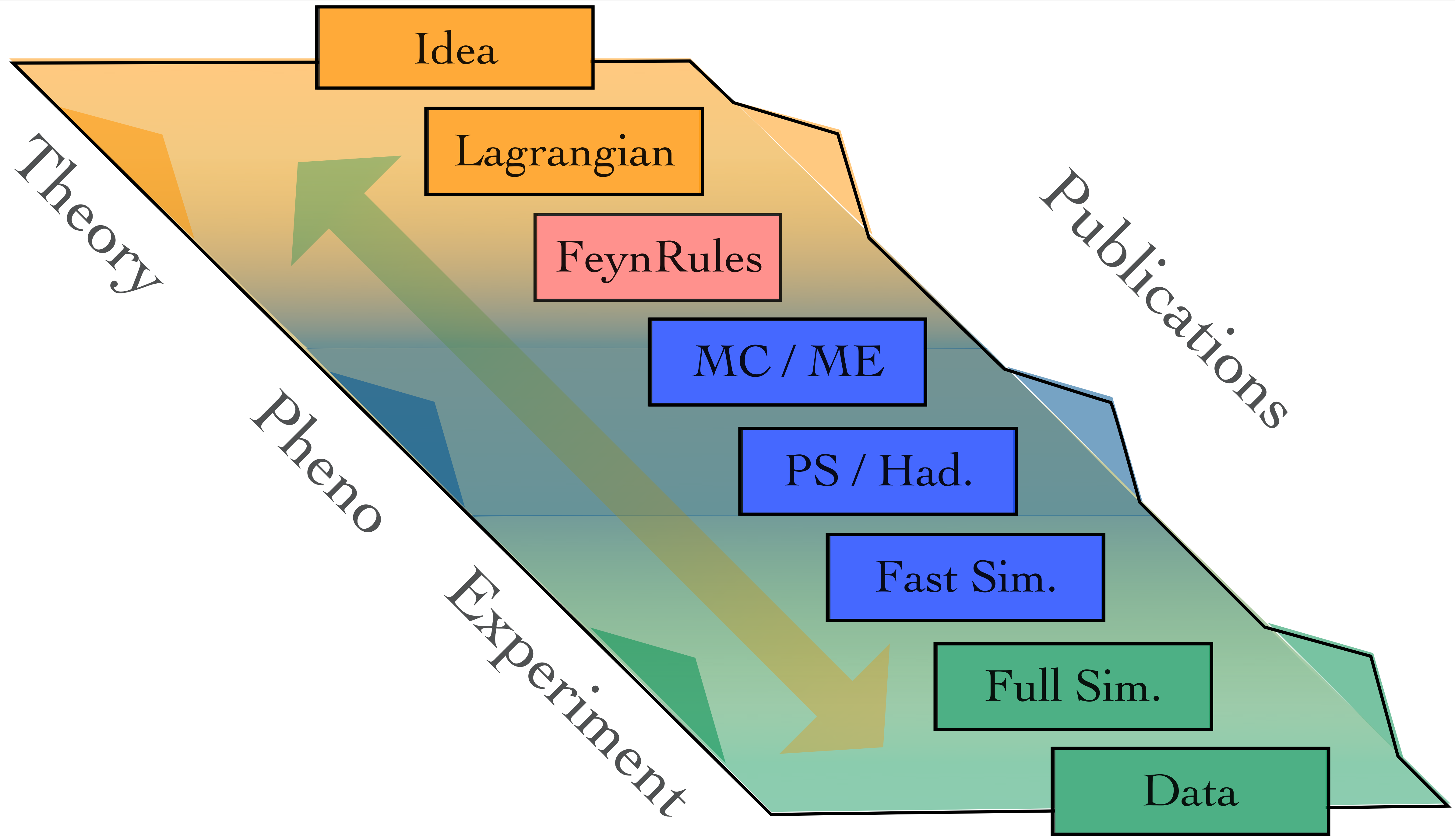
Fast Sim.
Publication
Experiment
PS / Had.
Exp. SW.
Full Sim.
Publication
Data

BSM @ LHC

- Workload is tripled, due to disconnected fields of expertise.
- Error-prone, painful validation at each step.
- Proliferation of private MC's/Pythia tunings:
  - ➡ No clear documentation.
  - ➡ Not traceable.
- We need more than just papers to communicate between theorists and experimentalists!

BSM @ LHC


Idea
Lagrangian
FeynRules
MC / ME
PS / Had.
Fast Sim.
Full Sim.
Data
Theory
Pheno
Experiment
Publications

Outline

- FeynRules in a nutshell.
- Recent developments:
  - ➡ Superfields.
  - ➡ UFO & ALOHA.
- Model database and validation
- Future developments: Towards 'FR@NLO'.

FeynRules
in a nutshell

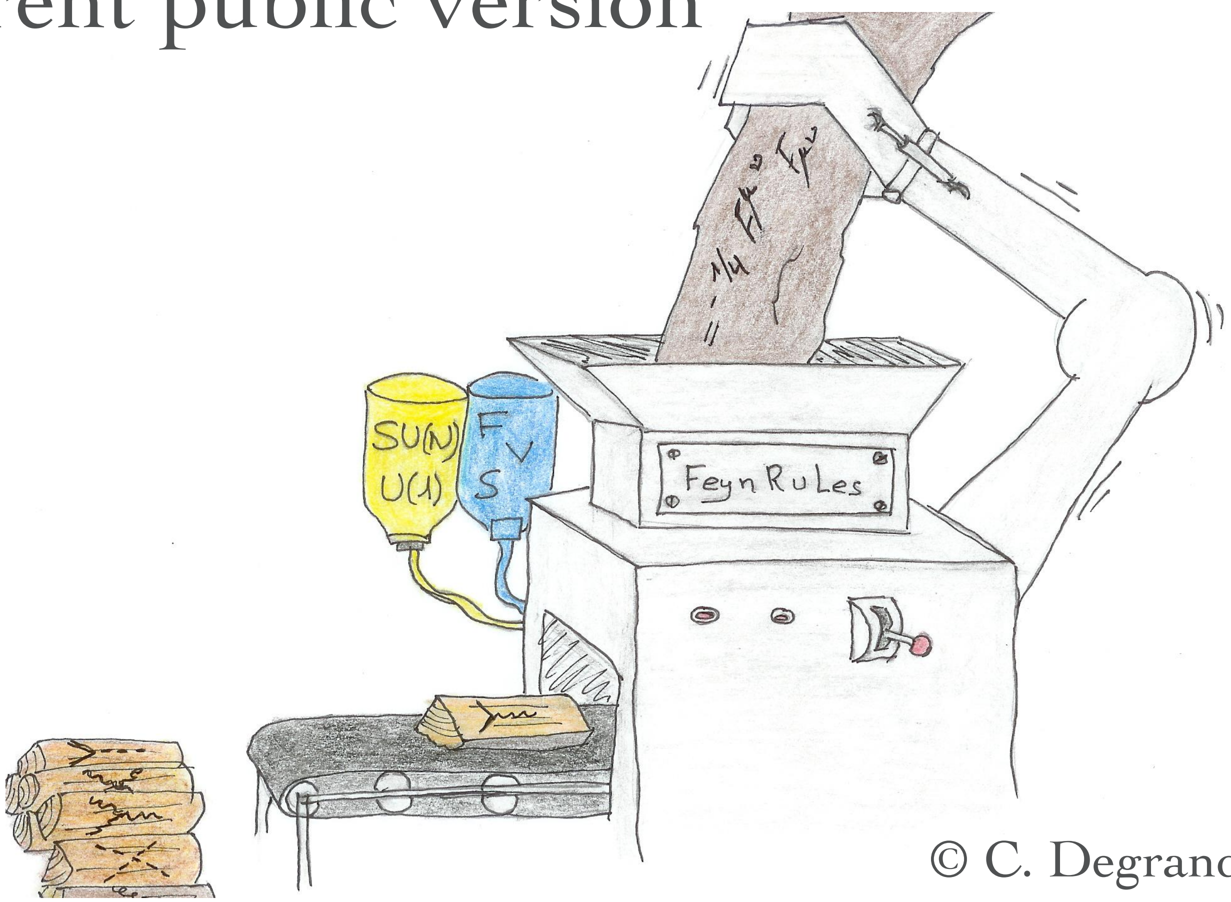
FeynRules in a nutshell

- FeynRules is a Mathematica package that allows to derive Feynman rules from a Lagrangian.
- Current public version: 1.6.x, available from

  http://feynrules.phys.ucl.ac.be
- The only requirements on the Lagrangian are:
  - ➡ All indices need to be contracted (Lorentz and gauge invariance)
  - ➡ Locality
  - ➡ Supported field types: spin 0, 1/2, 1, 2 & ghosts

FeynRules in a nutshell

- FeynRules comes with a set of interfaces, that allow to export the Feynman rules to various matrix element generators.
- Interfaces coming with current public version
  - ➡ CalcHep / CompHep
  - ➡ FeynArts / FormCalc
  - ➡ MadGraph 4
  - ➡ Sherpa
  - ➡ Whizard / Omega



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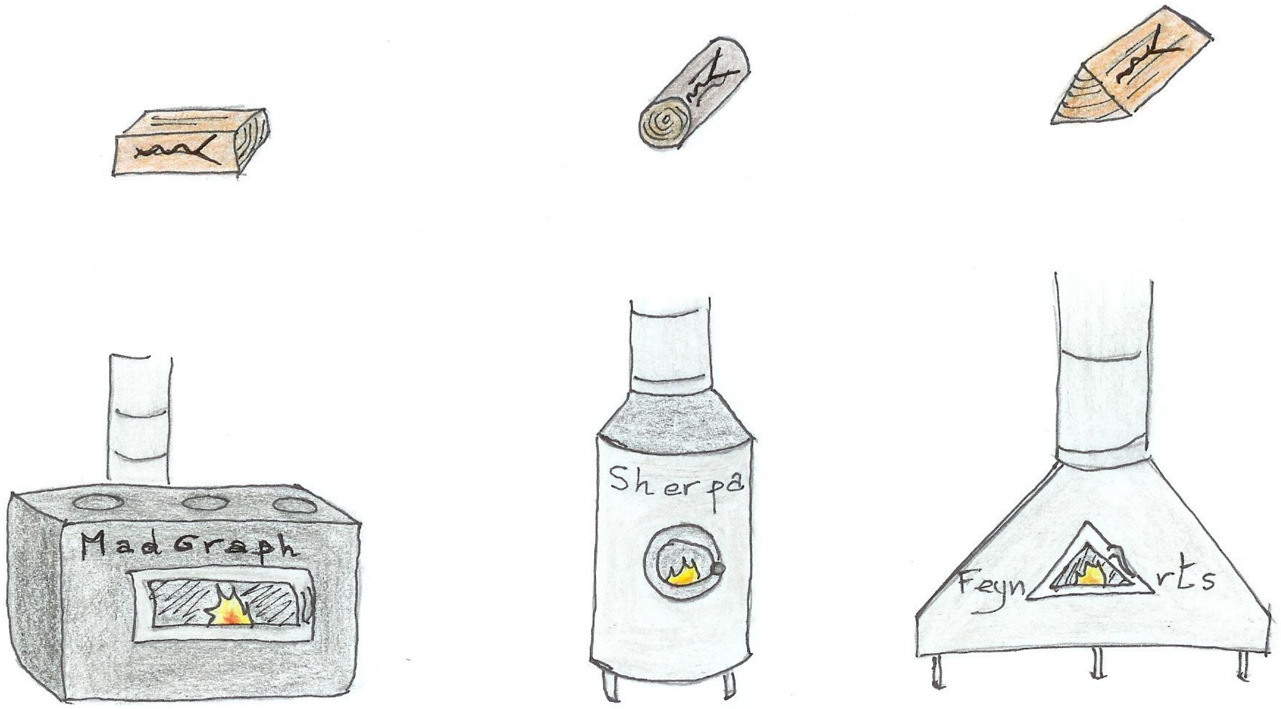

FeynRules in a nutshell

- The input requested form the user is twofold.

- The Model File:
  Definitions of particles and parameters (e.g., a quark)

```
F[1]  ==
  {ClassName      ->   q,
   SelfConjugate ->  False,
   Indices           ->  {Index[Colour]},
   Mass               ->  {MQ,  200},
   Width             ->  {WQ, 5}   }
```

- The Lagrangian:

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu}\, G_a^{\mu\nu} + i\bar{q}\,\gamma^\mu\, D_\mu q - M_q\,\bar{q}\,q$$

```
L =
-1/4 FS[G,mu,nu,a] FS[G,mu,nu,a]
+ I qbar.Ga[mu].del[q,mu]
- MQ qbar.q
```

FeynRules in a nutshell

- Once this information has been provided, FeynRules can be used to compute the Feynman rules for the model:

```
FeynmanRules[ L ]
```

FeynRules in a nutshell

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```
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```

Vertex 1

Particle 1 : Vector , G

Particle 2 : Dirac , $q^{\dagger}$

Particle 3 : Dirac , q

Vertex:

$$i\, \mathrm{gs}\, \gamma^{\mu_1}{}_{s_2,s_3}\, \delta_{f_2,f_3}\, T^{a_1}{}_{i_2,i_3}$$

FeynRules in a nutshell

- Equivalently, we can export the Feynman rules to a matrix element generator, e.g., for MadGraph 4,

WriteMGOutput[L]

- This produces a set of files that can be directly used in the matrix element generator (“plug ‘n’ play”).

interactions.dat

```
  q  q G      GG        QCD
   G G G     MGVX1  QCD
G G G G      MGVX2  QCD QCD
```

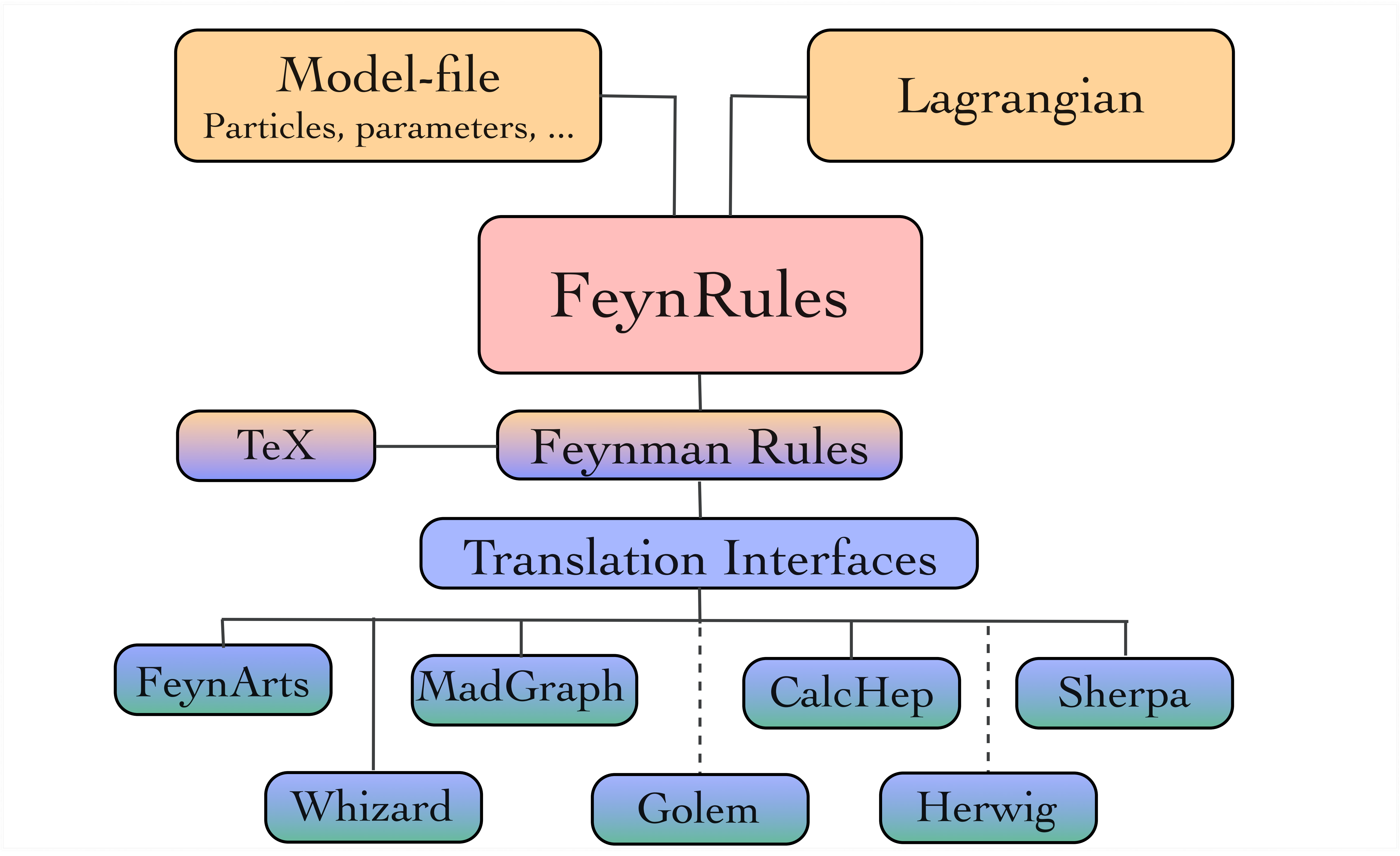
particles.dat

```
q   q~  F   S   ZERO  ZERO  T   d   1
G   G    V  C   ZERO  ZERO  O   G  21
```

couplings.dat

```
GG(1)   =  -G
GG(1)   =  -G
MGVX1 = G
MGVX2 = G^2
```

FeynRules


Model-file
Particles, parameters, ...
Lagrangian
FeynRules
TeX
Feynman Rules
Translation Interfaces
FeynArts
MadGraph
CalcHep
Sherpa
Whizard
Golem
Herwig

FeynRules in a nutshell

- The ‘old’ FeynRules version already did a good job, but it presented various obstacles…
  - ➡ Lagrangian needs to be entered in component fields.
  - ➡ Existing model formats and interfaces did not accommodate higher-dimensional operators.

- These issues have recently been solved!

Recent developments

Superfields

- FeynRules 1.4.x required the Lagrangian to be written in component fields.

Superfields

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$$\mathcal{L} = \Phi^\dagger e^{-2gV}\Phi_{|_{\theta^2\bar{\theta}^2}} + \frac{1}{16g^2\tau_{\mathcal{R}}}\mathrm{Tr}(W^\alpha W_\alpha)_{|_{\theta^2}} + \frac{1}{16g^2\tau_{\mathcal{R}}}\mathrm{Tr}(\bar{W}_{\dot{\alpha}}\bar{W}^{\dot{\alpha}})_{|_{\bar{\theta}^2}}$$

$$+ W(\Phi)_{|_{\theta^2}} + W^\star(\Phi^\dagger)_{|_{\bar{\theta}^2}} + \mathcal{L}_{\mathrm{soft}}$$

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$$+ W(\Phi)_{|_{\theta^2}} + W^\star(\Phi^\dagger)_{|_{\bar\theta^2}} + \mathcal{L}_{\mathrm{soft}}$$

- ‘Monte Carlo description’:
  - ➡ Express superfields in terms of component fields.
  - ➡ Express everything in terms of 4-component fermions (beware of the Majoranas!).
  - ➡ Integrate out D and F terms.

Superfields

- FeynRules 1.6.x allows to define superfields directly:

```
CSF[1] == { ClassName  -> ER,
            Chirality      -> Left,
            Weyl             -> ERw,
            Scalar           -> ERs,
            QuantumNumbers -> {Y-> 1},
            Indices         -> {Index[GEN]}
          }
```

- The F term does not need to be defined, but is added automatically.
- Once the superfields (and their component fields) have been defined, FeynRules takes care of the rest.

Superfields

- Once the superfields (and their component fields) have been defined, FeynRules takes care of the rest.
  - ➡ Expands the superfields in Grassmann parameters.
  - ➡ Integrates out the Grassmann parameters.
  - ➡ Integrates out the D and F terms.
  - ➡ Transforms Weyl fermions into Dirac and Majorana fermions.
  - ➡ Computes the Feynman rules.
- The implementation of a SUSY model is now straightforward!

Higher-dimensional operators

- Even though FeynRules 1.4.x could already compute the Feynman rules for higher-dimensional operators, they were 'useless', in the sense that they could be exported to almost no Monte Carlo code.
- Reason: Most Monte Carlo codes have internal limitations for the vertices:
  - ➡ hardcoded library of color and/or Lorentz structures.
  - ➡ Upper limit on the number of particles enter in a vertex (usually 4).
- To overcome this problem, a joint effort between the FeynRules team and the MC developers was needed!

The Universal FeynRules Output

UFO = Universal FeynRules Output

- Idea: Create Python modules that can be linked to other codes and contain all the information on a given model.
- The UFO is a self-contained Python code, and not tied to a specific matrix element generator.
- The content of the FR model files, together with the vertices, is translated into a library of Python objects, that can be linked to other codes.
- By design, the UFO does not make any assumptions on Lorentz/color structures, or the number of particles.
- GoSam and MadGraph 5 use the UFO as the default model format.

The UFO & ALOHA

- The development of the UFO goes hand in hand with the development of ALOHA.
- Idea: ALOHA uses the information contained in the UFO to create the (previously-hardcoded) library of Lorentz structures for MadGraph 5 on the fly.

The UFO & ALOHA

- The development of the UFO goes hand in hand with the development of ALOHA.
- Idea: ALOHA uses the information contained in the UFO to create the (previously-hardcoded) library of Lorentz structures for MadGraph 5 on the fly.

```
FFV1 = Lorentz(name = 'FFV1',
               spins = [ 2, 2, 3 ],
               structure = 'Gamma(3,2,1)')
```

The UFO & ALOHA

```
C    This File is Automatically generated by ALOHA
C    The process calculated in this file is:
C    Gamma(3,2,1)
C
      SUBROUTINE FFV1_0(F1,F2,V3,COUP,VERTEX)
      IMPLICIT NONE
      DOUBLE COMPLEX F1(*)
      DOUBLE COMPLEX F2(*)
      DOUBLE COMPLEX V3(*)
      DOUBLE COMPLEX COUP
      DOUBLE COMPLEX VERTEX


      VERTEX = COUP*( (F2(1)*( (F1(3)*( (0, -1)*V3(1)+(0, 1)*V3(4)))
     $ +(F1(4)*( (0, 1)*V3(2)+V3(3)))))+( (F2(2)*( (F1(3)*( (0, 1)
     $ *V3(2)-V3(3)))+(F1(4)*( (0, -1)*V3(1)+(0, -1)*V3(4)))))
     $ +( (F2(3)*( (F1(1)*( (0, -1)*V3(1)+(0, -1)*V3(4)))+(F1(2)
     $ *( (0, -1)*V3(2)-V3(3)))))+(F2(4)*( (F1(1)*( (0, -1)*V3(2)
     $ +V3(3)))+(F1(2)*( (0, -1)*V3(1)+(0, 1)*V3(4)))))))
      END
```

The UFO & ALOHA

- Example: $\mathcal{L} = g_1 \, \Phi \, \bar{Q}_L \sigma^{\mu\nu} T^a t_R \, G^a_{\mu\nu}$

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- FeynRules input:

```
L = g1 Phi[i]  QLbar[s1, i, f, c1].tR [s2, f, c2]
    Si[mu,nu,s1,s2] T[a,c1,c2]  FS[G[mu,nu,a]]
```

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- Run the interface:

```
WriteUFO[ LSM + L ]
```

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```

- Run the interface:

```
WriteUFO[ LSM + L ]
```

- Run MadGraph 5 (no user intervention needed!)

The UFO & ALOHA

```
mg5>import model dim6
```

```
mg5>generate g g > t t~ H
```

```
mg5>output
```

The UFO & ALOHA

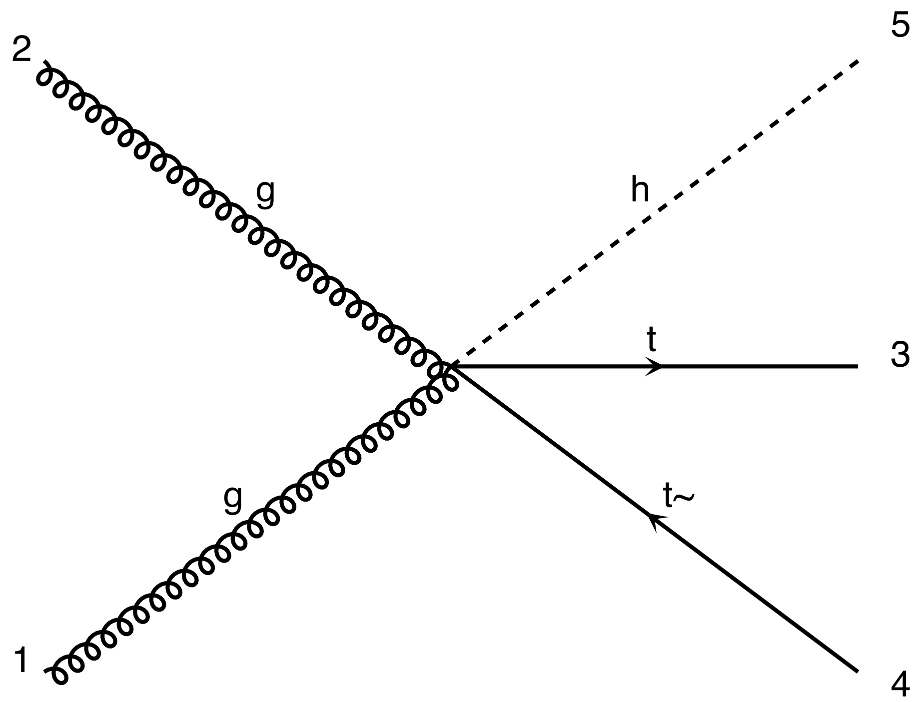
```
mg5>import model dim6
```

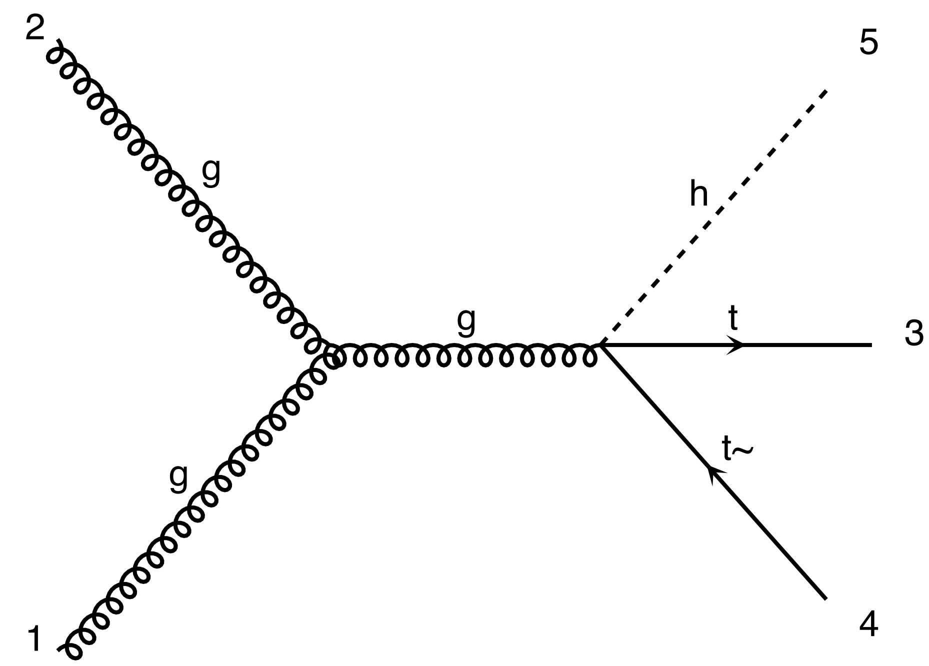
```
mg5>generate g g > t t~ H
```

```
mg5>output
```

```
INFO: Generating Helas calls for process: g g > t t~ h
INFO: Processing color information for process: g g > t t~ h
Export UFO model to MG4 format
ALOHA: aloha creates FFV8 routines
ALOHA: aloha creates FFVV8 routines
ALOHA: aloha creates FFVS2 routines
ALOHA: aloha creates FFVVS2 routines
```

The UFO & ALOHA





The model database

Model database

We encourage model builders writing
order to make them useful to a comm
FeynRules model database, please ser

- claude.duhr@durham.ac.uk
- neil@hep.wisc.edu
- fuks@cern.ch

Available models

Standard Model

Simple extensions of the SM (9)

Supersymmetric Models (4)

Extra-dimensional Models (4)

Strongly coupled and effective field theories (4)

Miscellaneous (0)

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Model	Contact
Higgs effective theory	C. Duhr
4th generation model	C. Duhr
Standard model + Scalars	C. Duhr
Hidden Abelian Higgs Model	C. Duhr
Hill Model	P. de Aquino, C. Duhr
The general 2HDM	C. Duhr, M. Herquet
Triplet diquarks	J. Alwall, C. Duhr
Sextet diquarks	J. Alwall, C. Duhr
Monotops	B. Fuks
Type III See-Saw Model	C. Biggio, F. Bonnet
DY SM extension	N. Christensen

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Extra-dimensional Models (4)

Strongly coupled and effective field theories (4)

Miscellaneous (0)

Model	Contact
MSSM	B. Fuks
NMSSM	B. Fuks
RPV-MSSM	B. Fuks
R-MSSM	B. Fuks

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- Miscellaneous (0)

Model	Contact
Mimimal Higgsless Model (3-Site Model)	N. Christensen
Minimal UED	P. de Aquino
Large Extra Dimensions	P. de Aquino
Compact HEIDI	C. Speckner

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FeynRules model database, please se

- claude.duhr@durham.ac.uk
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Available models

- Standard Model
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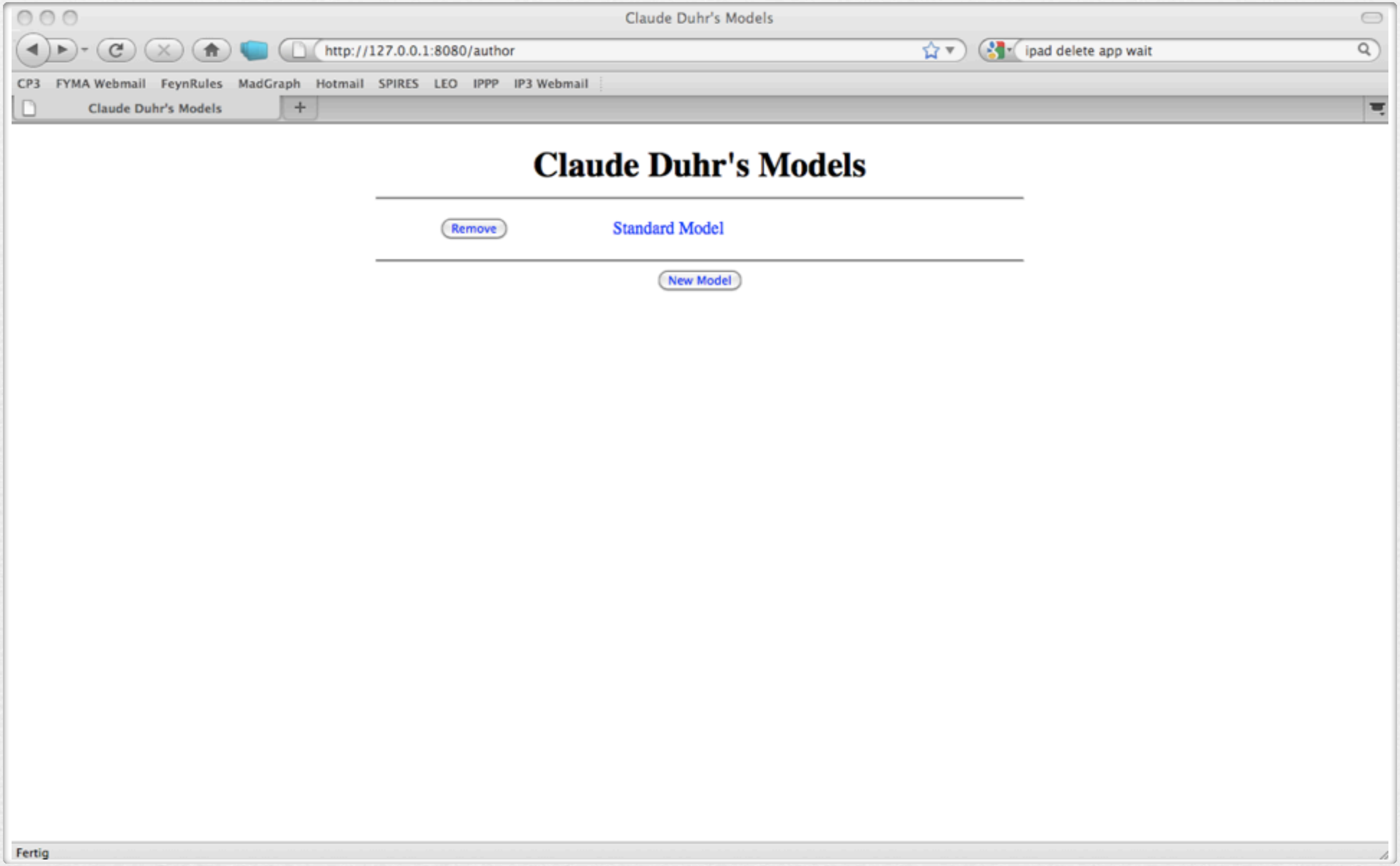
- Extra-dimensional Models (4)
- Strongly coupled and effective field theories (4)
- Miscellaneous (0)

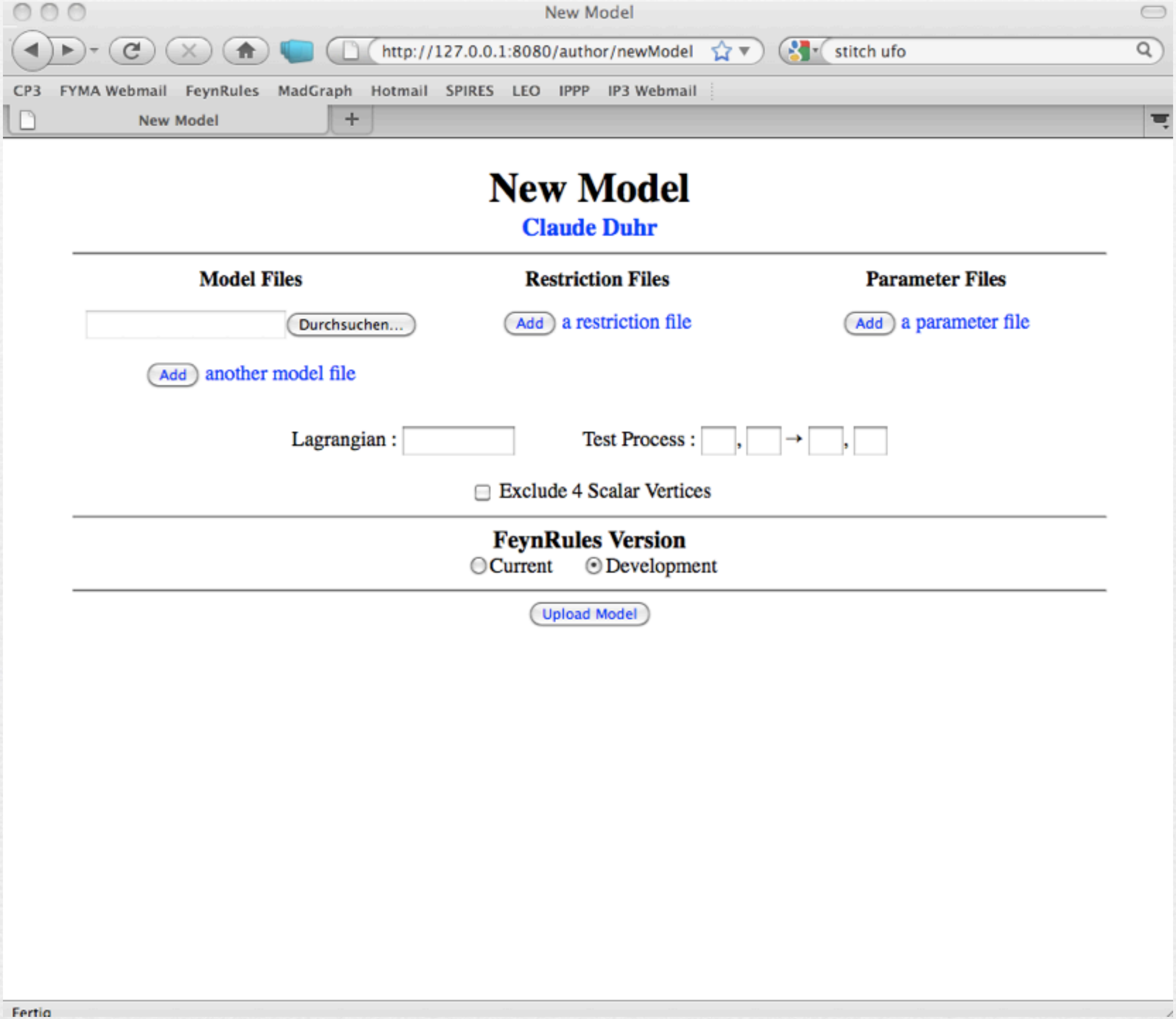
Model	Contact
Mimimal Higgsless Model (3-Site Model)	N. Christensen
Chiral perturbation theory	C. Degrande
Strongly Interacting Light Higgs	C. Degrande
Technicolor	M. Järvinen, T. Hapola, E. Del Nobile, C. Pica

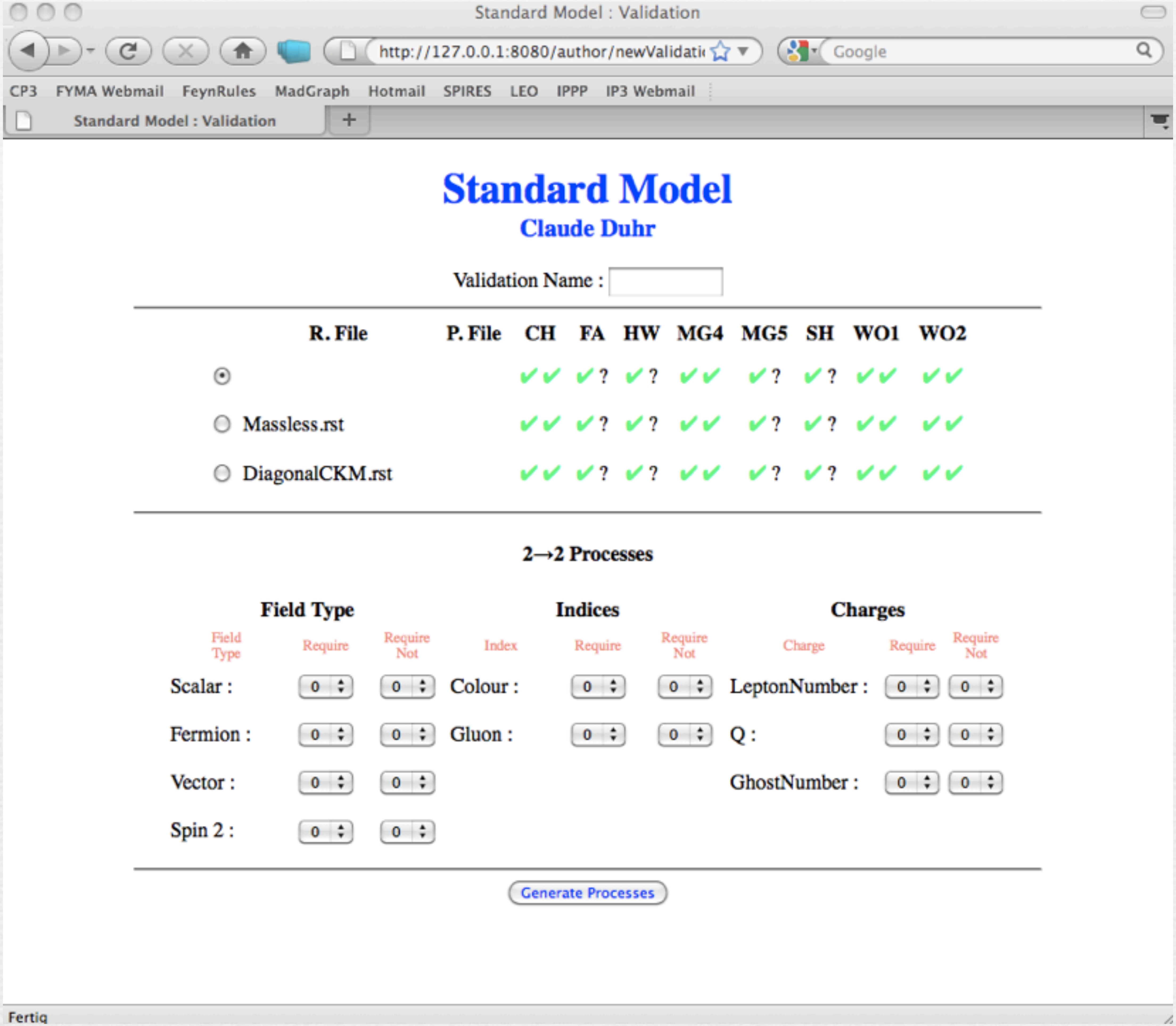
Validation of new models

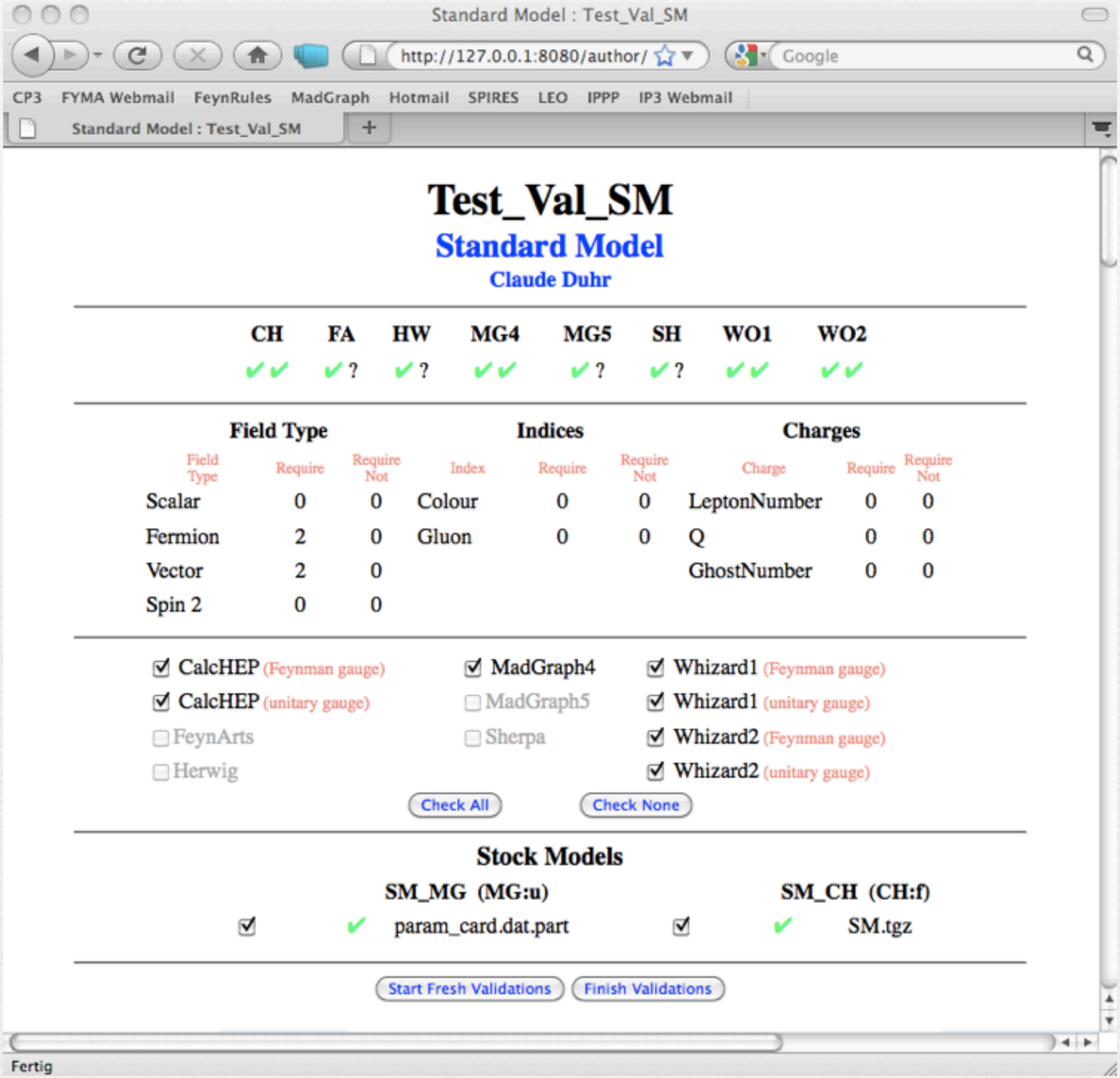
- FeynRules does not only provide the power to develop and validate new models, but also to validate them to an unprecedented level!
- A given model can be output to more than one matrix element generator, and their results can be compared
  - ➡ Different conventions
  - ➡ Different gauges
  - ➡ Different ways of handling large cancellations.
- This procedure can easily be automatized!

Web validation




New Model
http://127.0.0.1:8080/author/newModel
stitch ufo
CP3 FYMA Webmail FeynRules MadGraph Hotmail SPIRES LEO IPPP IP3 Webmail
New Model
New Model
Claude Duhr
Model Files
Restriction Files
Parameter Files
Durchsuchen...
Add a restriction file
Add a parameter file
Add another model file
Lagrangian :
Test Process : , → ,
Exclude 4 Scalar Vertices
FeynRules Version
Current
Development
Upload Model
Fertig


Standard Model : Validation
http://127.0.0.1:8080/author/newValidati
Google
CP3 FYMA Webmail FeynRules MadGraph Hotmail SPIRES LEO IPPP IP3 Webmail
Standard Model : Validation
Standard Model
Claude Duhr
Validation Name :
R. File P. File CH FA HW MG4 MG5 SH WO1 WO2
Massless.rst
DiagonalCKM.rst
2→2 Processes
Field Type
Indices
Charges
Field Type
Require
Require Not
Index
Charge
Scalar :
Fermion :
Vector :
Spin 2 :
Colour :
Gluon :
LeptonNumber :
Q :
GhostNumber :
Generate Processes
Fertig


Standard Model : Test_Val_SM
http://127.0.0.1:8080/author/
Google
CP3 FYMA Webmail FeynRules MadGraph Hotmail SPIRES LEO IPPP IP3 Webmail
Standard Model : Test_Val_SM
Test_Val_SM
Standard Model
Claude Duhr
CH FA HW MG4 MG5 SH WO1 WO2
? ? ? ?
Field Type
Field Type Require Require Not
Scalar 0 0
Fermion 2 0
Vector 2 0
Spin 2 0 0
Indices
Index Require Require Not
Colour 0 0
Gluon 0 0
Charges
Charge Require Require Not
LeptonNumber 0 0
Q 0 0
GhostNumber 0 0
CalcHEP (Feynman gauge)
CalcHEP (unitary gauge)
FeynArts
Herwig
MadGraph4
MadGraph5
Sherpa
Whizard1 (Feynman gauge)
Whizard1 (unitary gauge)
Whizard2 (Feynman gauge)
Whizard2 (unitary gauge)
Check All
Check None
Stock Models
SM_MG (MG:u)
param_card.dat.part
SM_CH (CH:f)
SM.tgz
Start Fresh Validations
Finish Validations
Fertig

Standard Model : Test_Val_SM

http://127.0.0.1:8080/author/validation?v

CP3 FYMA Webmail FeynRules MadGraph Hotmail SPIRES LEO IPPP IP3 Webmail

Standard Model : Test_Val_SM

ve , ve~ → Z , Z	730.0	182.5	0.49452	0.49452	0.49384	0.494604	0.494622	0.494547	0.494668	0.49351	0.4945	●	0.17%
ve , ve~ → W+ , W-	639.0	159.75	1.0603	1.0603	1.0604	1.06053	1.0604	1.06035	1.06073	1.0665	1.0603	●	0.51%
ve , ve~ → G , G	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vm~ → A , A	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vm~ → A , Z	365.0	91.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vm~ → Z , Z	730.0	182.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vm~ → W+ , W-	639.0	159.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vm~ → G , G	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vt~ → A , A	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vt~ → A , Z	365.0	91.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vt~ → Z , Z	730.0	182.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vt~ → W+ , W-	639.0	159.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , vt~ → G , G	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , e+ → A , W+	319.0	79.75	2.2219	1.9846	1.9809	1.98496	1.98478	1.98454	1.98491	1.9756	1.9845	✘	10.56%
ve , e+ → Z , W+	684.0	171.0	0.71578	0.54663	0.54717	0.54657	0.546756	0.54641	0.546869	0.54864	0.54661	✘	26.53%
ve , m+ → A , W+	320.0	80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , m+ → Z , W+	684.0	171.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , tt+ → A , W+	326.0	81.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
ve , tt+ → Z , W+	691.0	172.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
vm , vm~ → A , A	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
vm , vm~ → A , Z	365.0	91.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
vm , vm~ → Z , Z	730.0	182.5	0.49452	0.49452	0.49384	0.494505	0.494545	0.494559	0.494447	0.49351	0.4945	●	0.17%
vm , vm~ → W+ , W-	639.0	159.75	1.0603	1.0603	1.0604	1.0604	1.06033	1.06027	1.06006	1.0665	1.0603	●	0.52%
vm , vm~ → G , G	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
vm , vt~ → A , A	200.0	50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
vm , vt~ → A , Z	365.0	91.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
vm , vt~ → Z , Z	730.0	182.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%
vm , vt~ → W+ , W-	639.0	159.75	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	✔	0%

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A look into the future...

Towards NLO

- We are slowly getting to the point that we have automated tools for NLO computations:
  - ➡ Blackhat
  - ➡ GoSam
  - ➡ Helac-NLO
  - ➡ MadLoops
  - ➡ Rocket
- Most of these codes only do SM processes so far.
- Reason: Beyond LO, we do not only need tree-level Feynman rules, but also counterterms, etc.
- Future releases of FeynRules will allow to compute also these quantities!

Extraction of counterterms

- The (not public) development version of FeynRules already allows to extract counterterm Feynman rules.

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

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

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

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

- At the moment, the values of the counterterms for the independent parameters and the fields must still be given by hand.

- Once this is done, GoSam and MadLoops will allow to generate events for any BSM model at NLO.

Conclusion

- FeynRules provides a streamlined way to go from model building to experiment.
- The current version of FeynRules comes with a lot of new features:
  - ➡ Superfields
  - ➡ UFO & ALOHA
  - ➡ Support of color sextets.
  - ➡ Spin 3/2 (will be public soon)
- To download the package and/or model files, have a look at

  http://feynrules.phys.ucl.ac.be