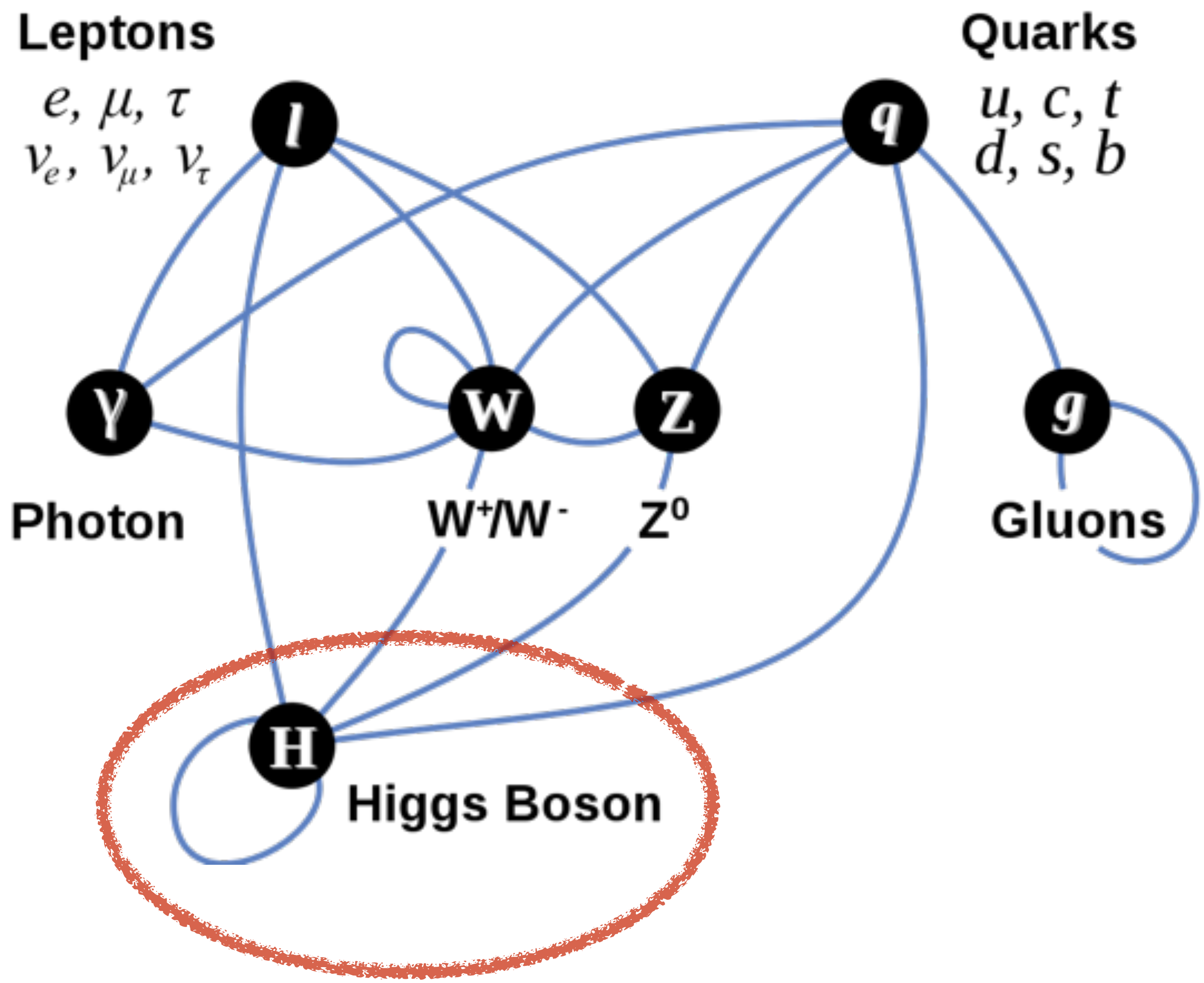
FeynRules

Neil Christensen

PITTsburgh Particle physics, Astrophysics and Cosmology Center (PITT PACC)

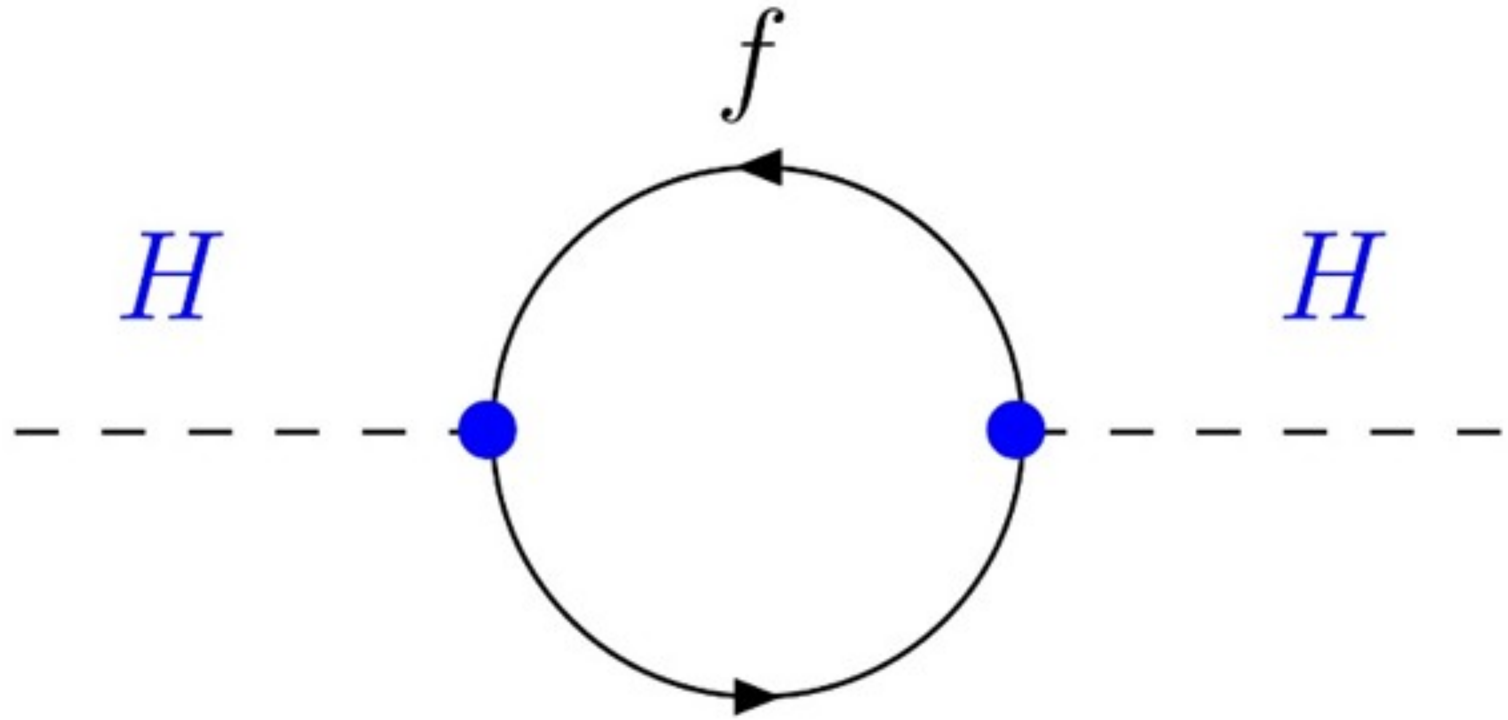
in collaboration with:

Adam Alloul, Celine DeGrande, Claude Duhr and Benjamin Fuks



The giant news of the last year is that we have discovered the Higgs boson!

Is it the SM Higgs?



$$\Delta M_H^2 = N_f \frac{\lambda_f^2}{8\pi^2}\left[-\Lambda^2 + 6m_f^2 \log\frac{\Lambda}{m_f} - 2m_f^2\right]$$

Good reason to expect new physics beyond the Standard Model (SM).

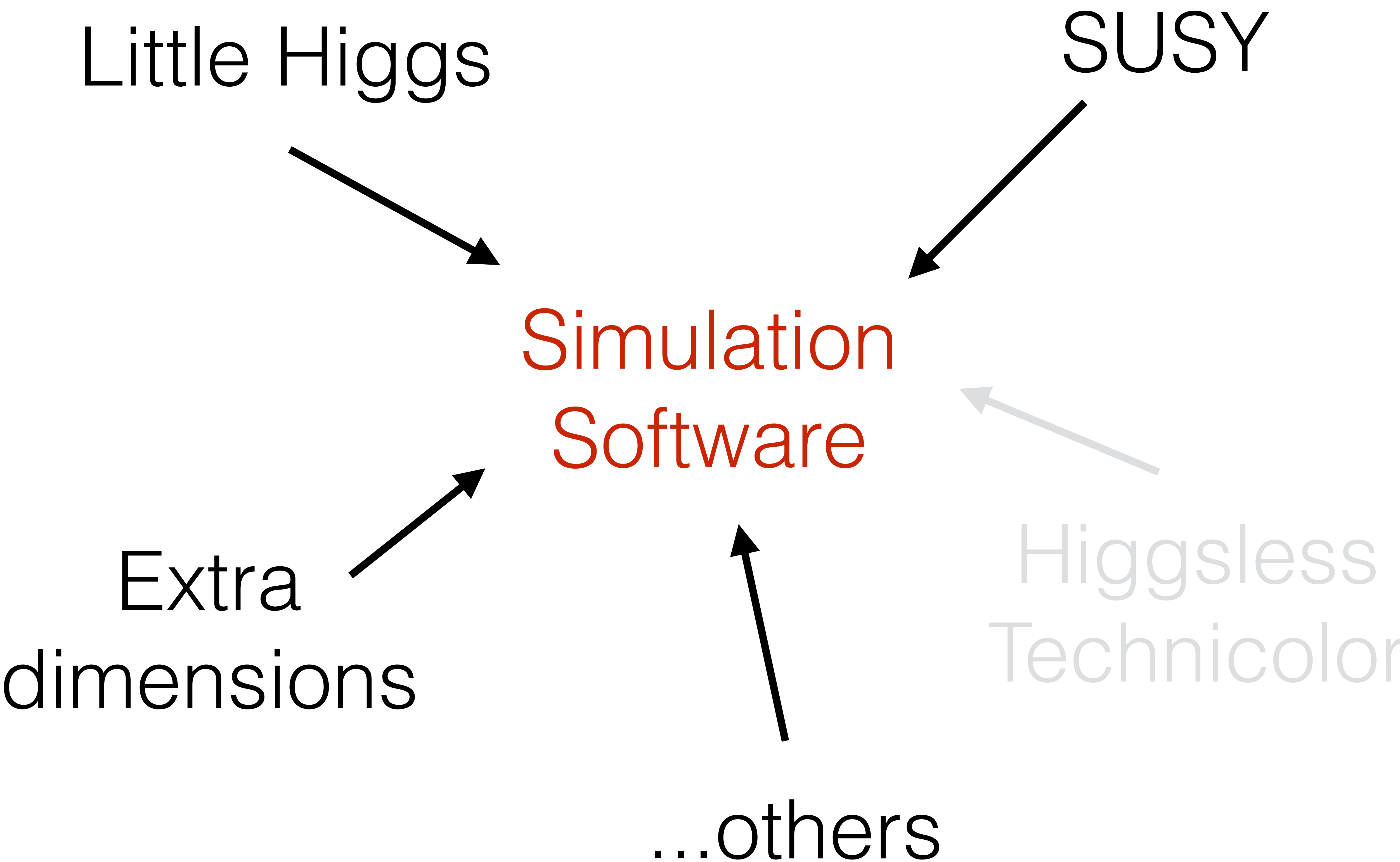
SUSY

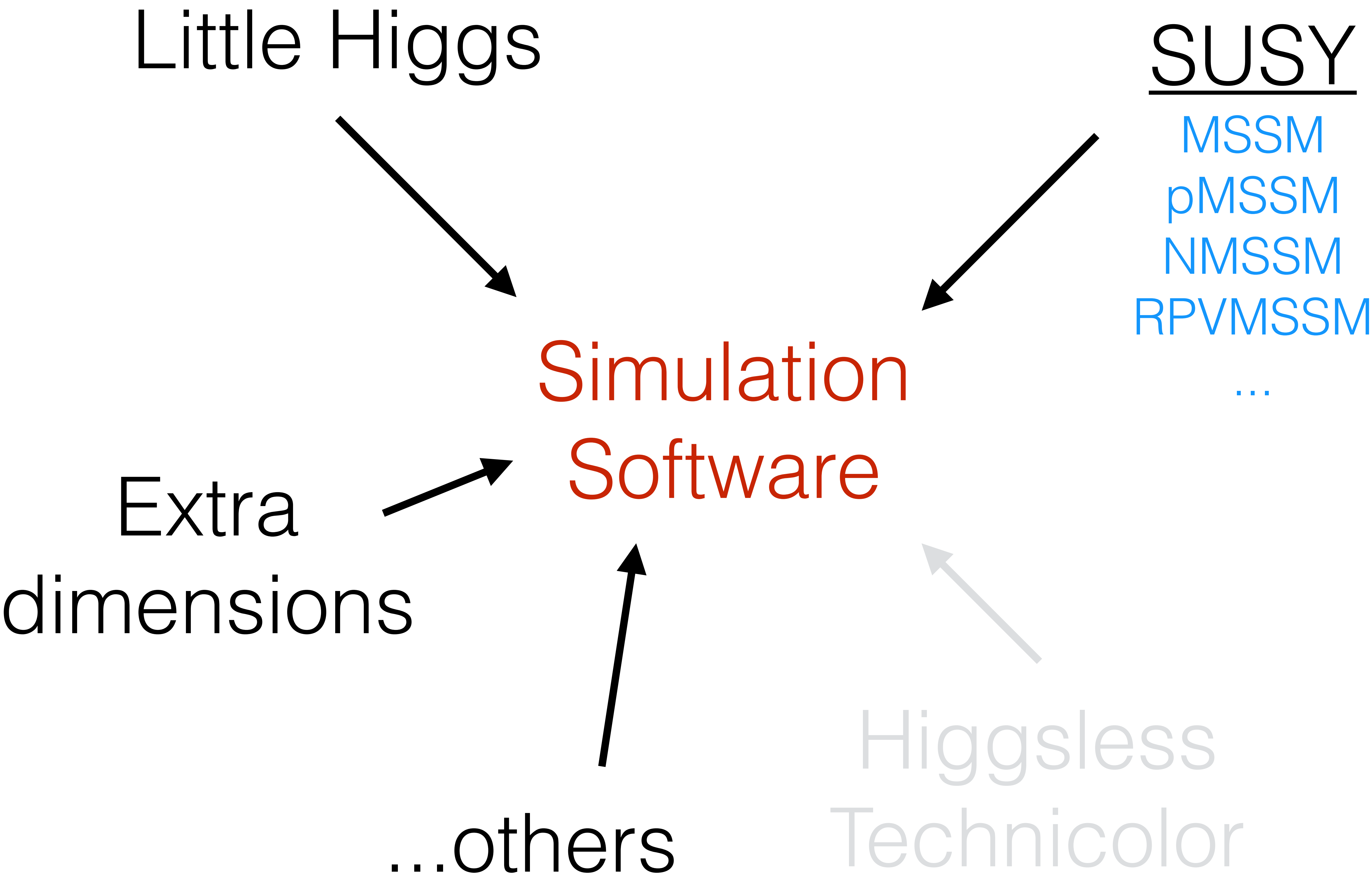
Little Higgs

Higgsless
Technicolor

Extra
dimensions

...others


Little Higgs
SUSY
Simulation Software
Extra dimensions
Higgsless Technicolor
...others


Little Higgs
SUSY
MSSM
pMSSM
NMSSM
RPVMSSM
...
Simulation Software
Extra dimensions
...others
Higgsless
Technicolor

Little Higgs

<u>SUSY</u>

MSSM
pMSSM
NMSSM
RPVMSSM
...

CalcHEP

MadGraph

Sherpa

Whizard

Extra dimensions

FeynArts

Higgsless
Technicolor

...others

What was the problem?

Problem 1:

Implementing a model was often tedious and error prone.

Terminal — less — 82×38

```
##################################
# QFD Interactions
# 2 heavy fermions - 1 light weak gauge boson
##################################

# FFV (qqZ)
dp dp z GZDp QED-HF
up up z GZUp QED-HF
sp sp z GZDp QED-HF
cp cp z GZUp QED-HF
bp bp z GZDp QED-HF
tp tp z GZTp QED-HF

# FFV (llZ)
ep-  ep-  z GZLp QED-HF
mup- mup- z GZLp QED-HF
tap- tap- z GZLp QED-HF
vep  vep  z GZNp QED-HF
vmp  vmp  z GZNp QED-HF
vtp  vtp  z GZNp QED-HF

# FFV (qq'W) - diagonal CKM
dp up w- GWFp QED-HF
sp cp w- GWFp QED-HF
bp tp w- GWTp QED-HF
up dp w+ GWFp QED-HF
cp sp w+ GWFp QED-HF
tp bp w+ GWTp QED-HF

# FFV (ll'W)
vep  ep-  w+ GWFp QED-HF
vmp  mup- w+ GWFp QED-HF
vtp  tap- w+ GWFp QED-HF
ep-  vep  w- GWFp QED-HF
mup- vmp  w- GWFp QED-HF
tap- vtp  w- GWFp QED-HF
:
```

Terminal — bash — 82×38

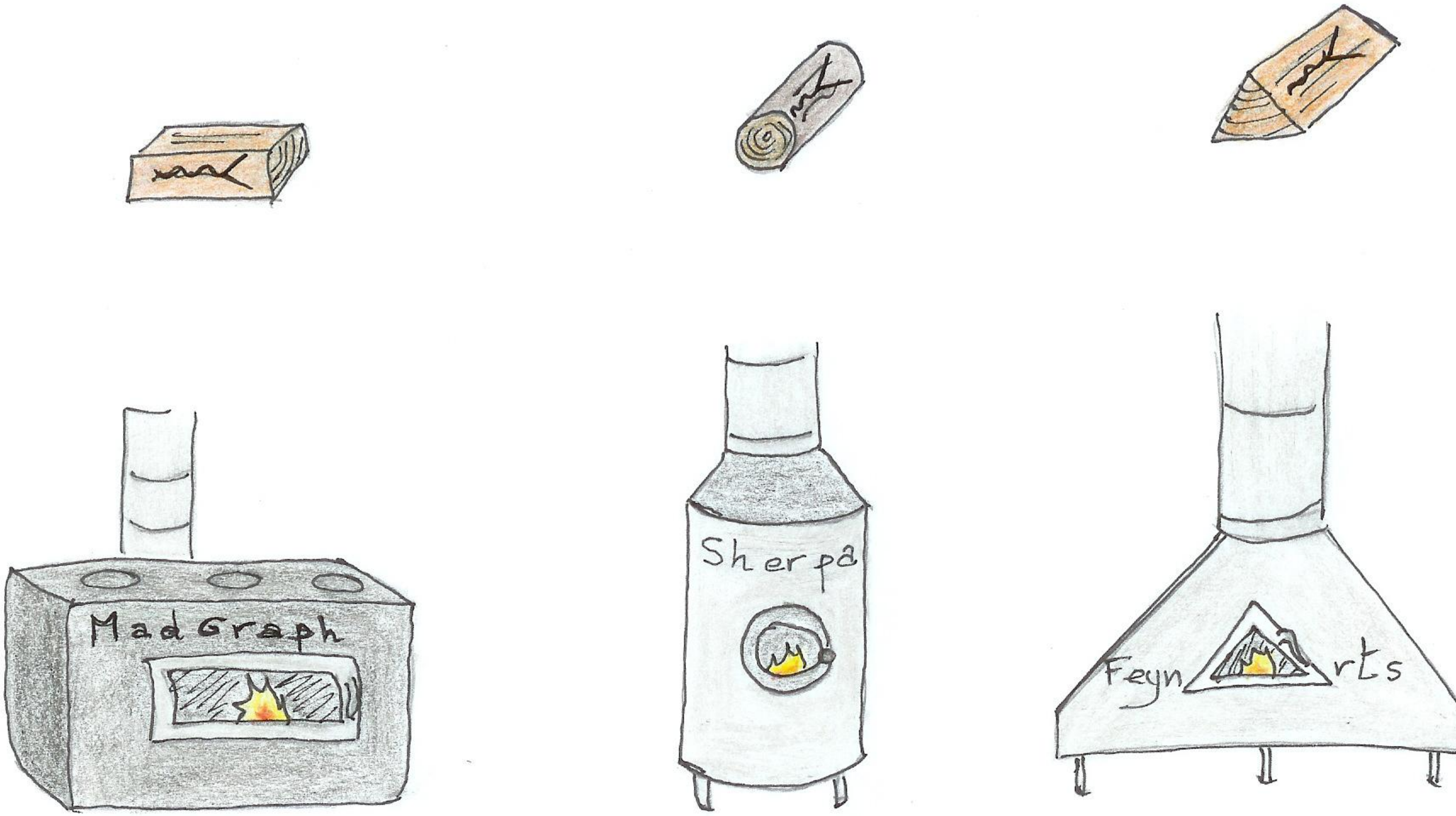
```
c----------------------------------------------
c     V-light   F-heavy    F-heavy
c----------------------------------------------
      GZDpL =
     - -1d0/2d0*gf(-ee,WMASS,ZMASS,MWP)
     -  *vZ0f(WMASS,ZMASS,MWP)*vLP0f(WMASS,MWP)**2
     - -1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)
     -  *VZ1f(WMASS,ZMASS,MWP)*vLP1f(WMASS,MWP)**2
     - +1d0/6d0*gpf(-ee,WMASS,ZMASS,MWP)
     -  *vZ2f(WMASS,ZMASS,MWP)
       GZDpR =
     - -1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)
     -  *VZ1f(WMASS,ZMASS,MWP)
     - +1d0/6d0*gpf(-ee,WMASS,ZMASS,MWP)
     -  *vZ2f(WMASS,ZMASS,MWP)
      GZDp(1)=dcmplx(GZDpL,Zero)
      GZDp(2)=dcmplx(GZDpR,Zero)
      write(*,10) 'GZDpL = ',GZDpL
      write(*,10) 'GZDpR = ',GZDpR

      GZUpL =
     - 1d0/2d0*gf(-ee,WMASS,ZMASS,MWP)
     -  *vZ0f(WMASS,ZMASS,MWP)*vLP0f(WMASS,MWP)**2
     - +1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)
     -  *VZ1f(WMASS,ZMASS,MWP)*vLP1f(WMASS,MWP)**2
     - +1d0/6d0*gpf(-ee,WMASS,ZMASS,MWP)
     -  *vZ2f(WMASS,ZMASS,MWP)
       GZUpR =
     - 1d0/2d0*gtf(-ee,WMASS,ZMASS,MWP)
     -  *VZ1f(WMASS,ZMASS,MWP)
     - +1d0/6d0*gpf(-ee,WMASS,ZMASS,MWP)
     -  *vZ2f(WMASS,ZMASS,MWP)
      GZUp(1)=dcmplx(GZUpL,Zero)
      GZUp(2)=dcmplx(GZUpR,Zero)
      write(*,10) 'GZUpL = ',GZUpL
      write(*,10) 'GZUpR = ',GZUpR

:
```

Problem 2:

Each matrix element generator has its strengths. What if you need more than one? In the past you had to start over.


MadGraph
Sherpa
Feyn
rts

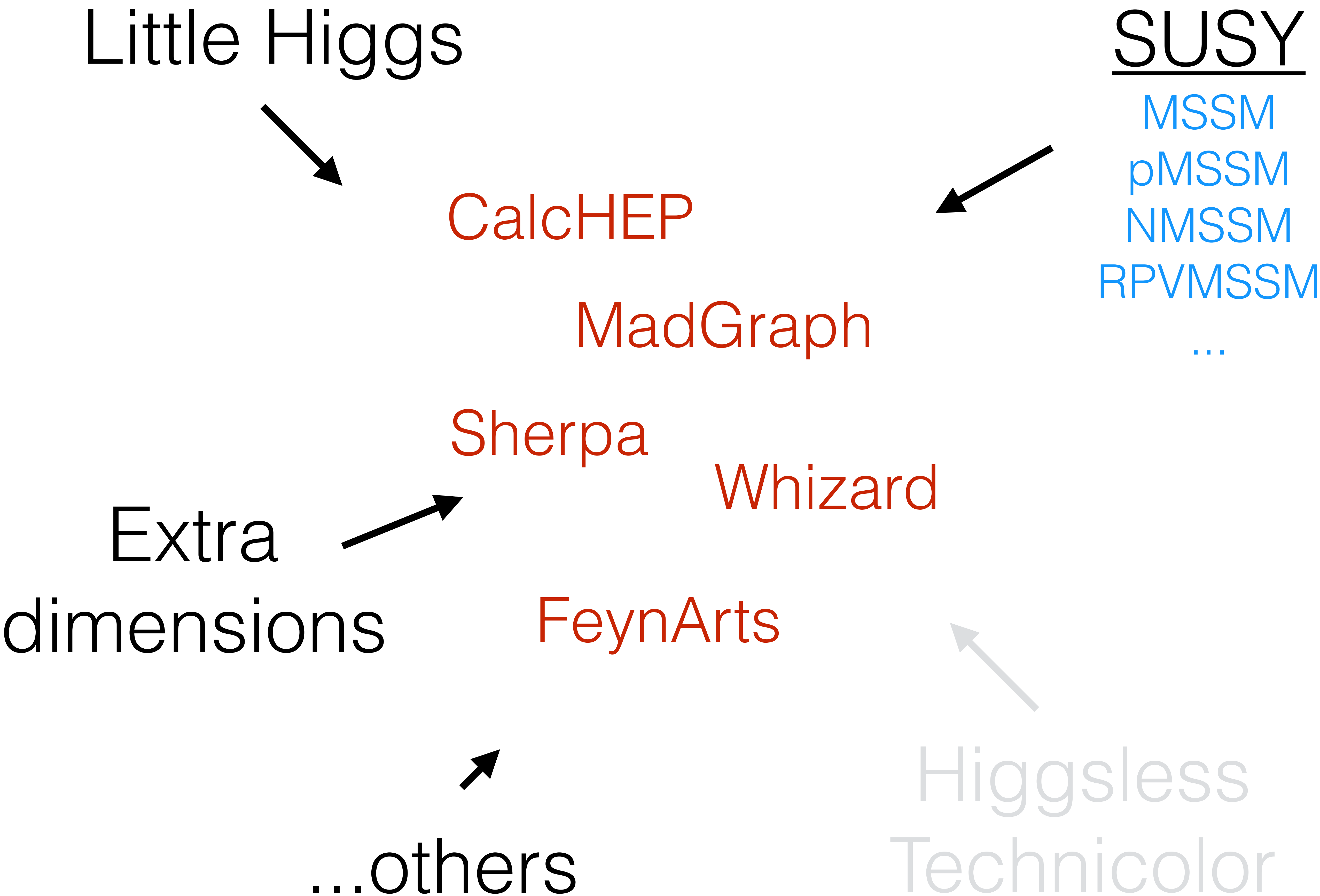
Problem 3:

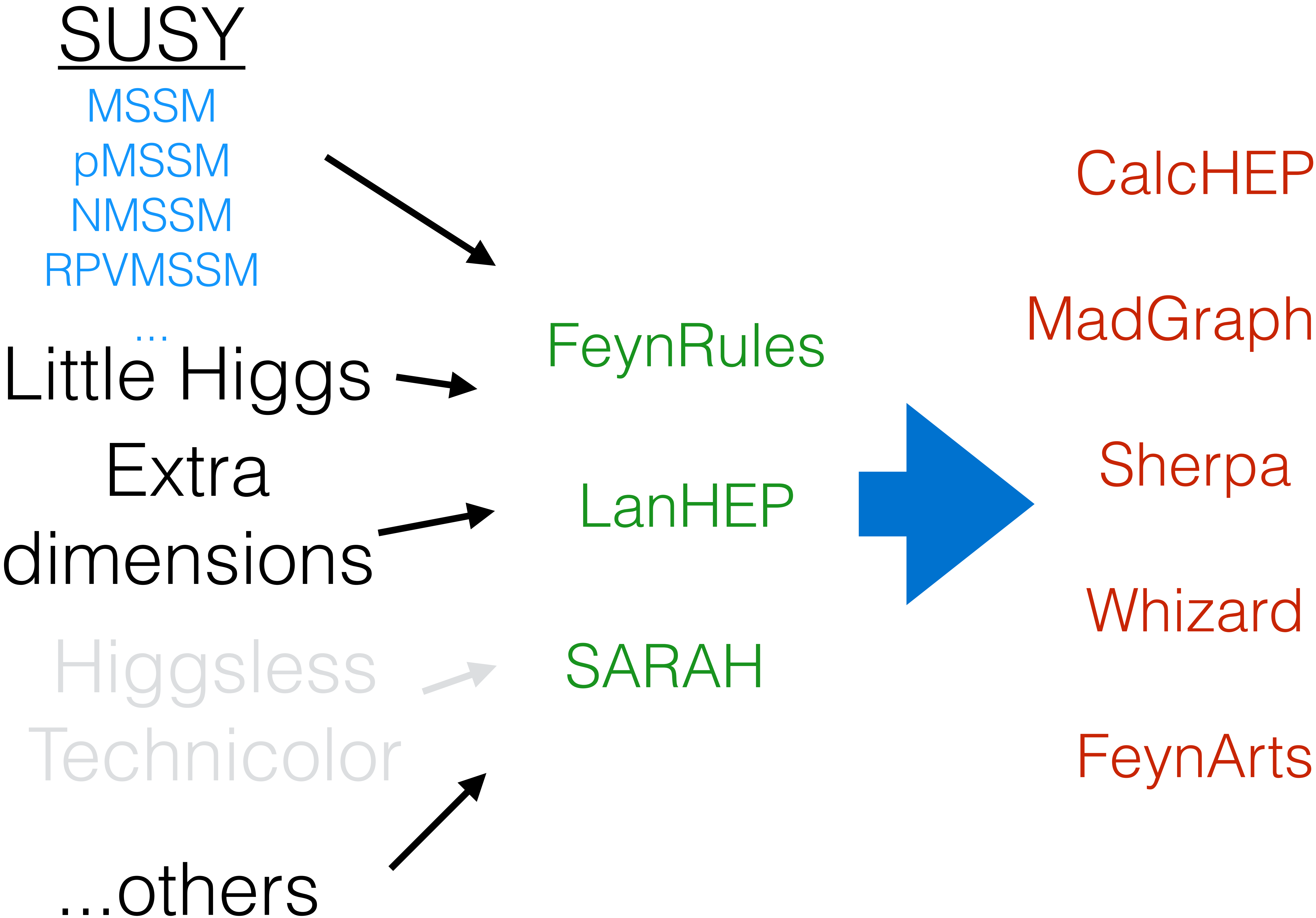
Implementations often did not transfer well to experimentalists.

Problem 3:

Implementations often did not transfer well to experimentalists.

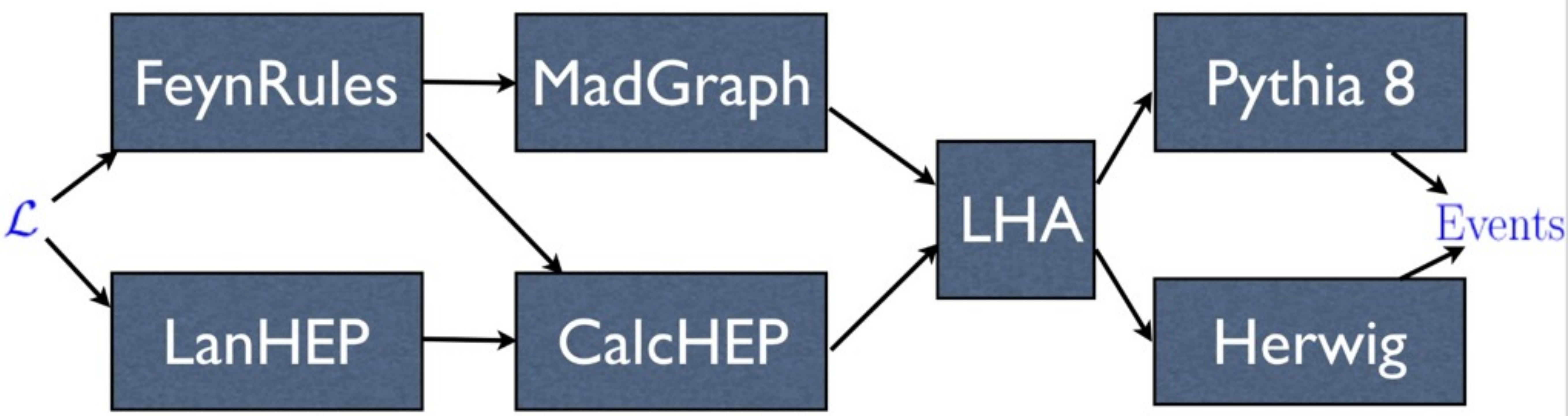
It often required modifying the code of the matrix element generator.

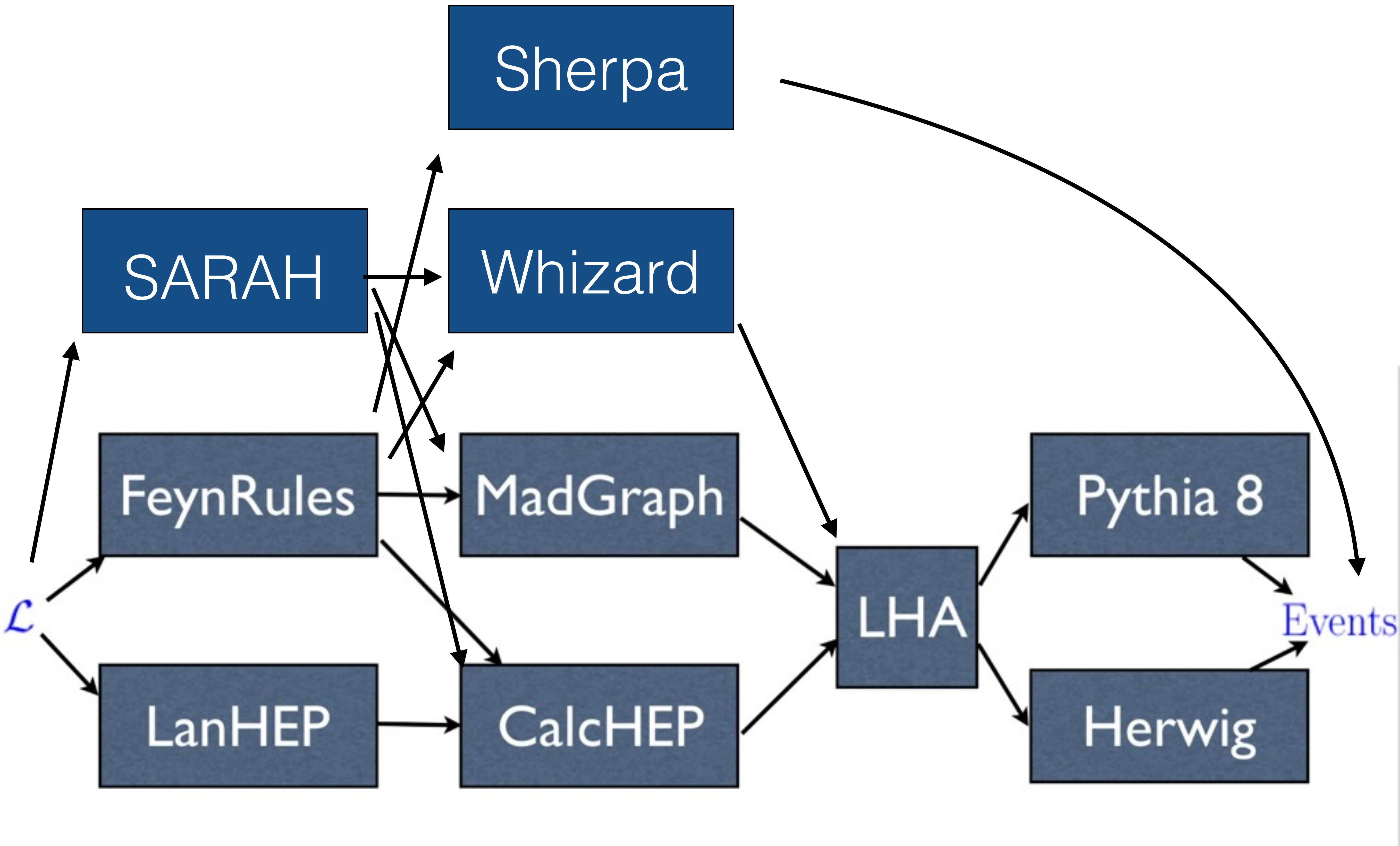

Little Higgs
SUSY
MSSM
pMSSM
NMSSM
RPVMSSM
...
CalcHEP
MadGraph
Sherpa
Whizard
FeynArts
Extra dimensions
...others
Higgsless
Technicolor


SUSY
MSSM
pMSSM
NMSSM
RPVMSSM
...
Little Higgs
Extra dimensions
Higgsless
Technicolor
...others
FeynRules
LanHEP
SARAH
CalcHEP
MadGraph
Sherpa
Whizard
FeynArts

MC4BSM 2012 Tutorial

arXiv:1209.0297




Sherpa
SARAH
Whizard
FeynRules
MadGraph
LanHEP
CalcHEP
LHA
Pythia 8
Herwig
$\mathcal{L}$
Events

	LanHEP	FeynRules	SARAH
First Released	1996	2008	2008
Programming Language	C	Mathematica	Mathematica
General Lagrangian	Yes	Yes	SUSY Only
Superfields	No	Yes	Yes
Parameter Running	No	In Progress	Yes
Aut. Mass Diagonalization	Yes	Yes	Yes
Spin	0,1/2,1,3/2,2	0,1/2,1,3/2,2	-
Superfields	-	Chiral, Vector	Chiral, Vector

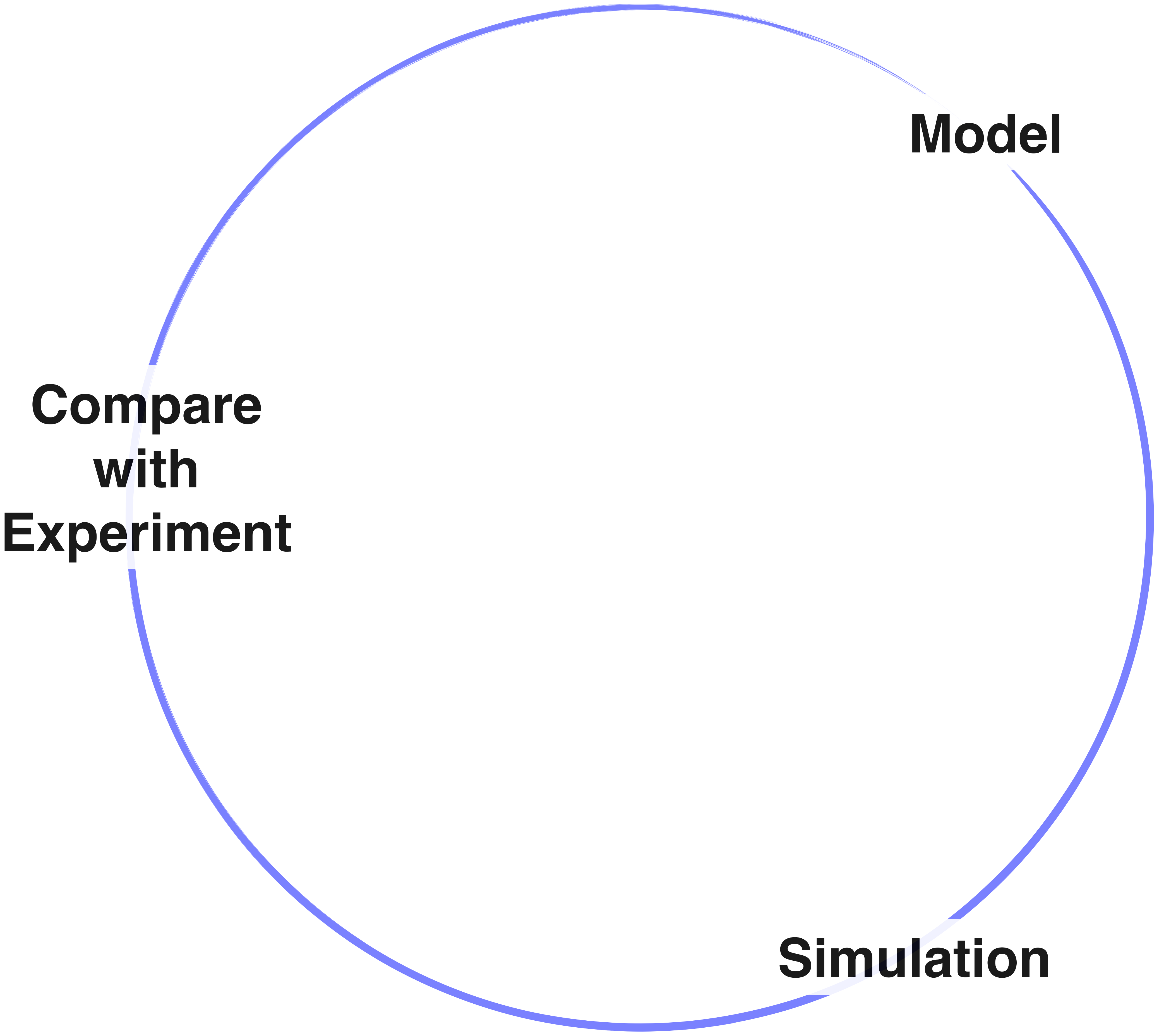
	LanHEP	FeynRules	SARAH
CalcHEP	Yes	Yes	Yes
FeynArts	Yes	Yes	Yes
MadGraph	In Progress	Yes	Yes
Sherpa	No	Yes	No
Whizard	No	Yes	Yes

FeynRules 2.0

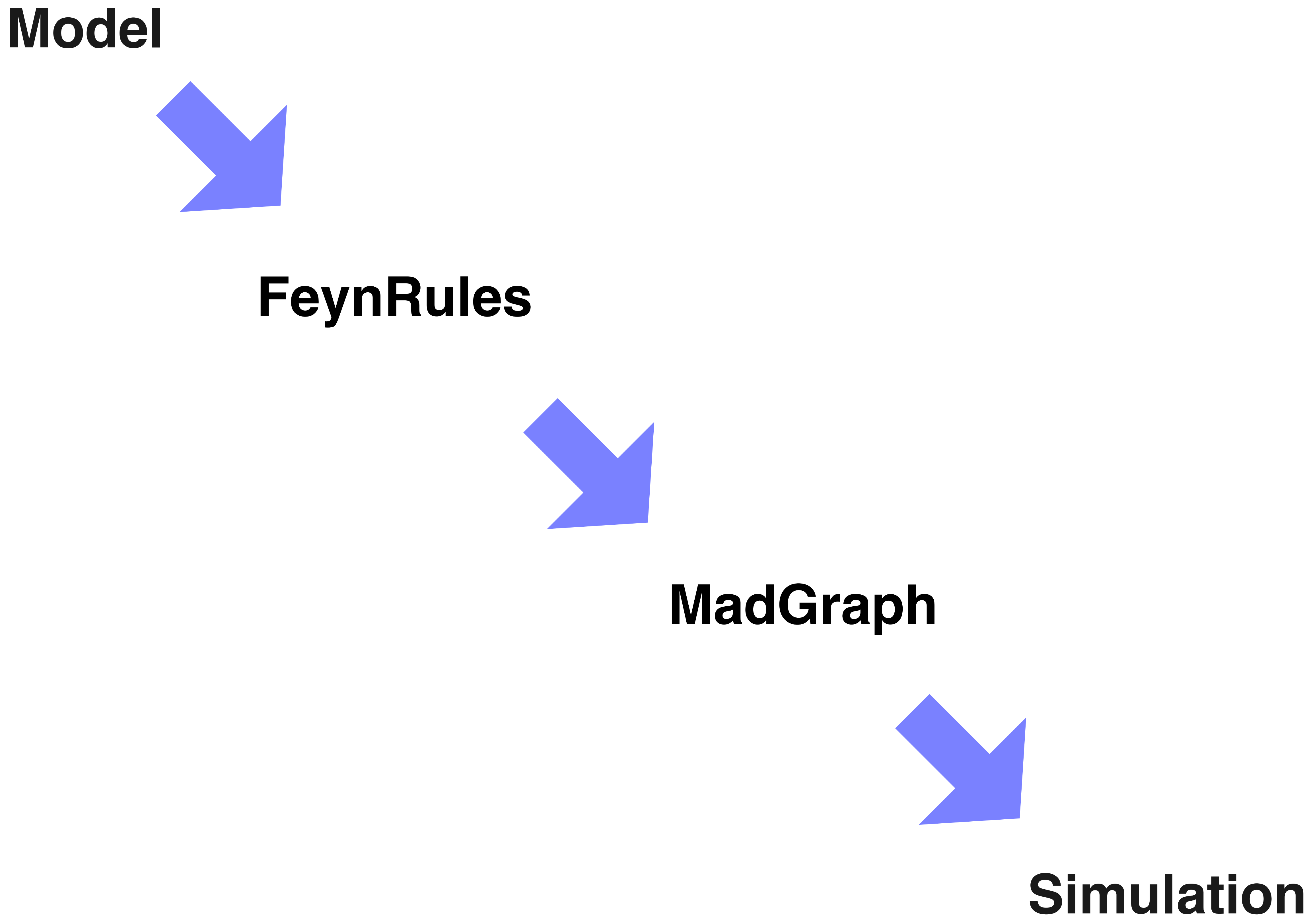
Coming soon!

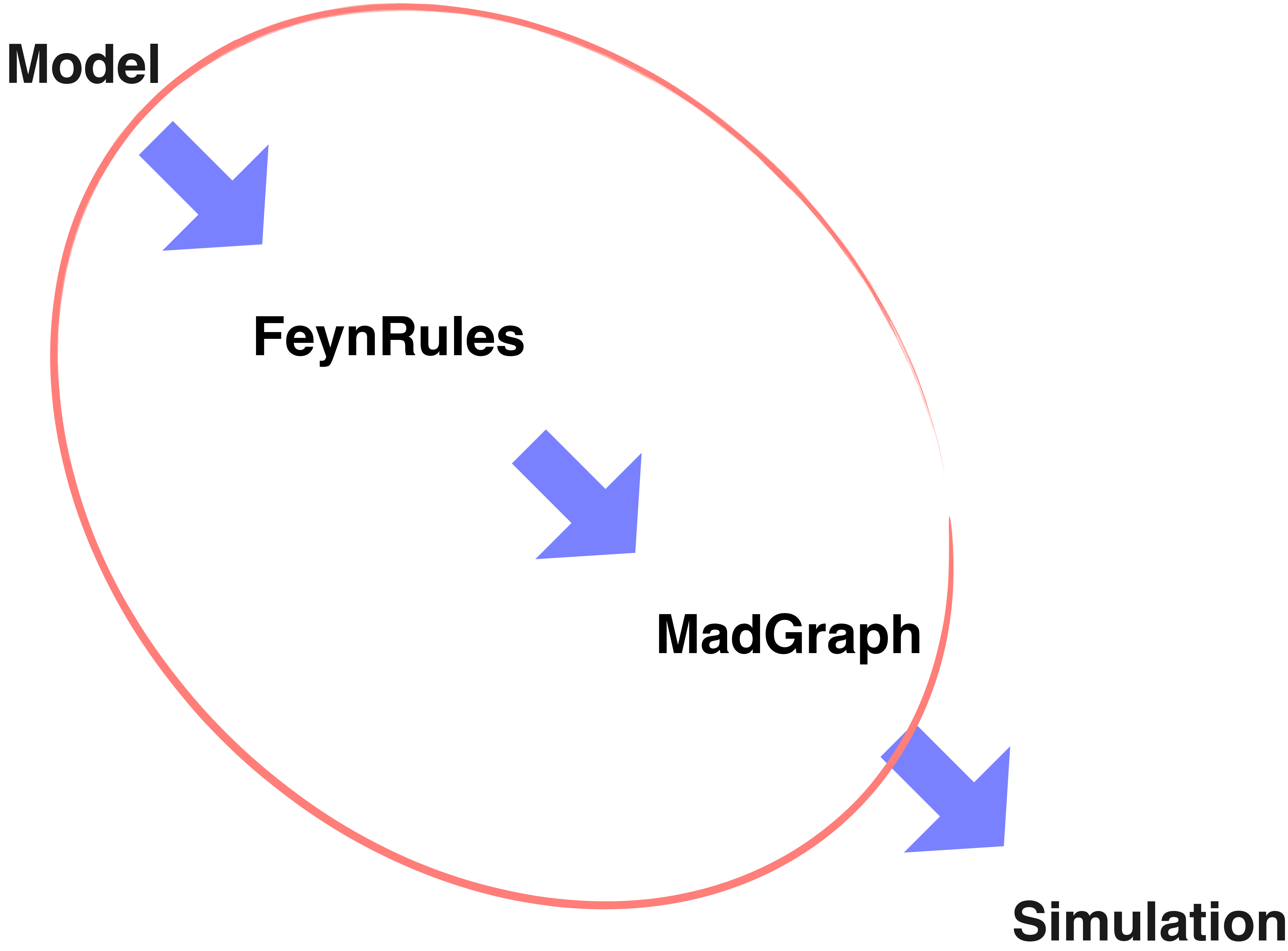
Beyond 1.0 (CPC 180, 1614):

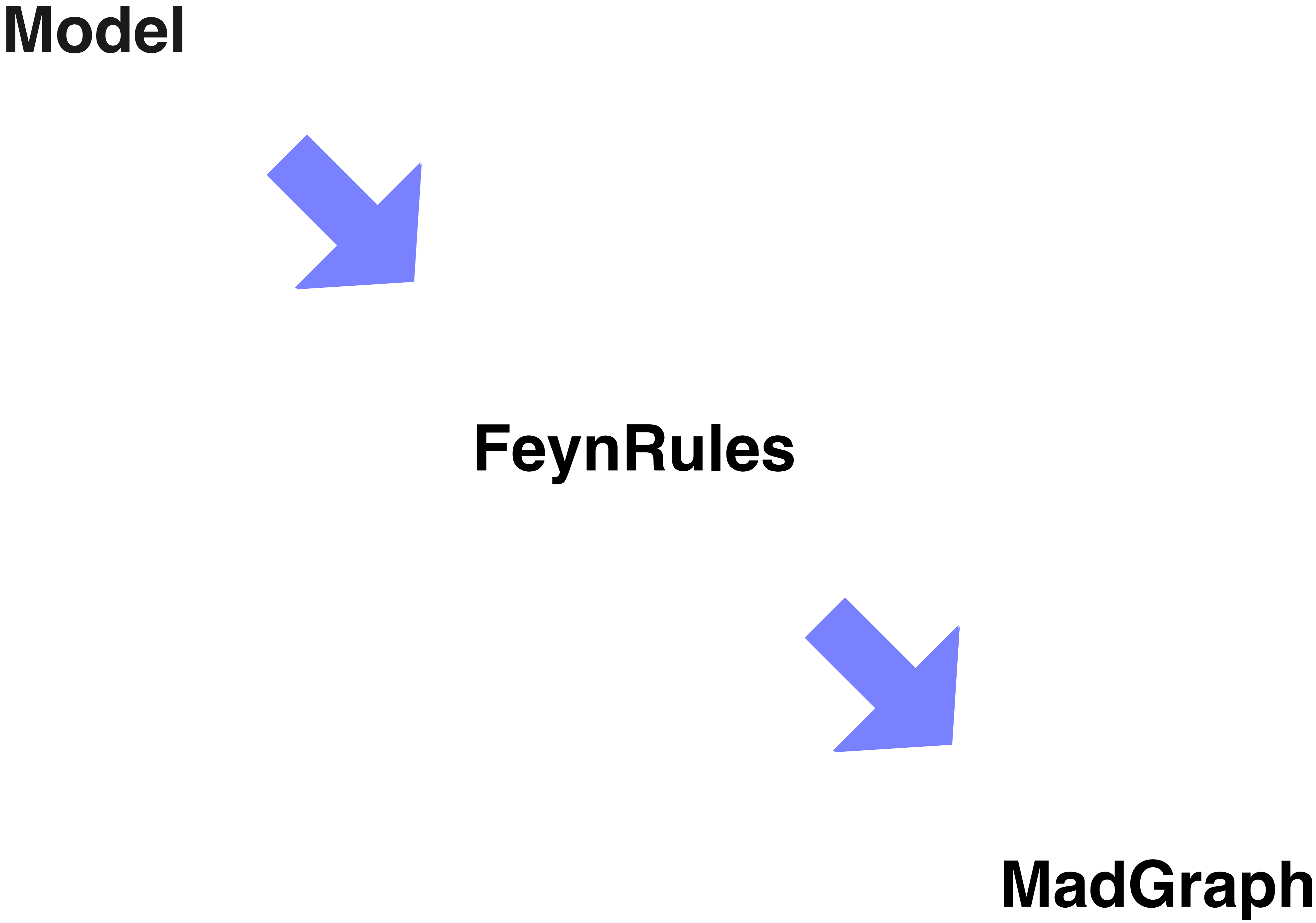
- 2-Component Weyl Notation (CPC 182, 2404)
- Spin-3/2 (arXiv:1308.1668)
- Superspace Notation (CPC 182, 2404)
- Automatic Mass Diagonalization (EPJC 73, 2325)
- ".gen" files in FA interface
- Universal FeynRules Output (UFO) (CPC 183, 1201)
- Whizard Interface (EPJC 72, 1990)
- Automatic $1 \to 2$ widths (in preparation)
- Speed & Efficiency Improvements
- Web Validation (arXiv:1003.1643)

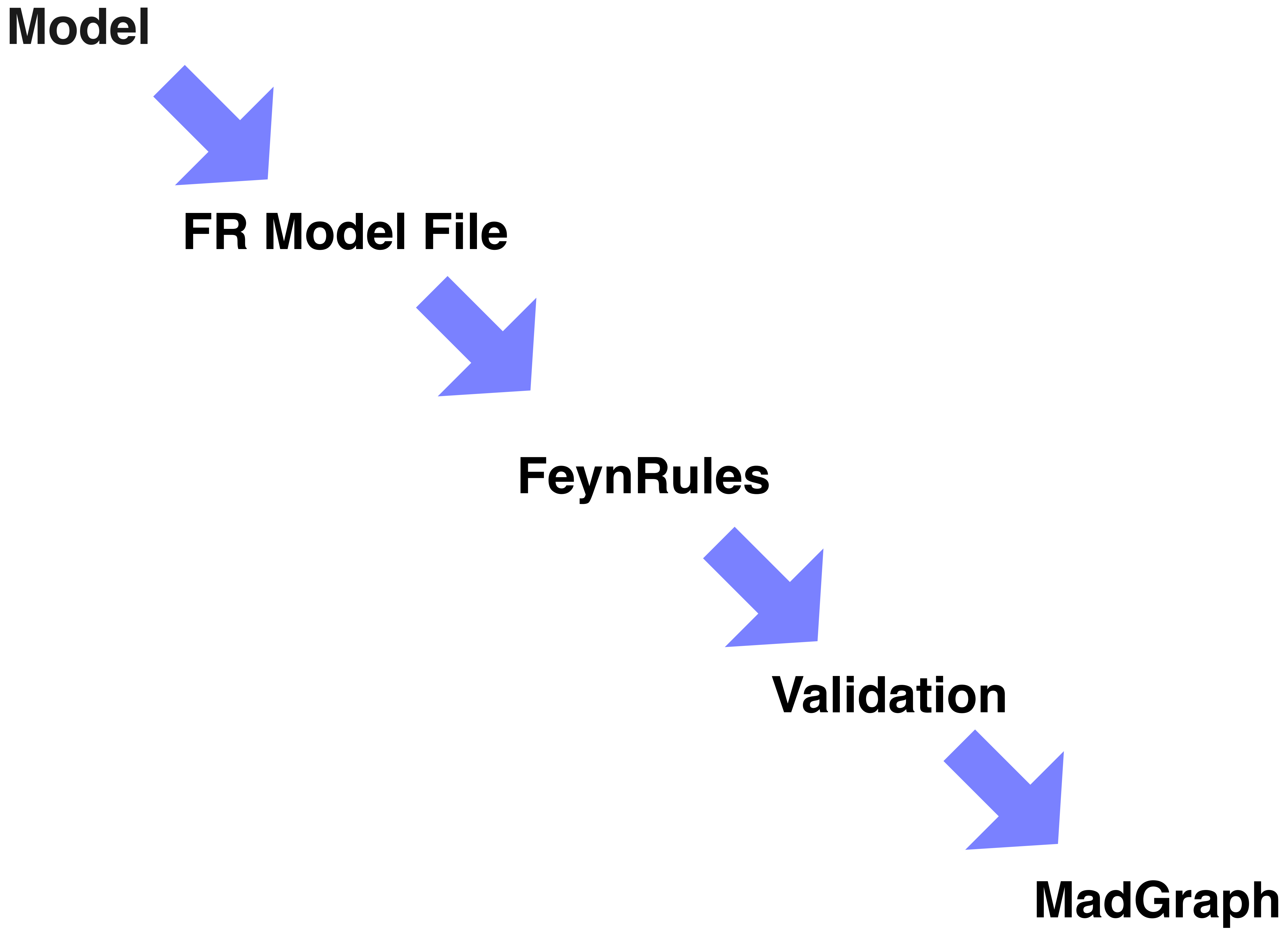

Model
Simulation
Compare with Experiment

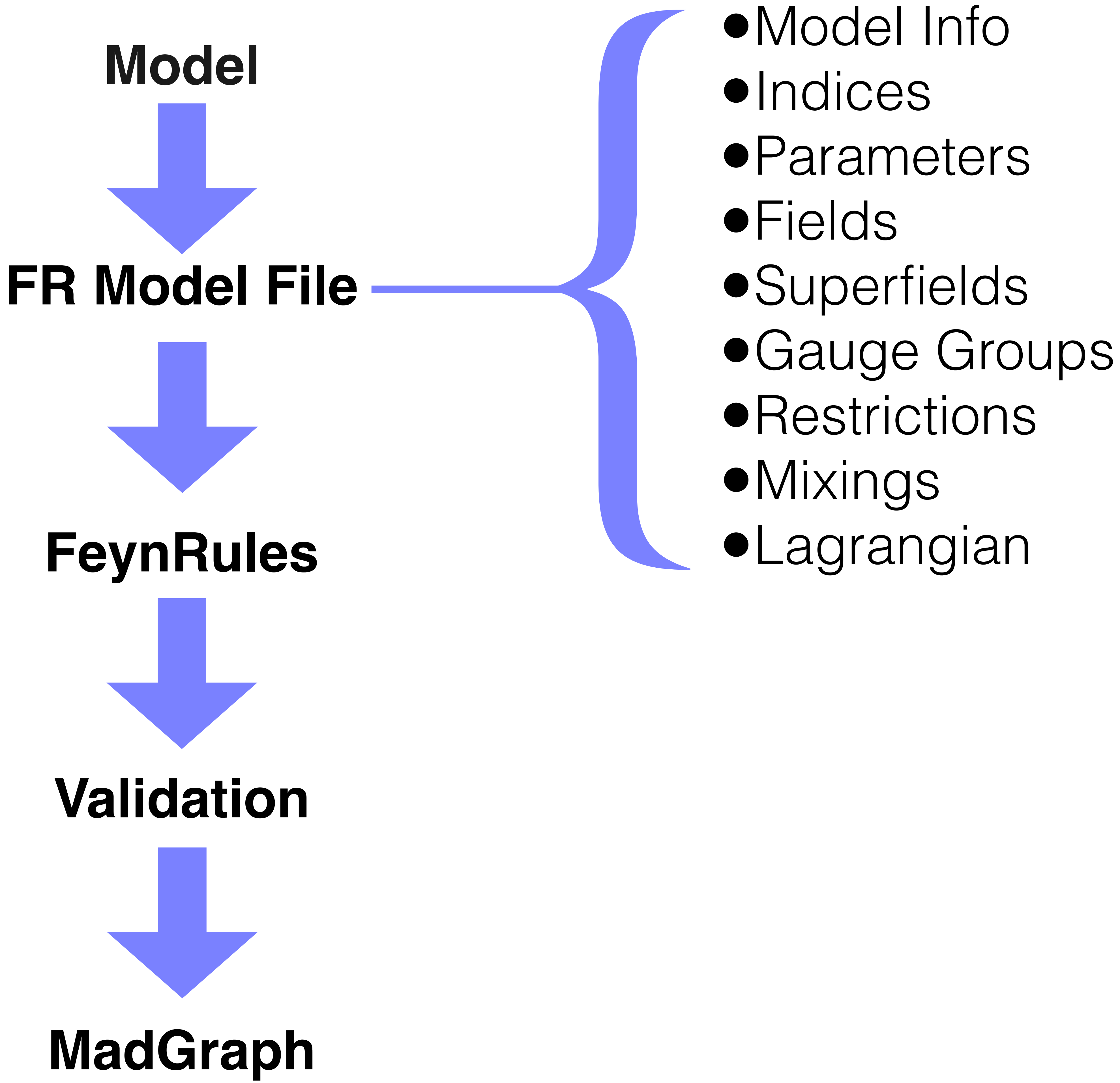
Model **Simulation**

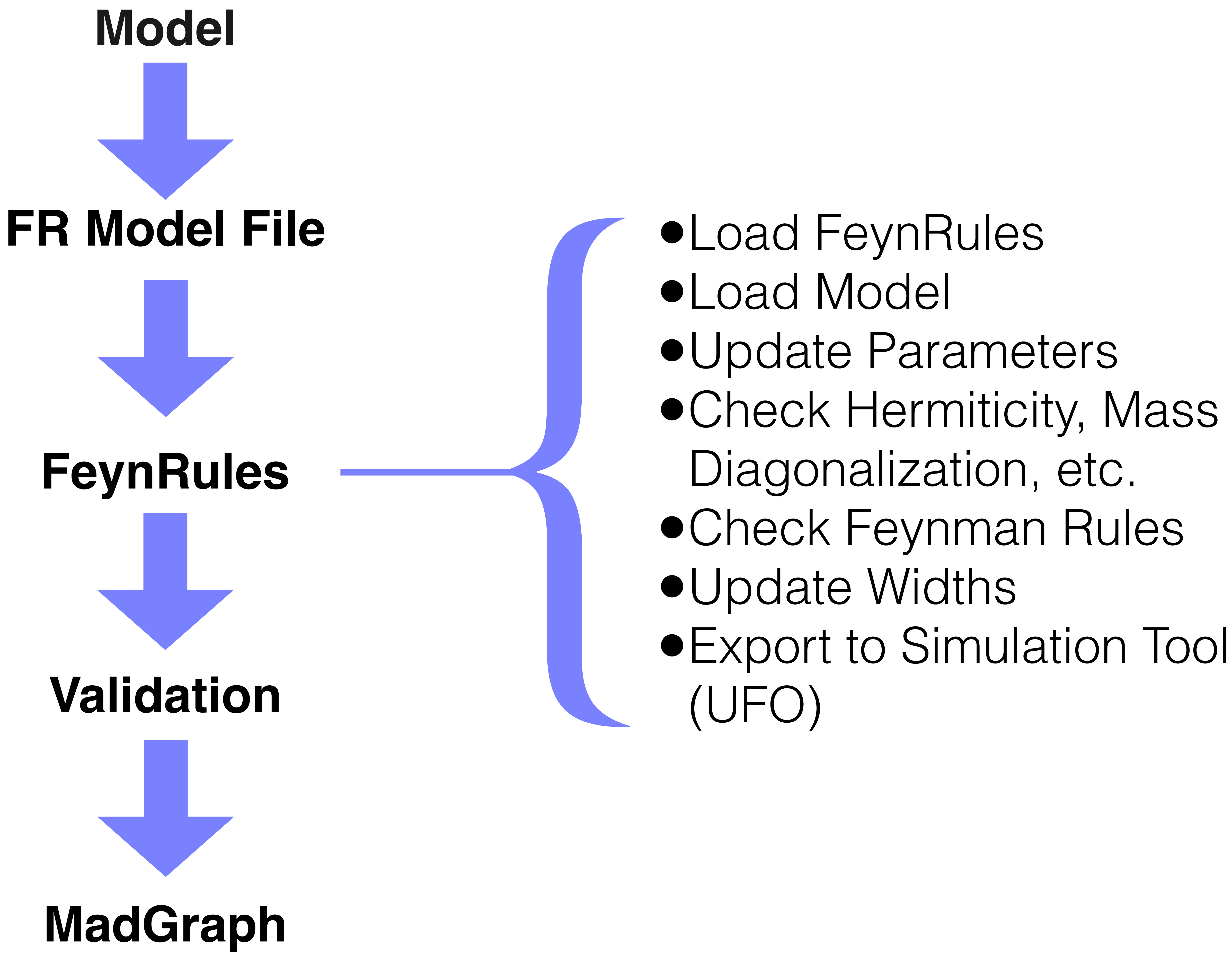

Model
FeynRules
MadGraph
Simulation

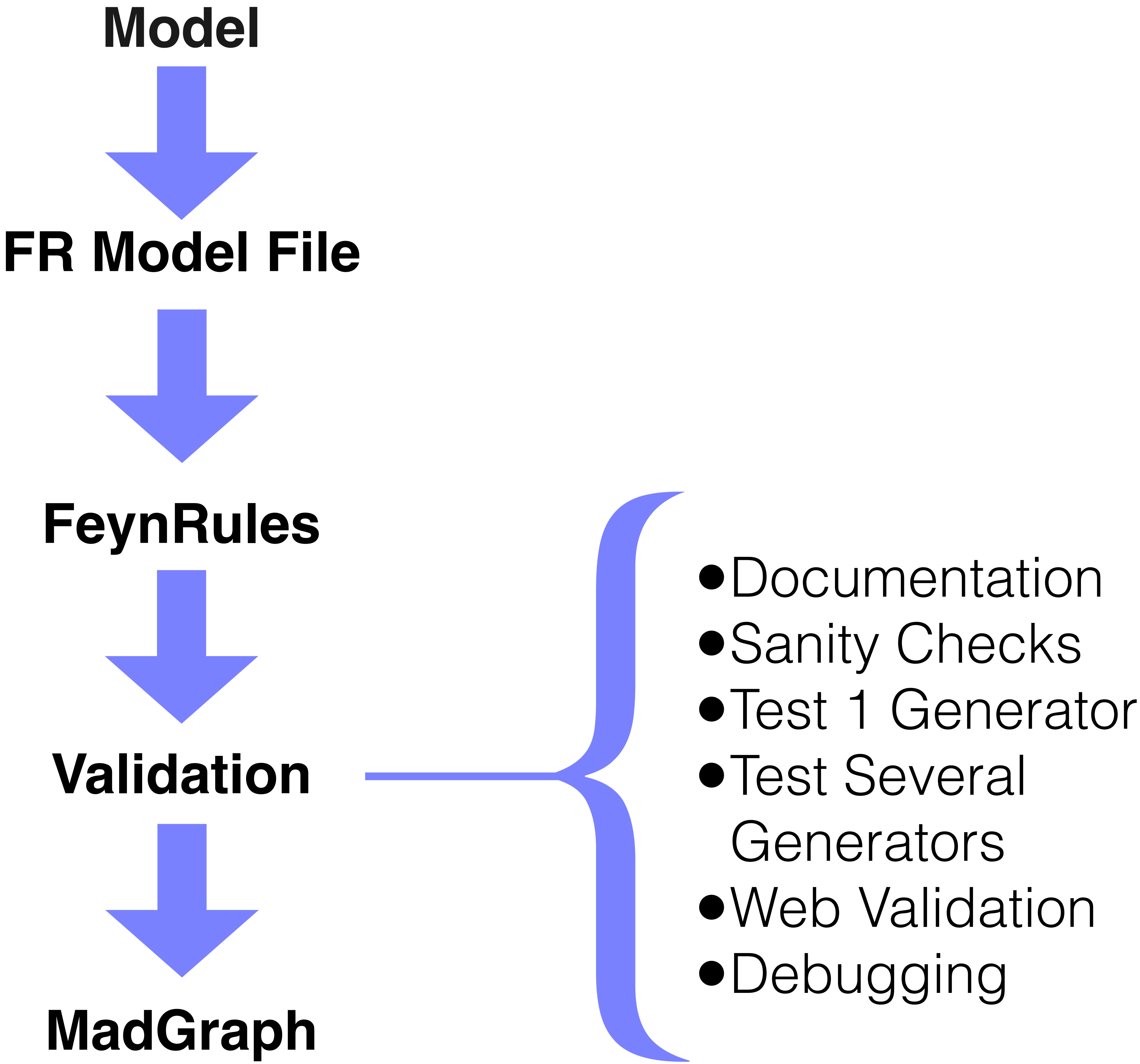

Model
FeynRules
MadGraph
Simulation

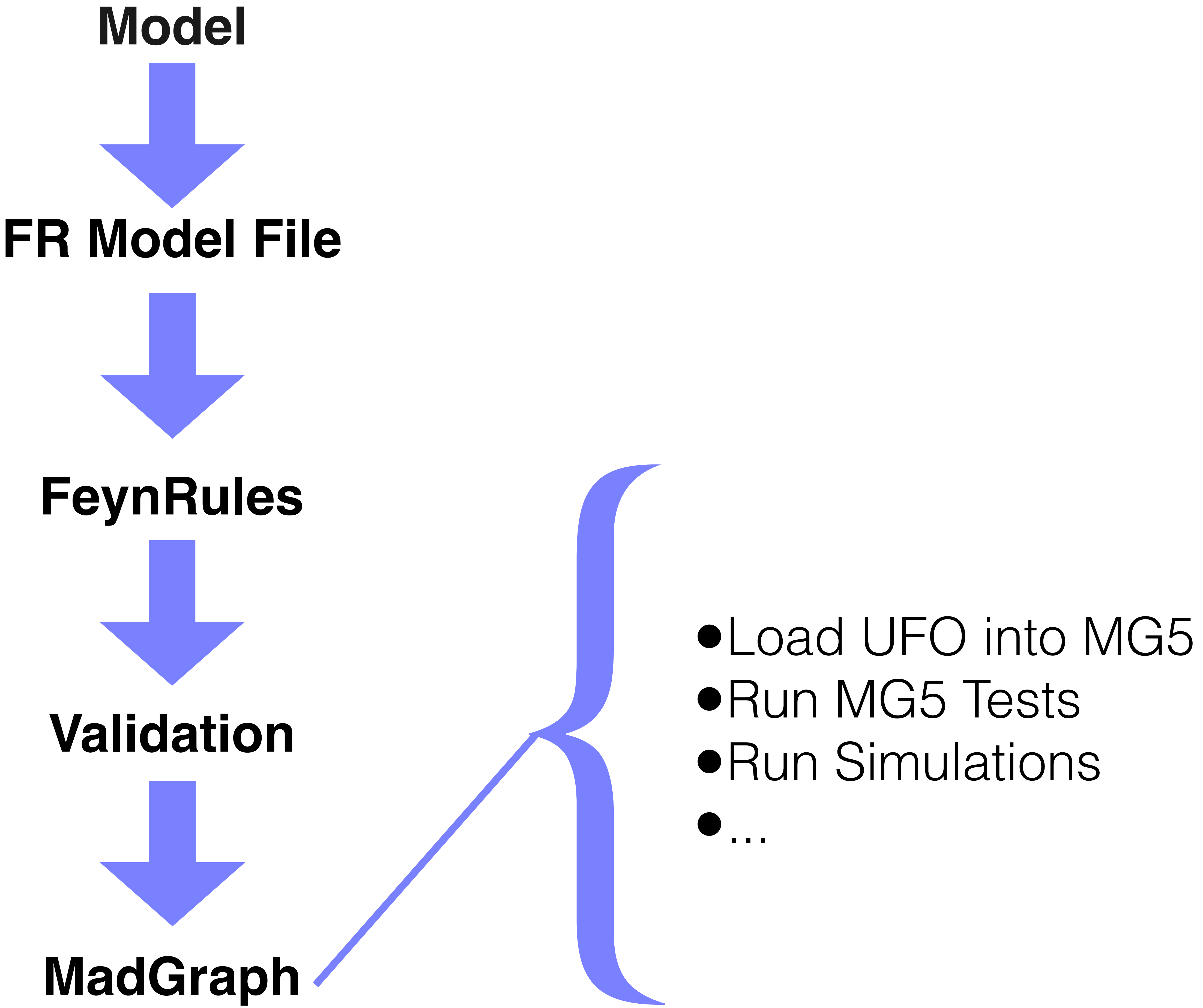

Model
FeynRules
MadGraph

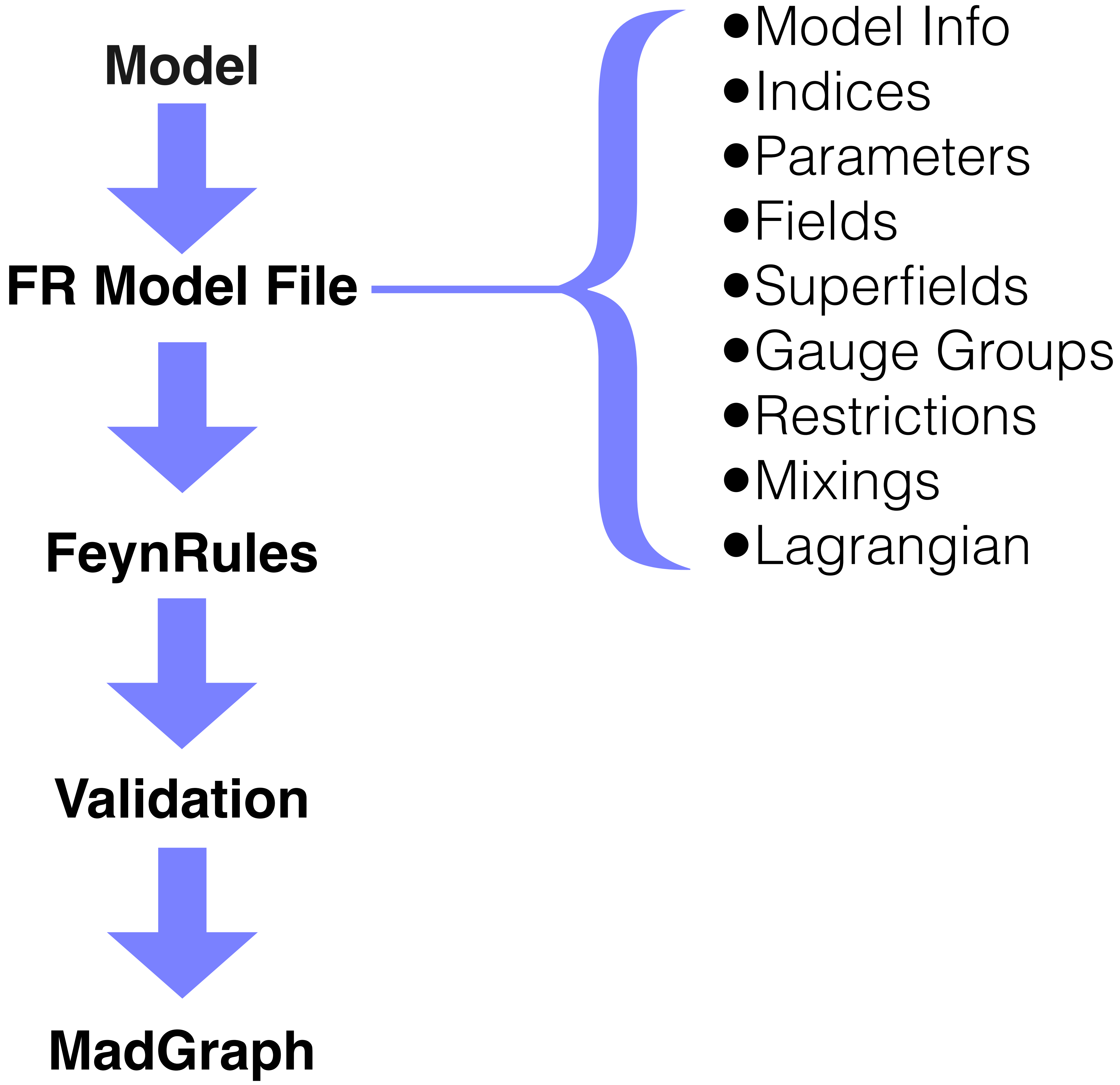

Model
FR Model File
FeynRules
Validation
MadGraph


Model
FR Model File
FeynRules
Validation
MadGraph
•Model Info
•Indices
•Parameters
•Fields
•Superfields
•Gauge Groups
•Restrictions
•Mixings
•Lagrangian


Model
FR Model File
FeynRules
Validation
MadGraph
Load FeynRules
Load Model
Update Parameters
Check Hermiticity, Mass Diagonalization, etc.
Check Feynman Rules
Update Widths
Export to Simulation Tool (UFO)


Model
FR Model File
FeynRules
Validation
MadGraph
•Documentation
•Sanity Checks
•Test 1 Generator
•Test Several Generators
•Web Validation
•Debugging


Model
FR Model File
FeynRules
Validation
MadGraph
Load UFO into MG5
Run MG5 Tests
Run Simulations
...


Model
FR Model File
FeynRules
Validation
MadGraph
Model Info
Indices
Parameters
Fields
Superfields
Gauge Groups
Restrictions
Mixings
Lagrangian

- Pure Text Files
    - Ending in ".fr"
- Mathematica Syntax

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

Model Info:

- Model Name
- Authors
- Institutions
- Emails
- Date
- References
- URLs
- Version

Model Info

```
M$ModelName = "my_new_model";

M$Information = {
          Authors      -> {"Mr. X", "Ms. Y"},
          Institutions -> {"UC Louvain"},
          Emails       -> {"X@uclouvain.be", "Y@uclouvain.be},
          Date         -> "01.03.2013",
          References   -> {"reference 1", "reference 2"},
          URLs         -> {"http://feynrules.irmp.ucl.ac.be"},
          Version      -> "1.0"
                };
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

Indices:

- Lorentz/Spin Indices Automatic
- Symmetry and Flavor Indices
- Index Range
- Index Style
- Unfold/NoUnfold
  - Unfold must be used for any index that expands the field into non-mass eigenstates.

Indices

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]  = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];

IndexStyle[ Colour, i ];
IndexStyle[ Gluon, a ];
```

$$\texttt{G[mu, a]} \longrightarrow \texttt{G[Index[Lorentz, mu], Index[Gluon, a]]}$$

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- External Parameters:
  - Independent
- Internal Parameters:
  - Dependent
  - Must only depend on parameters above it.

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- External Parameters:
  - Independent
- Internal Parameters:
  - Dependent
  - Must only depend on parameters above it.

```
ParameterType     -> External
```
or
```
ParameterType     -> Internal
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Value
  - Numerical (External)
  - Analytic (Internal)

```
Value          -> 0.1184
```
or
```
Value          -> Sqrt[4 Pi aS]
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Definitions
  - Numerical (External)
  - Analytic (Internal)
  - Replacement during Feynman rule calculation

```
Definitions -> { gs -> Sqrt[4 Pi aS] }
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Indices
  - Tensorial parameters

```
Indices          -> {Index[Generation], Index[Generation]}
```

Parameters

```
M$Parameters = {
   param1 == { options1 },
   param2 == { options2 },
              ...
};
```

Parameters

```
aS == {
  TeX                 -> Subscript[\[Alpha],s],
  ParameterType       -> External,
  InteractionOrder    -> {QCD, 2},
  Value               -> 0.1184,
  BlockName           -> SMINPUTS,
  OrderBlock          -> 3,
  Description         -> "Strong coupling constant at the Z pole"
}

gs == {
  TeX                 -> Subscript[g,s],
  ParameterType       -> Internal,
  ComplexParameter    -> False,
  InteractionOrder    -> {QCD, 1},
  Value               -> Sqrt[4 Pi aS],
  ParameterName       -> G,
  Description         -> "Strong coupling constant at the Z pole"
 }
```

Parameters

```
CKM == {
   ParameterType    -> Internal,
   Indices          -> {Index[Generation], Index[Generation]},
   Unitary          -> True,
   ComplexParameter -> True,
   Definitions      -> {
     CKM[i_,3] :> 0 /; i!=3,
     CKM[3,i_] :> 0 /; i!=3,
     CKM[3,3]  -> 1 },
   Value            -> {
     CKM[1,1] ->  Cos[cabi],
     CKM[1,2] ->  Sin[cabi],
     CKM[2,1] -> -Sin[cabi],
     CKM[2,2] -> Cos[cabi] },
   Description      -> "CKM-Matrix"
 }
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- S[...] : Spin-0 Scalar
- F[...] : Spin-1/2 Fermion
    - 4-component
    - Dirac & Majorana
- W[...] : Spin-1/2 Fermions
    - 2-component
    - Left & Right Chiral
- V[...] : Spin-1 Vectors
- R[...] : Spin-3/2 Fermion
    - 4-component
    - Dirac & Majorana
- RW[...] : Spin-3/2 Fermion
    - 2-component
    - Left & Right Chiral
- T[...] : Spin-2 Tensor
- U[...] : Spin-0 Ghost

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- SelfConjugate
  - Whether the particle has an antiparticle

```
SelfConjugate -> False
```

or

```
SelfConjugate -> True
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- ClassName
  - Name of Particle Class
  - Each class can have multiple members

```
ClassName    -> uq,
ClassMembers -> {u, c, t}
```

FR Model File

- Model Info
- Indices
- Parameters
- <u>Fields</u>
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- ClassName
  - Name of Particle Class
  - Each class can have multiple members
  - If not self-conjugate, FeynRules automatically generates antiparticles:
    `uqbar`
    `{ubar, cbar, tbar}`

```
ClassName    -> uq,
ClassMembers -> {u, c, t}
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Indices
  - Symmetry & Flavor Indices
  - Spin & Lorentz Indices automatic: Do Not Add Them!
- FlavorIndex
  - Index for Class Members

```
Indices -> {Index[ Colour ]}
Indices -> {Index[ Colour ], Index[ SU2D ]}

Indices -> { Index[ Colour ], Index[ Flavour ] },
FlavorIndex -> Flavour
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Quantum Numbers
  - Discrete Charges
  - Abelian Charges
  - Conservation checked during Feynman rule calculation

```
QuantumNumbers -> {Q -> -1, LeptonNumber -> 1}
QuantumNumbers -> {Q -> 2/3}
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Mass
  - Class
  - Class Members
  - Numerical Value or Internal

```
Mass -> {MW, Internal}
Mass -> {MZ, 91.188}
Mass -> {{MU,0}, {MC,0}, {MT, 174.3}}
Mass -> {Mu, {MU, 0}, {MC, 0}, {MT, 174.3}}
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Mass
  - Class
  - Class Members
  - Numerical Value or Internal
- Width is analogous

```
Mass -> {MW, Internal}
Mass -> {MZ, 91.188}
Mass -> {{MU,0}, {MC,0}, {MT, 174.3}}
Mass -> {Mu, {MU, 0}, {MC, 0}, {MT, 174.3}}
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Unphysical
  - Not Mass Eigenstates

`Unphysical -> True`

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Unphysical
  - Not Mass Eigenstates
- Definitions
  - Replacements before calculation of Feynman rules

```
Unphysical -> True

Definitions -> {B[mu_] -> -sw Z[mu] + cw A[mu]}
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Majorana Fermions
  - Charge Conjugation Phase
  - Chirality

```
MajoranaPhase -> Phi
Chirality     -> Left
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Majorana Fermions
  - Charge Conjugation Phase
  - Chirality
  - WeylComponents (inside 4-component fermion)

```
MajoranaPhase -> Phi
Chirality      -> Left
WeylComponents -> {chi, xibar}
```

Fields

```
M$ClassesDescription = {
    spin1[1] == { options1 },
    spin1[2] == { options2 },
    spin2[1] == { options3 },
    ...}
```

Fields

```
F[3] == {
  ClassName        -> uq,
  ClassMembers     -> {u, c, t},
  Indices          -> {Index[Generation], Index[Colour]},
  FlavorIndex      -> Generation,
  SelfConjugate    -> False,
  Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
  Width            -> {0, 0, {WT,1.50833649}},
  QuantumNumbers   -> {Q -> 2/3},
  PropagatorLabel  -> {"uq", "u", "c", "t"},
  PropagatorType   -> Straight,
  PropagatorArrow  -> Forward,
  PDG              -> {2, 4, 6},
  ParticleName     -> {"u",  "c",  "t" },
  AntiParticleName -> {"u~", "c~", "t~"},
  FullName         -> {"u-quark", "c-quark", "t-quark"}
},
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- CSF[...] : Chiral Superfields
- VSF[...] : Vector Superfields
  - Wess-Zumino Gauge

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Shared Features
    - ClassName
    - Indices
    - QuantumNumbers

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Chiral Superfields
  - Chirality
  - Weyl
  - Scalar
  - Auxiliary field optional

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Vector Superfields
  - Gauge Boson
  - Gaugino
  - Auxiliary field optional

Superfields

```
M$Superfields = {
   superfield1[1] == { options1 },
   superfield2[2] == { options2 },
                 ...
}
```

Superfields

```
CSF[1] == {
  ClassName -> PHI,
  Chirality -> Left,
  Weyl      -> psi,
  Scalar    -> z,
  Auxiliary -> FF
}
CSF[2] == {
  ClassName -> XI,
  Chirality -> Right,
  Weyl       -> psibar,
  Scalar     -> zbar
}
```

Superfields

```
VSF[1] == {
  ClassName   -> VWZ,
  GaugeBoson  -> V,
  Gaugino     -> lambda,
  Indices     -> {Index[SU2W]}
  }
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Abelian
  - True or False
- CouplingConstant
  - Symbol
- GaugeBoson
  - ClassName
  - (Superfield can also be consistently specified)
- StructureConstant
  - Symbol

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Representation
  - {{Symbol,Index}, {Symbol,Index},...}

```
Representations    -> {{T,Colour}}
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Definitions
  - Applied before Feynman rule calculation

```
Representations    -> {{Ta,SU2D}},
Definitions        -> {Ta[a__]->PauliSigma[a]/2, ep->Eps}
```

Gauge Groups

```
M$GaugeGroups = {
  U1Y  == {
    Abelian          -> True,
    CouplingConstant -> gp,
    GaugeBoson       -> B,
    Charge           -> Y
  },
  SU2L == {
    Abelian           -> False,
    CouplingConstant  -> gw,
    GaugeBoson        -> Wi,
    StructureConstant -> ep,
    Representations   -> {{Ta,SU2D}},
    Definitions       -> {Ta[a__]->PauliSigma[a]/2, ep->Eps}
  },
  SU3C ==  {
    Abelian           -> False,
    CouplingConstant  -> gs,
    GaugeBoson        -> G,
    StructureConstant -> f,
    Representations   -> {{T,Colour}},
    SymmetricTensor   -> dSUN
  }
}
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Covariant Derivative
- Field Strength Tensor
- Superfield Strength Tensor

Gauge Groups

```
FS[A, mu, nu]
FS[ A, mu, nu, a ]
SuperfieldStrengthL[ V, sp    ]
SuperfieldStrengthR[ V, spdot ]
SuperfieldStrengthL[ V, sp   , a ]
SuperfieldStrengthR[ V, spdot, a ]
```

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a{}_{bc} A^b_\mu A^c_\nu \ ,$$

$$W_\alpha = \ -\frac{1}{4}\bar{D}\cdot\bar{D}e^{2gV}D_\alpha e^{-2gV} \ ,$$

$$\overline{W}_{\dot\alpha} = \ -\frac{1}{4}D\cdot De^{-2gV}\bar{D}_{\dot\alpha}e^{2gV} \ ,$$

Gauge Groups

```
DC[phi, mu]
```

$$D_\mu \phi = \partial_\mu \phi - igA_\mu^a T_a \phi$$

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Restrict models
  - Simpler form appropriate for a particular pheno study
  - E.G. CKM matrix can be replaced by a delta function
  - Applied before calculating Feynman rules

Restrictions

```
M$Restrictions = {
            CKM[i_,i_] -> 1,
            CKM[i_?NumericQ, j_?NumericQ] :> 0 /; (i =!= j)
}
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Mass Basis
  - Physical or Unphysical Basis
- Gauge Basis
  - Unphysical Basis

```
MassBasis  -> {W, Wbar},
GaugeBasis -> {Wi[1], Wi[2]},
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Mass Basis
  - Physical or Unphysical Basis
- Gauge Basis
  - Unphysical Basis
- Value
  - Numerical Transformation Matrix

```
MassBasis   -> {W, Wbar},
GaugeBasis -> {Wi[1], Wi[2]},
Value       -> {{1/Sqrt[2],-I/Sqrt[2]},{1/Sqrt[2],I/Sqrt[2]}}
```

Mixings

$$W_\mu^+ = \frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}} \quad \text{and} \quad W_\mu^- = \frac{W_\mu^1 + iW_\mu^2}{\sqrt{2}}$$

```
Mix["l1"] == {
  MassBasis  -> {W, Wbar},
  GaugeBasis -> {Wi[1], Wi[2]},
  Value      -> {{1/Sqrt[2],-I/Sqrt[2]},{1/Sqrt[2],I/Sqrt[2]}}
}
```

```
MassBasis = Value . GaugeBasis
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Mass Basis
  - Physical or Unphysical Basis
- Gauge Basis
  - Unphysical Basis
- Mixing Matrix
  - Defines Transformation Matrix

```
MassBasis     -> {A, Z},
GaugeBasis    -> {B, Wi[3]},
MixingMatrix -> UW,
```

Mixings

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = U_w \begin{pmatrix} B_\mu \\ W^3_\mu \end{pmatrix}$$

```
Mix["l3"] == {
  MassBasis     -> {A, Z},
  GaugeBasis    -> {B, Wi[3]},
  MixingMatrix -> UW,
  BlockName     -> WEAKMIX
}
```

Mixings

```
Mix["dq"] == {
  MassBasis     -> {dq[1, _], dq[2, _], dq[3, _]},
  GaugeBasis    -> {
                     {QL[2, 1, _], QL[2, 2, _], QL[2, 3, _]},
                     {dR[1, _], dR[2, _], dR[3, _]}
                   },
  MixingMatrix -> {CKM, _},
  Value         -> {_, {{1,0,0}, {0,1,0}, {0,0,1}} },
  Inverse       -> {True, _}
}
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Vacuum Expectation Values

```
M$vevs = { { phi1, vev1 }, { phi2, vev2 } }
```

Mixings

```
M$vevs = { { phi1, vev1 }, { phi2, vev2 } }
```

```
Mix["phi"] == {
  MassBasis     -> { {h1, h2}, {a1, a2} },
  GaugeBasis    -> { phi1, phi2 },
  MixingMatrix -> { US, UP }
}
```

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \frac{1}{\sqrt{2}} \left[\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} + U_s^\dagger \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} + i U_p^\dagger \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \right]$$

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Built from the Fields, Parameters, etc.

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Built from the Fields, Parameters, etc.
  - Use ClassName or ClassMembers
  - Antiparticle automatic psi→psibar or anti[psi]
    - Includes γ^0 for fermions
  - Dummy Indices can be used
    - Lorentz/Spin Indices come first
  - Dot/Inner used for anticommuting objects

```
gs Ga[mu, s, r] T[a, i, j] dqbar[s, f, i].dq[r, f, j] G[mu, a]
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Field Strength Tensor
  - FS[G, mu, nu, a]
- Covariant Derivative
  - DC[psi, mu]

```
L = -1/4 FS[G, mu, nu, a] FS[G, mu, nu, a]
          +  I dqbar.Ga[mu].DC[dq, mu]
```

Lagrangian

```
L = -1/4 FS[G, mu, nu, a] FS[G, mu, nu, a]
          +  I dqbar.Ga[mu].DC[dq, mu]
```

$$\mathcal{L}^{\mathcal{QCD}} \equiv -\frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a + i\bar{d}\not{D}d,$$

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- SUSY
  - Kinetic & Gauge Interactions for Chiral Superfields

```
Theta2Thetabar2Component[ CSFKineticTerms[ ] ]
```

Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{chiral}} &= \left[\Phi_i^\dagger\, e^{-2g_j V^j}\,\Phi^i\right]_{\theta\cdot\theta\bar{\theta}\cdot\bar{\theta}} \\ &= D_\mu \phi_i^\dagger D^\mu \phi^i + F_i^\dagger F^i - \frac{i}{2}\Big(D_\mu \bar{\psi}_i \bar{\sigma}^\mu \psi^i - \bar{\psi}_i \bar{\sigma}^\mu D_\mu \psi^i\Big) \\ &+ i\sqrt{2} g_j \bar{\lambda}^{ja}\cdot\bar{\psi}_i T_a \phi^i - i\sqrt{2} g_j \phi_i^\dagger T_a \psi^i \cdot \lambda^{ja} - g_j D^{ja} \phi_i^\dagger T_a \phi^i\end{aligned}$$

```
Theta2Thetabar2Component[ CSFKineticTerms[ ] ]
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- SUSY
  - Kinetic & Gauge Interactions for Vector Superfields

```
Theta2Component[ VSFKineticTerms[ ] ] +
Thetabar2Component[ VSFKineticTerms[ ] ]
```

Lagrangian

$$\begin{aligned}\mathcal{L}_V &= \frac{1}{16g^2}\Big[W^{\alpha a}W_{\alpha a}\Big]_{\theta\cdot\theta} + \text{h.c.}\\ &= -\frac{1}{4}F_a^{\mu\nu}F_{\mu\nu}^a + \frac{i}{2}(\lambda_a\sigma^\mu D_\mu\bar{\lambda}^a - D_\mu\lambda_a\sigma^\mu\bar{\lambda}^a) + \frac{1}{2}D^aD_a\end{aligned}$$

```
Theta2Component[ VSFKineticTerms[ ] ] +
Thetabar2Component[ VSFKineticTerms[ ] ]
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Superpotential
  - Represented here by SuperW

```
Theta2Component[SuperW] + Thetabar2Component[HC[SuperW]]
```

Lagrangian

$$\mathcal{L}_W = \Big[W(\Phi)\Big]_{\theta\cdot\theta} + \text{h.c.} = F^i \frac{\partial W(\phi)}{\partial \phi^i} + \frac{1}{2}\frac{\partial^2 W(\phi)}{\partial \phi^i \partial \phi^j}\psi^i \cdot \psi^j + \text{h.c.}$$

```
Theta2Component[SuperW] + Thetabar2Component[HC[SuperW]]
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Equations of Motion
  - Auxiliary Fields

```
SolveEqMotionFD[Lag]
SolveEqMotionF[SolveEqMotionD[Lag]]
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian

- Weyl→Dirac Fields

`WeylToDirac[]`

Lagrangian

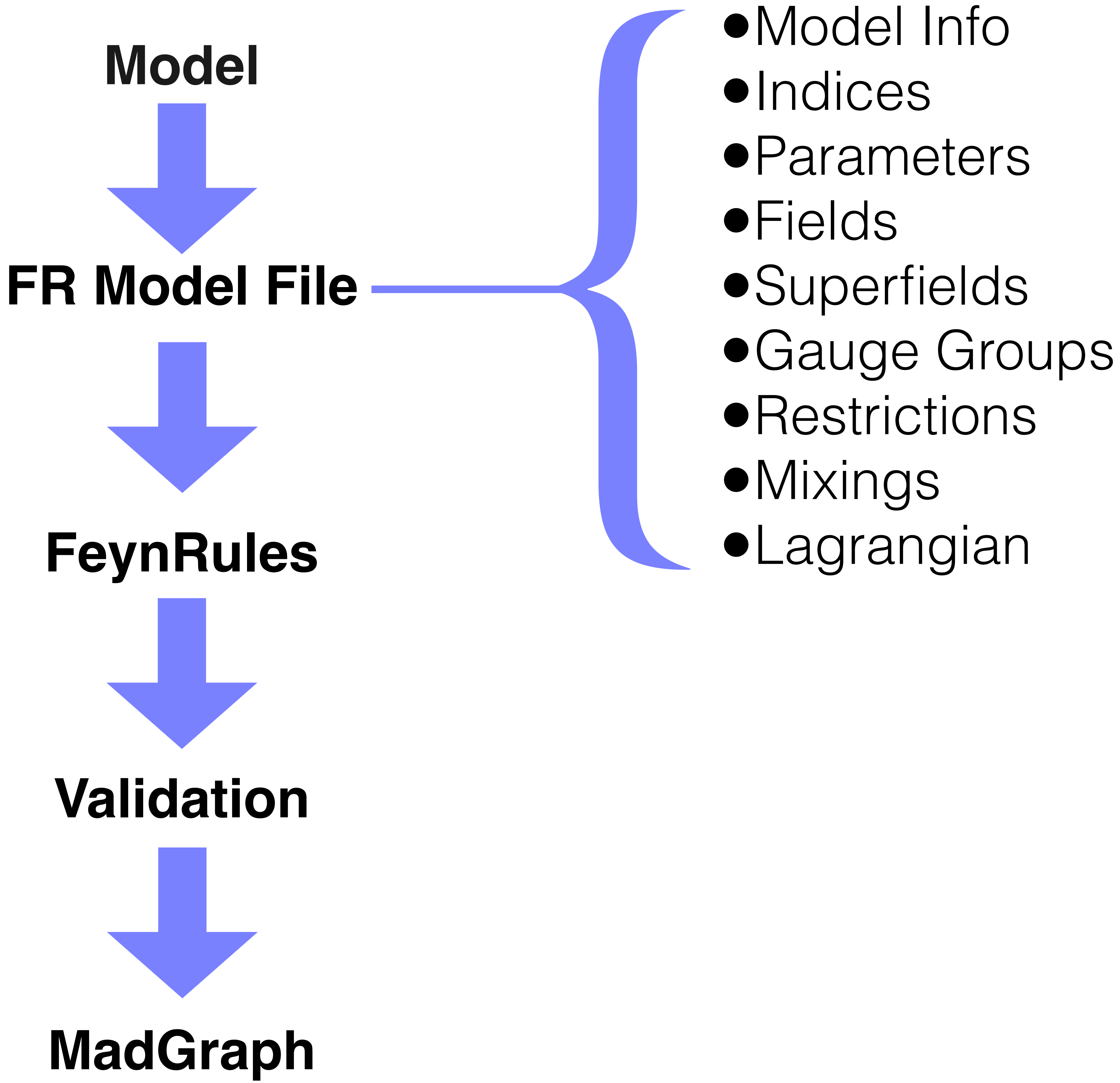
```
LC=Theta2Thetabar2Component[CSFKineticTerms[]];
LV=Theta2Component[VSFKineticTerms[]] +
      Thetabar2Component[VSFKineticTerms[]];
LW=Theta2Component[SuperW]+Thetabar2Component[HC[SuperW]];
Lag = LC + LV + LW;
```

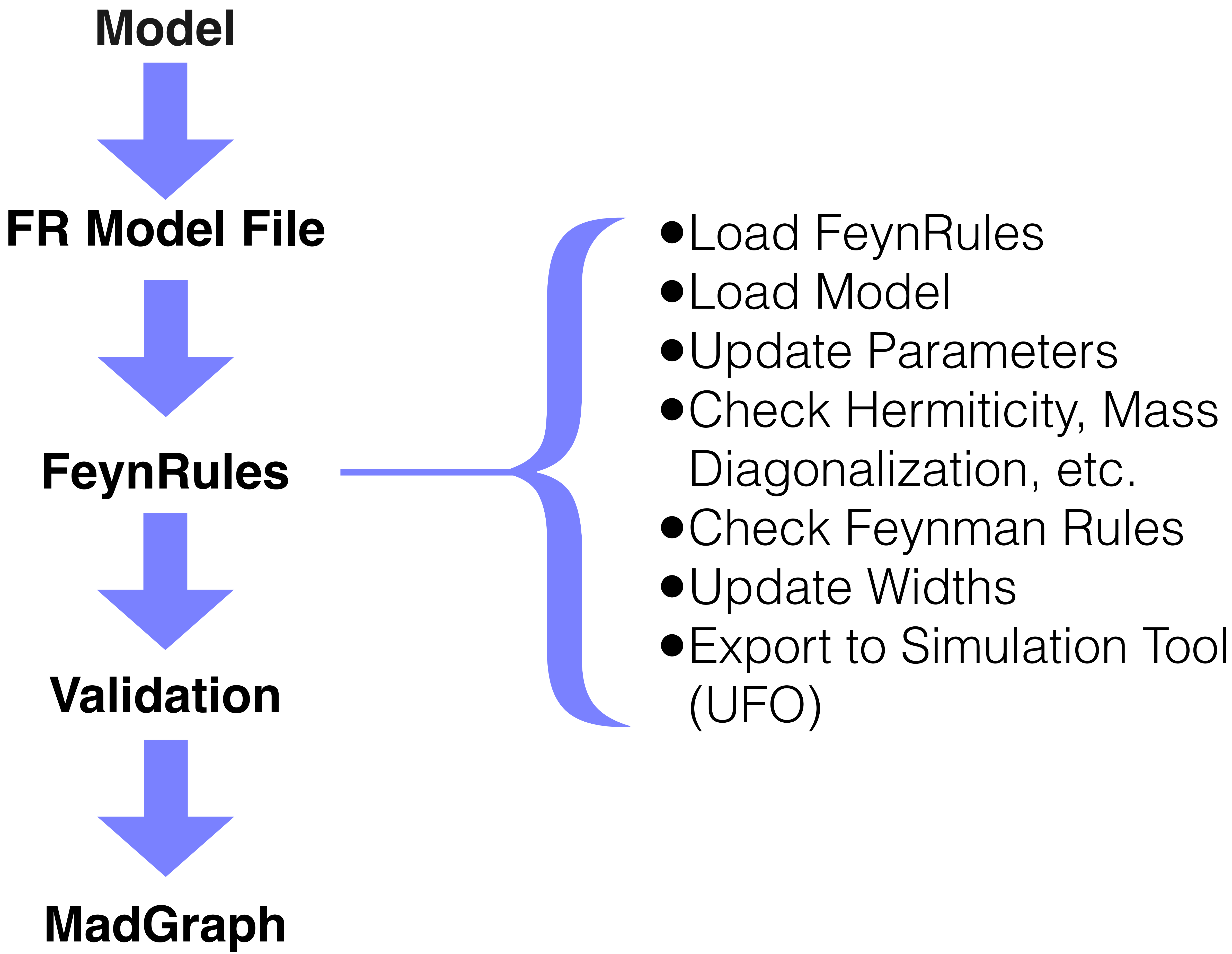
```
SolveEqMotionFD[Lag]
SolveEqMotionF[SolveEqMotionD[Lag]]
```

```
WeylToDirac[]
```

FR Model File

- Model Info
- Indices
- Parameters
- Fields
- Superfields
- Gauge Groups
- Restrictions
- Mixings
- Lagrangian


Model
FR Model File
FeynRules
Validation
MadGraph
Model Info
Indices
Parameters
Fields
Superfields
Gauge Groups
Restrictions
Mixings
Lagrangian


Model
FR Model File
FeynRules
Validation
MadGraph
•Load FeynRules
•Load Model
•Update Parameters
•Check Hermiticity, Mass Diagonalization, etc.
•Check Feynman Rules
•Update Widths
•Export to Simulation Tool (UFO)

FeynRules

- Load FeynRules
- Load Model
- Update Parameters
- Check Hermiticity, Mass Diagonalization, etc.
- Check Feynman Rules
- Update Widths
- Export to Simulation Tool (UFO)

FeynRules

- <u>Load FR</u>
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

- Set $FeynRulesPath
- Set Directory
- <<FeynRules`

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

- Set Directory
  - Else output will be put in FR directory
- Load Model

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

- Set Directory
  - Else output will be put in FR directory
- Load Model
- Load Restrictions

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
LoadRestriction[ file1.rst, file2.rst, ... ]
```

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

- Update Parameters

```
UpdateParameters[ gs -> 0.118 , ee -> 0.33 ]
ReadLHAFile[ Input -> "LH-file" ]
```

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

- Check Hermiticity
- Check Mass Spectrum

`CheckHermiticity[` $\mathcal{L}$ `];`

`CheckMassSpectrum[` $\mathcal{L}$, *options* `]`

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

- FeynmanRules
    - ScreenOutput
    - FlavorExpand
    - MinParticles
    - MaxParticles
    - SelectParticles
    - Contains
    - Free

```
vertsQCD = FeynmanRules[ LQCD ];
```

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

- Many SUSY Commands

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

- Compute Widths
- Update Widths

```
vertices = FeynmanRules[ L ];
decays = ComputeWidths[ vertices ];
UpdateWidths[ decays ];
```

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- **Export**

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- FeynRules Core
  - Does Not Require these Conventions
- Feynman Diagram Calculators
  - Do Require these Conventions
- Export Interfaces
  - Do Require these Conventions

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- Pure ASCII
  - ParticleName
  - AntiParticleName

```
ParticleName     -> {"ne", "nm", "nt"},
AntiParticleName -> {"ne~", "nm~", "nt~"}
```

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- Particle Data Group ID
  - Many particles already numbered
  - New particles should be numbered starting from 9000001
  - FR will automatically assign these

```
PDG -> {2,4,6}
```

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- Some SM parameters fixed:
  - aS (Strong Coupling)
  - gs (Strong Coupling)
  - aEWM1 (EW Coupling)
  - Gf (Fermi Constant)
  - ee (Electric Coupling)

SM Parameters

```
aS    == {
   ParameterType    -> External,
   BlockName        -> SMINPUTS,
   OrderBlock       -> 3,
   Value            -> 0.1184,
   InteractionOrder -> {QCD,2},
   Description      -> "Strong coupling constant at the Z pole"
  },

gs == {
   ParameterType    -> Internal,
   Value            -> Sqrt[4 Pi aS],
   InteractionOrder -> {QCD,1},
   ParameterName    -> G,
   Description      -> "Strong coupling constant at the Z pole"
  },
```

SM Parameters

```
Gf == {
   ParameterType    -> External,
   BlockName        -> SMINPUTS,
   OrderBlock       -> 2,
   Value            -> 1.16637*^-5,
   InteractionOrder -> {QED,2},
   Description      -> "Fermi constant"
  },
```

SM Parameters

```
aEWM1 == {
   ParameterType    -> External,
   BlockName        -> SMINPUTS,
   OrderBlock       -> 1,
   Value            -> 127.9,
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z pole"
  },
aEW == {
   ParameterType    -> Internal,
   Value            -> 1/aEWM1,
   InteractionOrder -> {QED,2},
   Description      -> "Electroweak coupling contant"
  },

ee == {
   ParameterType    -> Internal,
   Value            -> Sqrt[4 Pi aEW],
   InteractionOrder -> {QED,1},
   Description      -> "Electric coupling constant"
  }
```

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- QCD Structure
  - Gauge group declaration
  - Indices

QCD

```
SU3C == {
    Abelian             -> False,
    CouplingConstant    -> gs,
    GaugeBoson          -> G,
    StructureConstant   -> f,
    Representations     -> {{T, Colour},
                            {T6, Sextet}},
    SymmetricTensor     -> dSUN
  }
```

```
IndexRange[ Index[ Colour ] ] = Range[3];
IndexRange[ Index[ Sextet ] ] = Range[6];
IndexRange[ Index[ Gluon ] ] = Range[8];
```

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- InteractionOrder
  - How many powers of a fundamental coupling
- Hierarchy
  - The hierarchy of fundamental couplings
- OrderLimit
  - The largest power of a fundamental coupling in a diagram

Interaction Order

```
InteractionOrder -> {QCD,2}

InteractionOrder -> {QED,1}

M$InteractionOrderHierarchy = {
  {QCD,1},
  {NP,1},
  {QED,2}
}

M$InteractionOrderLimit = {
  {NP,2}
}
```

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- Automatic Mass Diagonalization
  - WriteASperGe[Lag, options]
  - Requires Gnu Scientific Library (GSL)

```
WriteASperGe[ Lag, Output -> dirname ]

./ASperGe <inputfile> <outputfile>
```

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- CalcHEP Output
  - WriteCHOutput[Lag, options]
  - Options:
    - CHAutoWidths : Automatic width calculation
    - LHASupport : Support for reading LHA files

$$\texttt{WriteCHOutput[}\ \mathcal{L}_1, \mathcal{L}_2, \ldots, \mathit{options}\ \texttt{]}$$

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- FeynArts Output
  - WriteFeynArtsOutput[Lag, options]
  - Completely general operators supported (.gen file)

$$\texttt{WriteFeynArtsOutput[}\ \mathcal{L}_1, \mathcal{L}_2, \ldots, \mathit{options}\ \texttt{]}$$

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- Sherpa Output
  - WriteSHOutput[Lag, options]

$$\texttt{WriteSHOutput}[\mathcal{L}_1, \mathcal{L}_2, \ldots, \mathit{options}]$$

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- TeX Output
  - WriteLaTeXOutput[Lag, Verts, options]

WriteLaTeXOutput[$\mathcal{L}_1, \mathcal{L}_2, \ldots, V_1, V_2, \ldots, \mathit{options}$]

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- Universal FeynRules Output
  - WriteUFO[Lag, options]
  - Options:
    - AddDecays : Automatic 1→2 Decays
  - Supported by Aloha, MadGraph5, MadAnalysis5
  - Planned support by GoSam and Herwig++

$$\texttt{WriteUFO}[\mathcal{L}_1, \mathcal{L}_2, \ldots, \, options]$$

Export

- Conventions
  - Name Restrictions
  - PDG ID
  - SM Restrictions
  - Gauge Choice
  - Interaction Order
- Interfaces
  - ASperGe
  - CalcHEP
  - FeynArts
  - Sherpa
  - TeX
  - UFO
  - Whizard

- Whizard Output
  - WriteWOOutput[Lag, options]
  - Options:
    - WOAutoGauge : Automatically generate R_ξ gauge from Feynman gauge

$$\texttt{WriteWOOutput}[\mathcal{L}_1, \mathcal{L}_2, \ldots, \textit{options}]$$

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- **Export**

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

Significantly Faster

Efficiency

SM

Command	FR 1.6	FR 2.0 - 1	FR 2.0 - 2	FR 2.0 - 4	FR 2.0 - 8
`FeynmanRules`	5.84 s	4.98 s	3.09 s	2.32 s	1.93 s
`WriteCHOutput`	9.33 s	9.51 s	8.05 s	6.26 s	5.53 s
`WriteUFO`	9.05 s	8.82 s	7.89 s	6.51 s	6.05 s

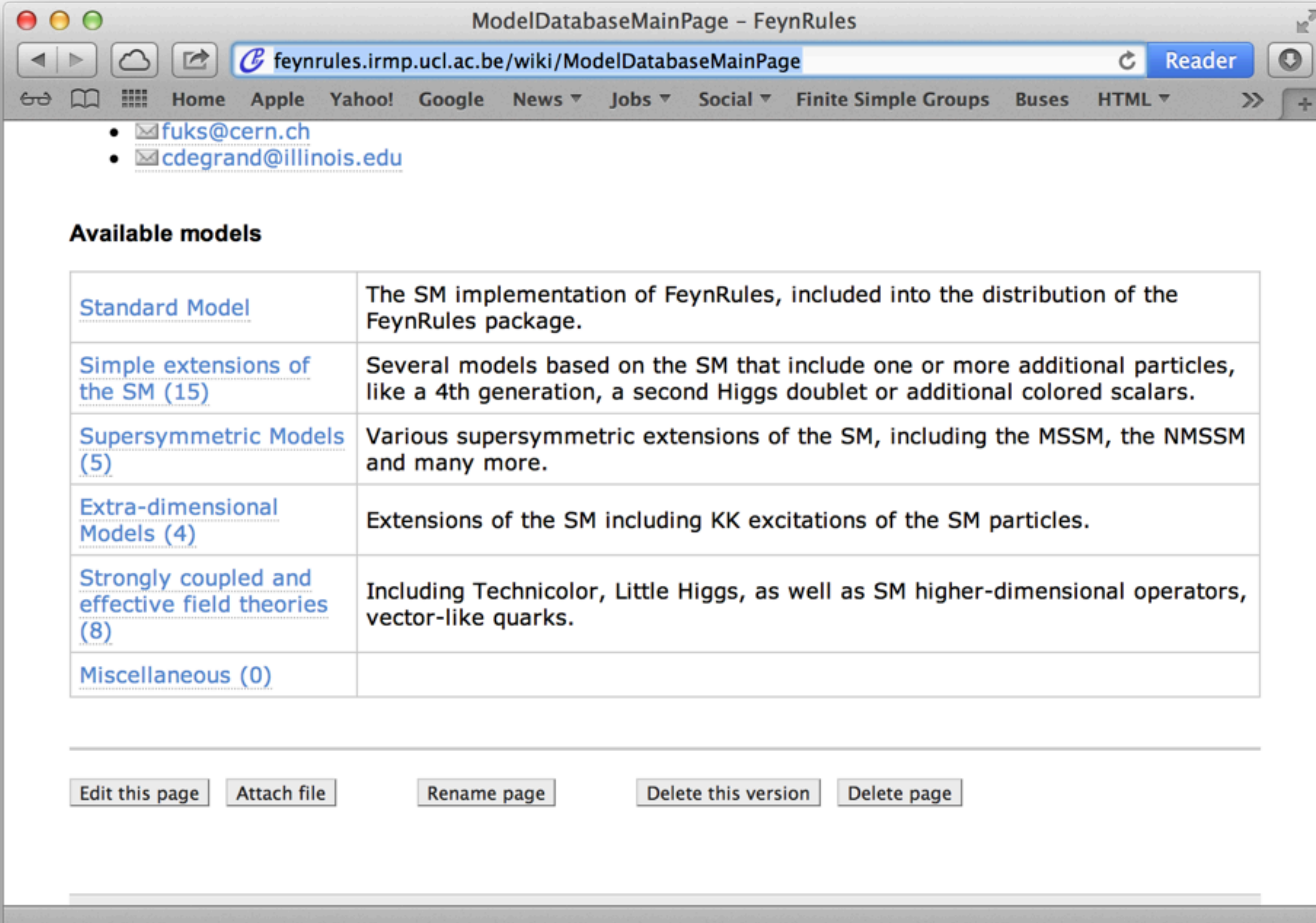
MSSM

Command	FR 1.6	FR 2.0 - 1	FR 2.0 - 2	FR 2.0 - 4	FR 2.0 - 8
`FeynmanRules`	325.5 s	213.7 s	79.7 s	62.6 s	41.0 s
`WriteCHOutput`	853.4 s	618.9 s	350.8 s	283.9 s	204.4 s
`WriteUFO`	436.0 s	518.5 s	316.1 s	273.8 s	239.7 s

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export

Model Database


ModelDatabaseMainPage – FeynRules

feynrules.irmp.ucl.ac.be/wiki/ModelDatabaseMainPage

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- fuks@cern.ch
- cdegrand@illinois.edu

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM (15)	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models (5)	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models (4)	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories (8)	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous (0)	

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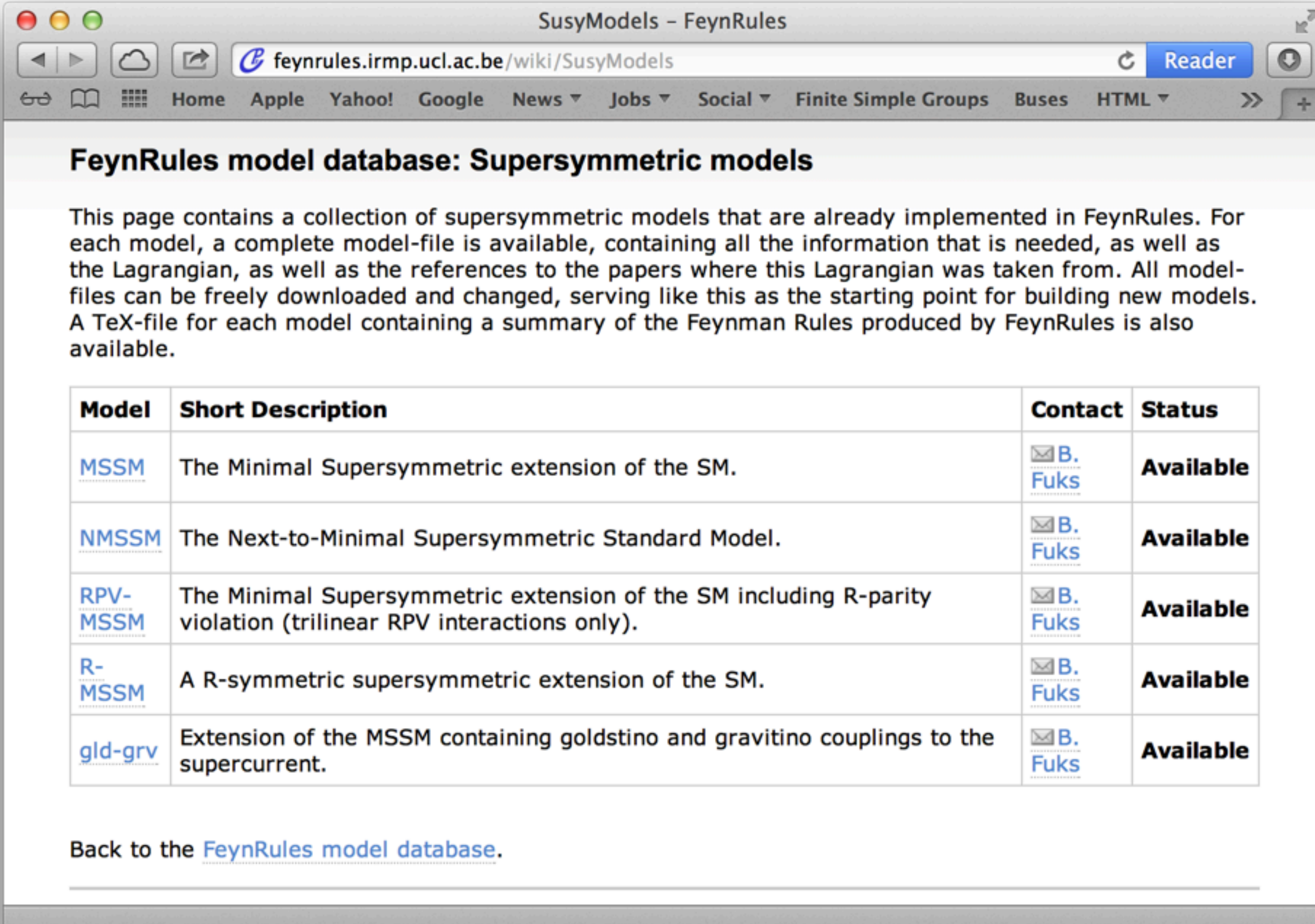


SusyModels – FeynRules

feynrules.irmp.ucl.ac.be/wiki/SusyModels

FeynRules model database: Supersymmetric models

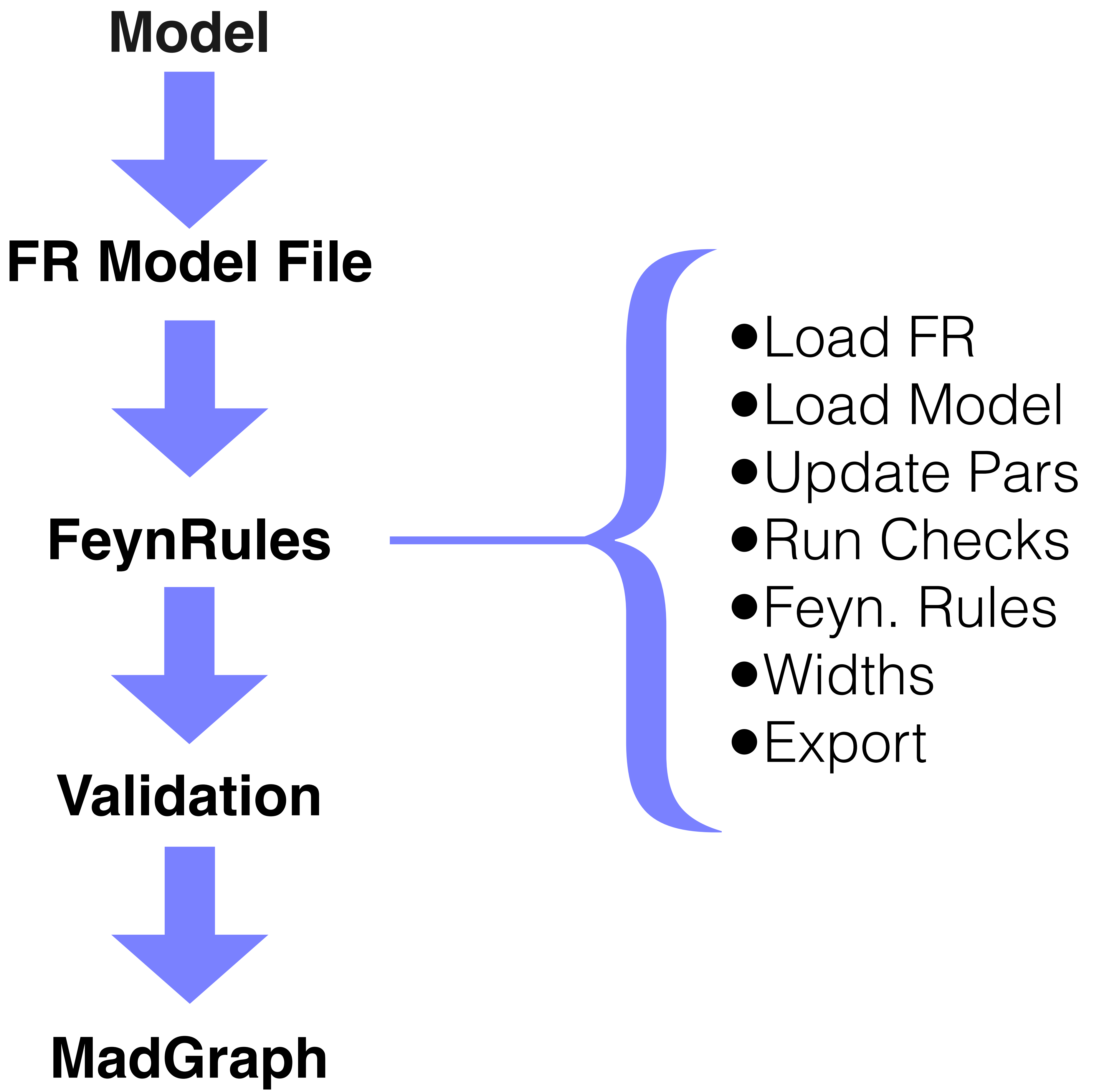
This page contains a collection of supersymmetric models that are already implemented in FeynRules. For each model, a complete model-file is available, containing all the information that is needed, as well as the Lagrangian, as well as the references to the papers where this Lagrangian was taken from. All model-files can be freely downloaded and changed, serving like this as the starting point for building new models. A TeX-file for each model containing a summary of the Feynman Rules produced by FeynRules is also available.

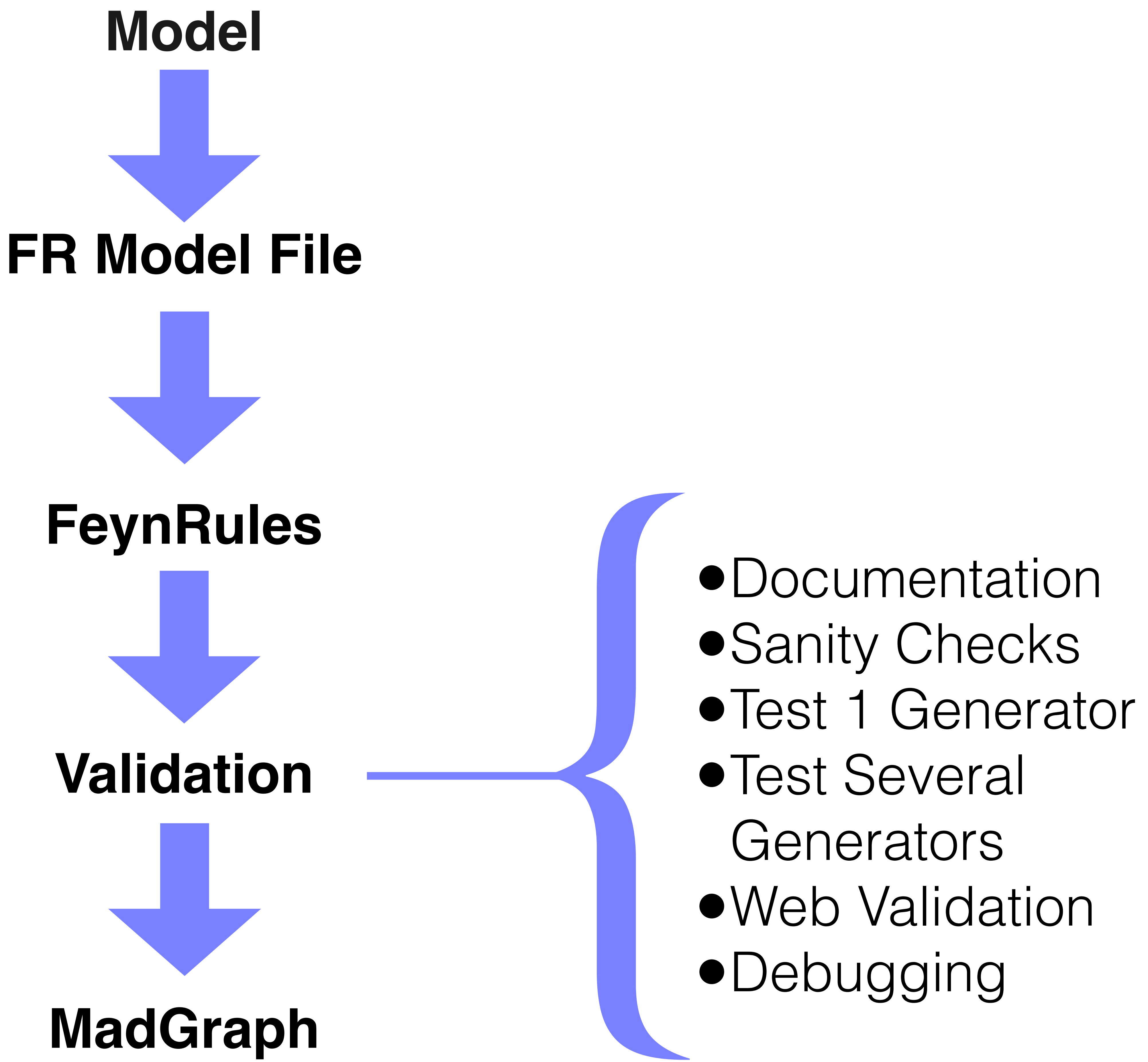
Model	Short Description	Contact	Status
MSSM	The Minimal Supersymmetric extension of the SM.	B. Fuks	**Available**
NMSSM	The Next-to-Minimal Supersymmetric Standard Model.	B. Fuks	**Available**
RPV-MSSM	The Minimal Supersymmetric extension of the SM including R-parity violation (trilinear RPV interactions only).	B. Fuks	**Available**
R-MSSM	A R-symmetric supersymmetric extension of the SM.	B. Fuks	**Available**
gld-grv	Extension of the MSSM containing goldstino and gravitino couplings to the supercurrent.	B. Fuks	**Available**

Back to the FeynRules model database.

FeynRules

- Load FR
- Load Model
- Update Pars
- Run Checks
- Feyn. Rules
- Widths
- Export


Model
FR Model File
FeynRules
Validation
MadGraph
Load FR
Load Model
Update Pars
Run Checks
Feyn. Rules
Widths
Export


Model
FR Model File
FeynRules
Validation
MadGraph
•Documentation
•Sanity Checks
•Test 1 Generator
•Test Several Generators
•Web Validation
•Debugging

Validation

- Documentation
- Sanity Checks
- 1 Generator
- >1 Generators
- Web Validation
- Debugging

Validation

- Documentation
- Sanity Checks
- 1 Generator
- >1 Generators
- Web Validation
- Debugging

- Tracibility & Reproducibility
  - Model Theory References
  - Model Implementation Details
  - Validation Details
  - Software Versions

Validation

- Documentation
- Sanity Checks
- 1 Generator
- >1 Generators
- Web Validation
- Debugging

- Hermiticity
- Gauge Invariance
- Agreement with literature

Validation

- Documentation
- Sanity Checks
- 1 Generator
- >1 Generators
- Web Validation
- Debugging

- Numerical Cross Sections/Widths
  - Compared with literature
  - Gauge Invariance
  - Unitarity Cancellations
  - Comparison with SM results where appropriate

Validation

- Documentation
- Sanity Checks
- 1 Generator
- <u>>1 Generators</u>
- Web Validation
- Debugging

- Between Generators
  - Large set of processes
  - Gauge invariance
  - With independent implementations if available

Validation

- Documentation
- Sanity Checks
- 1 Generator
- >1 Generators
- Web Validation
- Debugging

- Automated comparison
  - All 2→2 processes
  - Feynman & unitary gauges
  - CalcHEP
  - MadGraph
  - Whizard
  - Need username/password

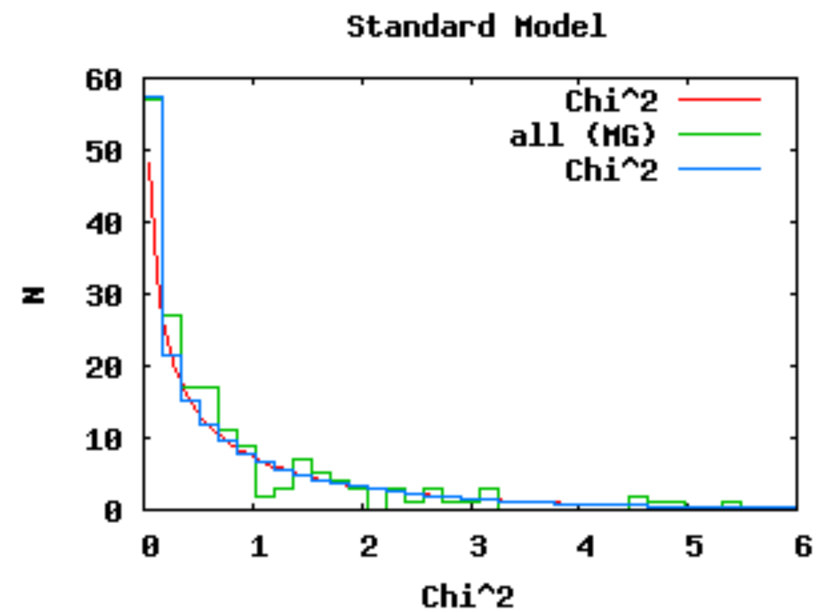
`http://feynrules.phys.ucl.ac.be/validation`

Web Validation

Standard Model : all (MG)

feynrules.irmp.ucl.ac.be/validation/author/validation?vdtnId=413;start=0

Home Apple Yahoo! Google News Jobs Social Finite Simple Groups Buses HTML



LL=17.9 for 22 degrees of freedom.
The probability of this being a statistical fluctuation is 71.4583054701%.

	$\sqrt{s}$	p_{Tcut}	Best	MG5(F)	MG5(u)	X^2
Z , W+ → c , s~	684.0	171.0	6.650E-01	6.633E-01	6.668E-01	5.3E+00
ve , e+ → t , b~	707.0	176.75	5.072E-01	5.081E-01	5.061E-01	4.9E+00
t , t~ → H , H	2336.0	584.0	5.680E-02	5.691E-02	5.665E-02	4.6E+00
Z , Z → d , d~	730.0	182.5	7.431E-01	7.411E-01	7.448E-01	4.6E+00
mu- , mu+ → t , t~	1376.0	344.0	7.423E-02	7.412E-02	7.433E-02	4.5E+00
Z , ta- → ta- , H	859.0	214.75	6.042E-01	6.034E-01	6.061E-01	3.2E+00

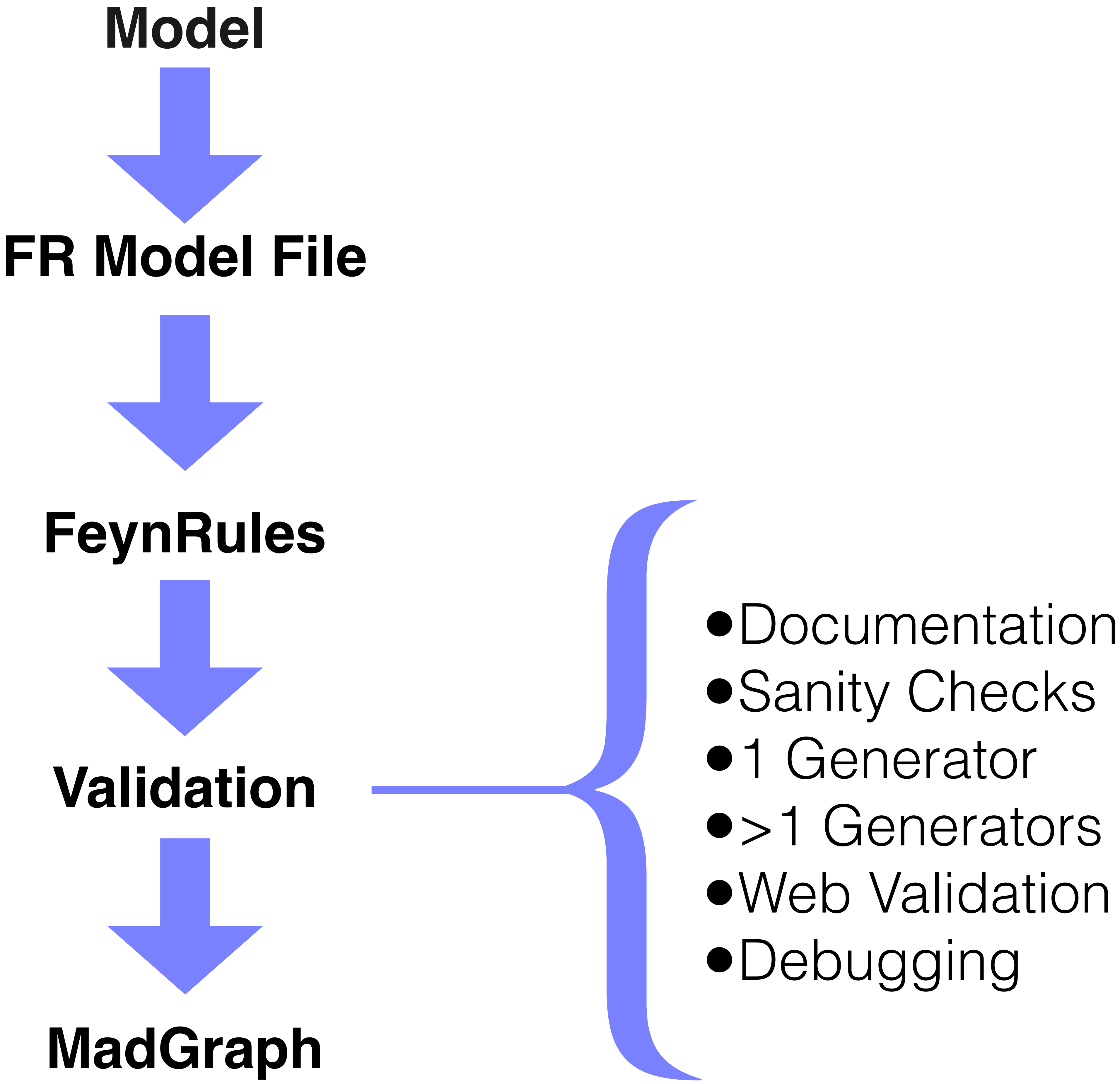
Validation

- Documentation
- Sanity Checks
- 1 Generator
- >1 Generators
- Web Validation
- <u>Debugging</u>

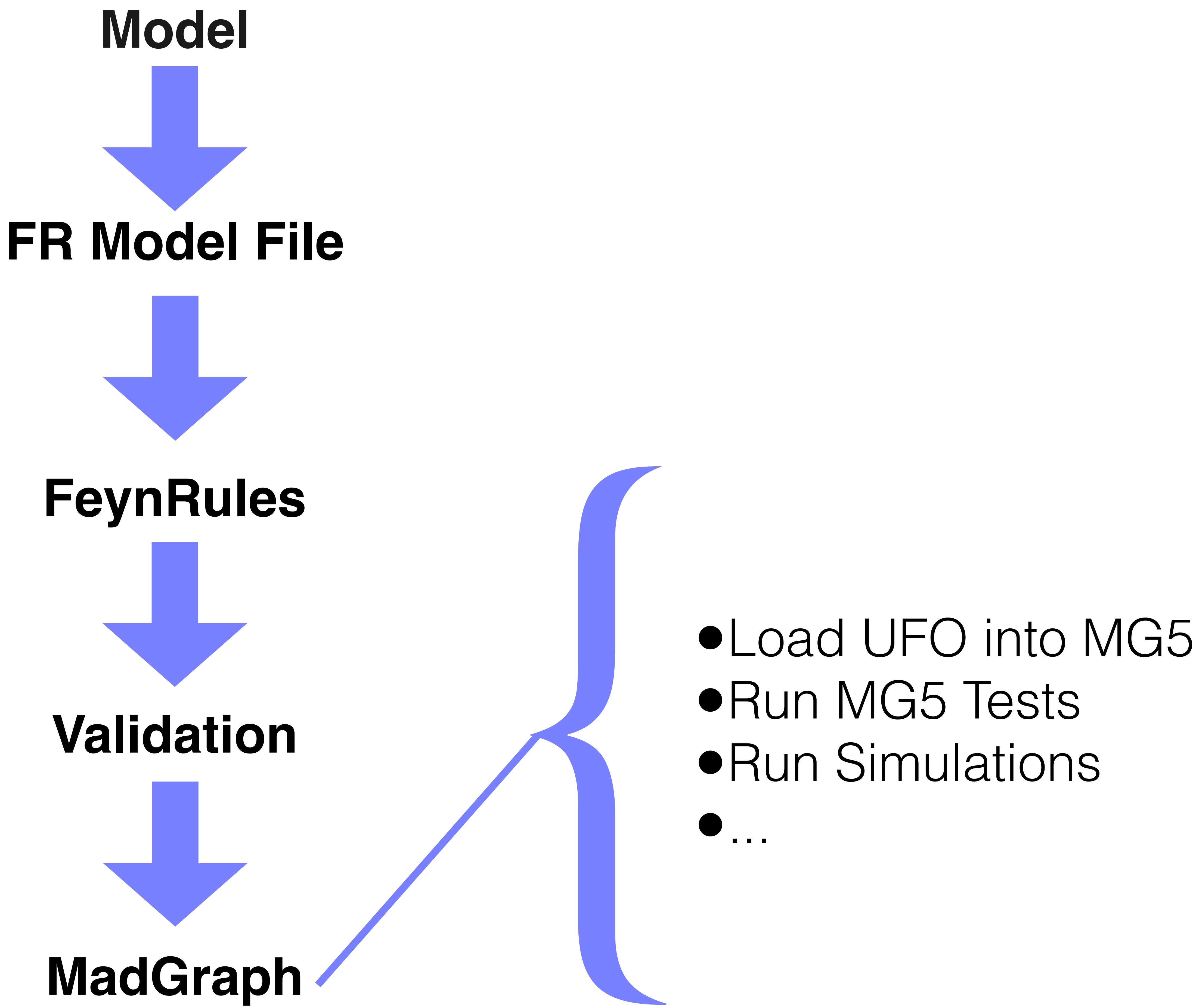
- Comment Out
  - Syntax errors can be found by commenting out until the error is found.
- Web validation
  - Help find problematic vertices

Validation

- Documentation
- Sanity Checks
- 1 Generator
- >1 Generators
- Web Validation
- Debugging



Model
FR Model File
FeynRules
Validation
MadGraph
•Documentation
•Sanity Checks
•1 Generator
•>1 Generators
•Web Validation
•Debugging


Model
FR Model File
FeynRules
Validation
MadGraph
Load UFO into MG5
Run MG5 Tests
Run Simulations
...

MadGraph

- Load UFO into MG5
- Run MG5 Tests
- Run Simulations
- ...

- UFO Model Dir
  - Copy the UFO Model dir to the MadGraph5 models dir

```
cp -r  ModelName_UFO  .../MadGraph5_v1_5_12/models/.
```

MadGraph

- Load UFO into MG5
- Run MG5 Tests
- Run Simulations
- ...

- Load UFO Model
  - During MG5 session

mg5>import model ModelName_UFO

MadGraph

- Load UFO into MG5
- Run MG5 Tests
- Run Simulations
- ...

- Import UFO Model
  - During MG5 session
- Like Built-In Model
  - Everything from this point like a built-in model

mg5>import model ModelName_UFO

MadGraph

- Load UFO into MG5
- Run MG5 Tests
- Run Simulations
- ...

- For example:
  - check process
    - Gauge invariance
    - Lorentz invariance
    - Permutation

mg5>check p p > uv uv~

MadGraph

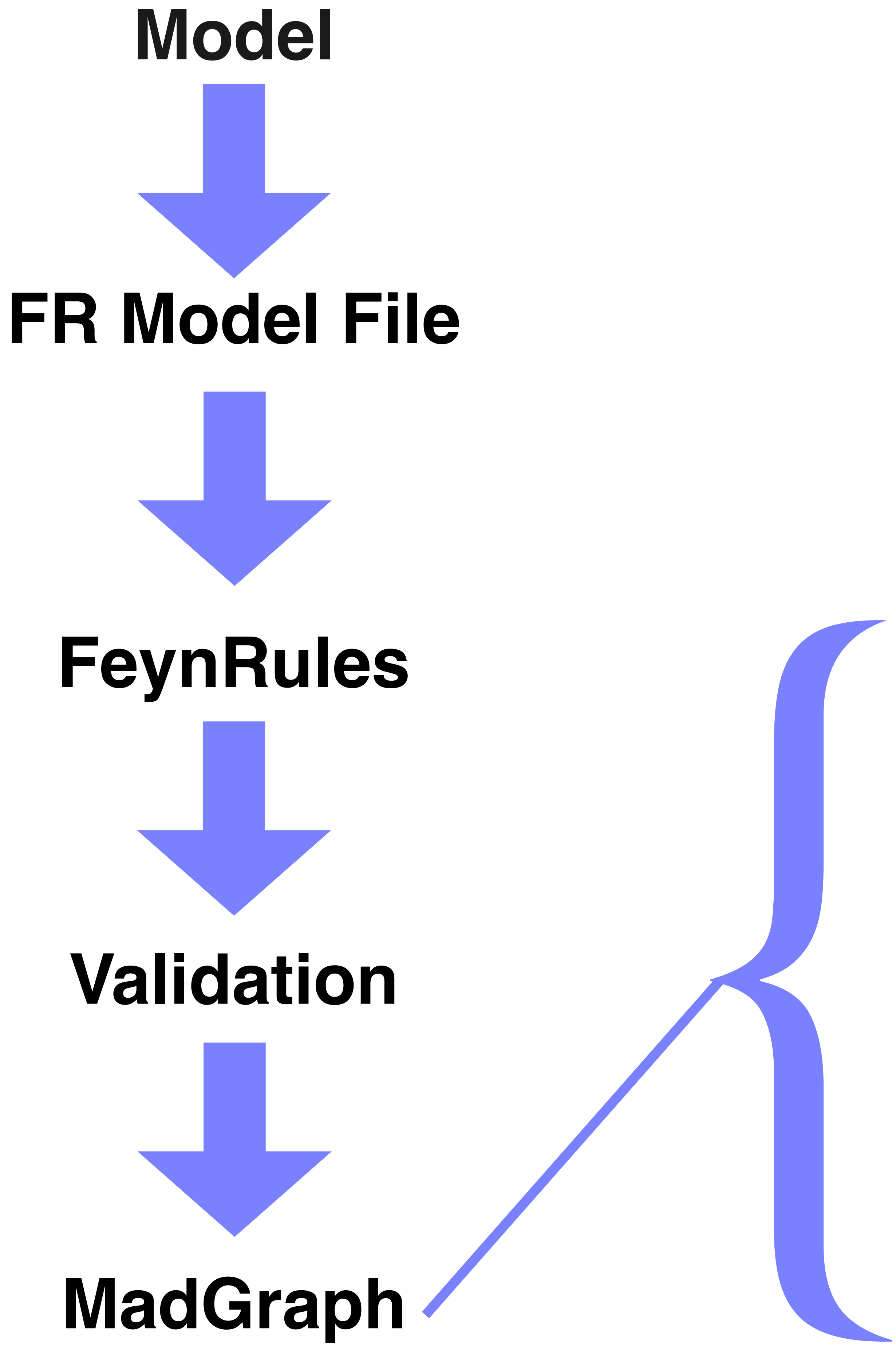
- Load UFO into MG5
- Run MG5 Tests
- Run Simulations
- ...

- Like Built-In Models
  - generate
  - output
  - launch
  - ...

mg5>generate p p > uv uv~
mg5>output
mg5>launch

MadGraph

- Load UFO into MG5
- Run MG5 Tests
- Run Simulations
- Enjoy!



- Load **UFO** into MG5
- Run MG5 Tests
- Run Simulations
- Enjoy!

UFO & ALOHA

- UFO
- ALOHA

- Universal FeynRules Output
  - DeGrande, Duhr, Fuks, Grellscheid, Mattelaer and Reiter (CPC 183, 1201 (2012))
  - Full FeynRules model info included

UFO & ALOHA

- UFO
- ALOHA

- Universal FeynRules Output
  - DeGrande, Duhr, Fuks, Grellscheid, Mattelaer and Reiter (CPC 183, 1201 (2012))
  - Full FeynRules model info included
- Not tied to specific matrix element generator (universal)
  - Default model format for MadGraph 5, GoSam and Herwig++(future)

UFO & ALOHA

- UFO
- ALOHA

- Universal FeynRules Output
  - DeGrande, Duhr, Fuks, Grellscheid, Mattelaer and Reiter (CPC 183, 1201 (2012))
  - Full FeynRules model info included
- Not tied to specific matrix element generator (universal)
  - Default model format for MadGraph 5, GoSam and Herwig++(future)
- General operators supported
  - Completely general Lorentz structures
    - 4-fermion operators
    - operators with >4 particles
  - 3, 6 and 8 color reps supported

UFO & ALOHA

- UFO
- ALOHA
  - Automatic Language-Independent Output of Helicity Amplitudes
    - de Aquino, Link, Maltoni, Mattelaer and Steltzer (CPC 183, 2254 (2012))
    - Convert UFO Lorentz structure to Fortran/C++ code required to calculate helicity amplitudes

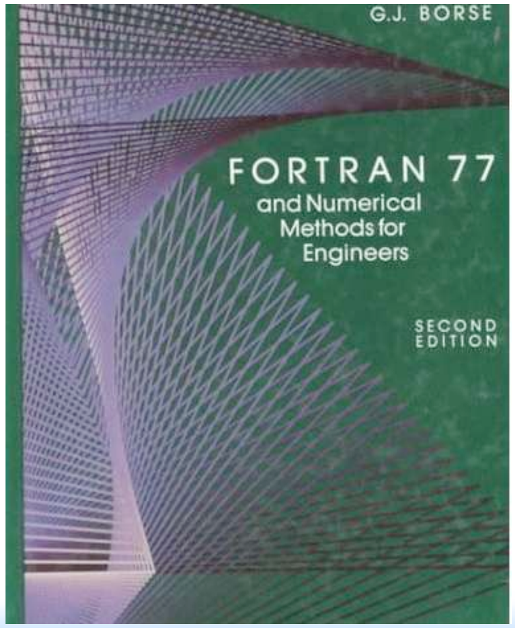
ALOHA

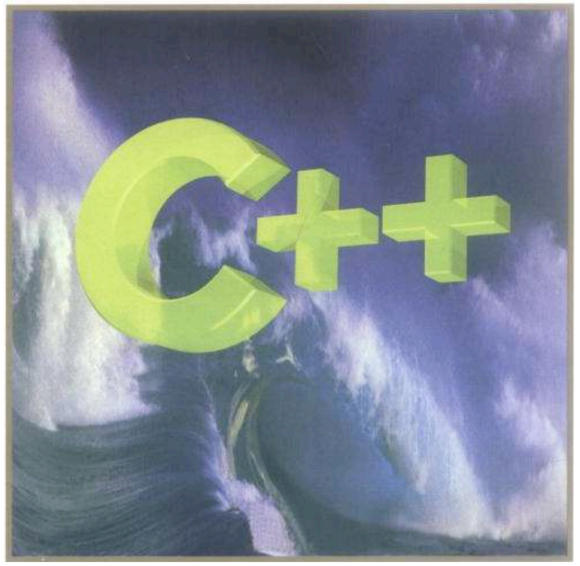
ALOHA ~~Google~~ translate

From: UFO ▾ To: Helicity [Translate]

```
VVVV6 = Lorentz(name = 'VVVV6',
              spins = [ 3, 3, 3, 3 ],
              structure = 'Metric(1,4)*Metric(2,3) -Metric(1,3)*Metric(2,4)')
```

Type text or a website address or translate a document.





ALOHA

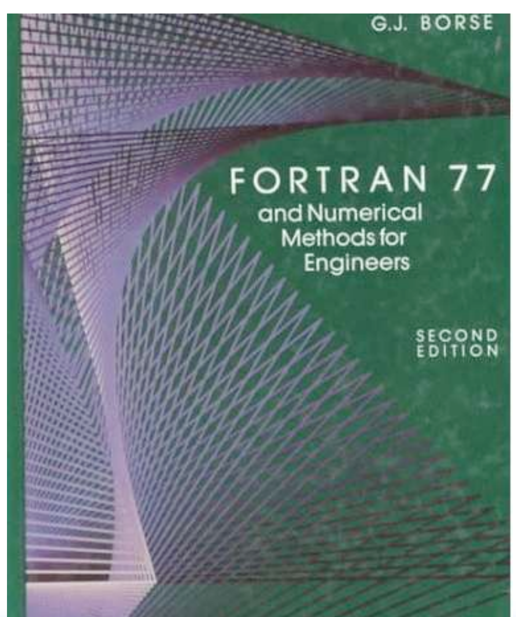
ALOHA

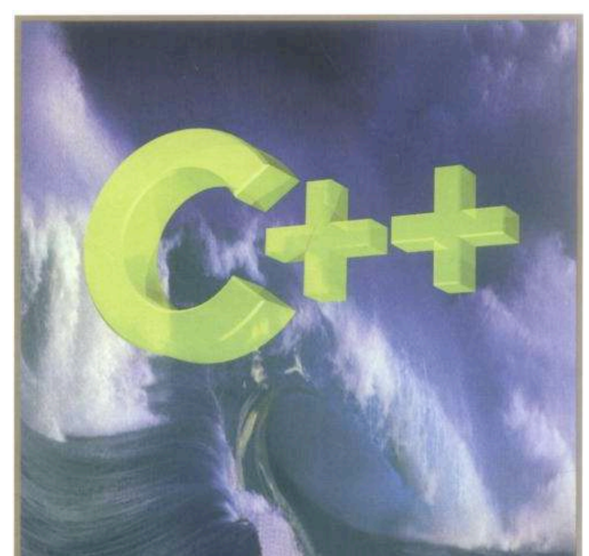
~~Google~~ translate

From: UFO ▾ To: Helicity Translate

```
 VERTEX = COUP*( (V4(1)*( (V2(1)*( (0, -1)*(V3(2)*V1(2))
$ +(0, -1)*(V3(3)*V1(3))+(0, -1)*(V3(4)*V1(4))))+(V1(1)*( (0, 1)
$ *(V3(2)*V2(2))+(0, 1)*(V3(3)*V2(3))+(0, 1)*(V3(4)*V2(4))))))
$ +( (V4(2)*( (V2(2)*( (0, -1)*(V3(1)*V1(1))+(0, 1)*(V3(3)*V1(3))
$ +(0, 1)*(V3(4)*V1(4))))+(V1(2)*( (0, 1)*(V3(1)*V2(1))+(0,
$ -1)*(V3(3)*V2(3))+(0, -1)*(V3(4)*V2(4))))))+( (V4(3)*( (V2(3)
```

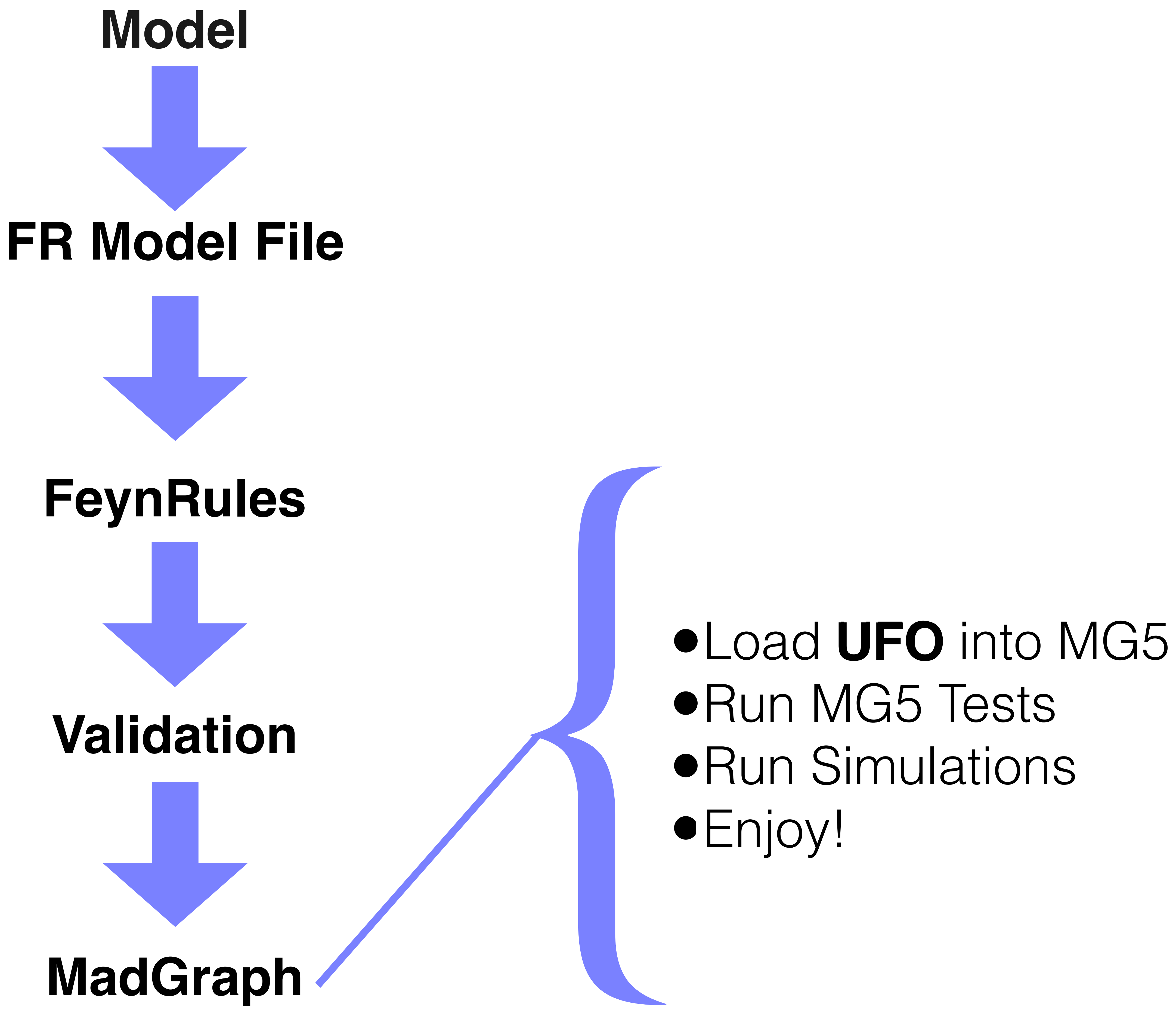
Type text or a website address or translate a document.



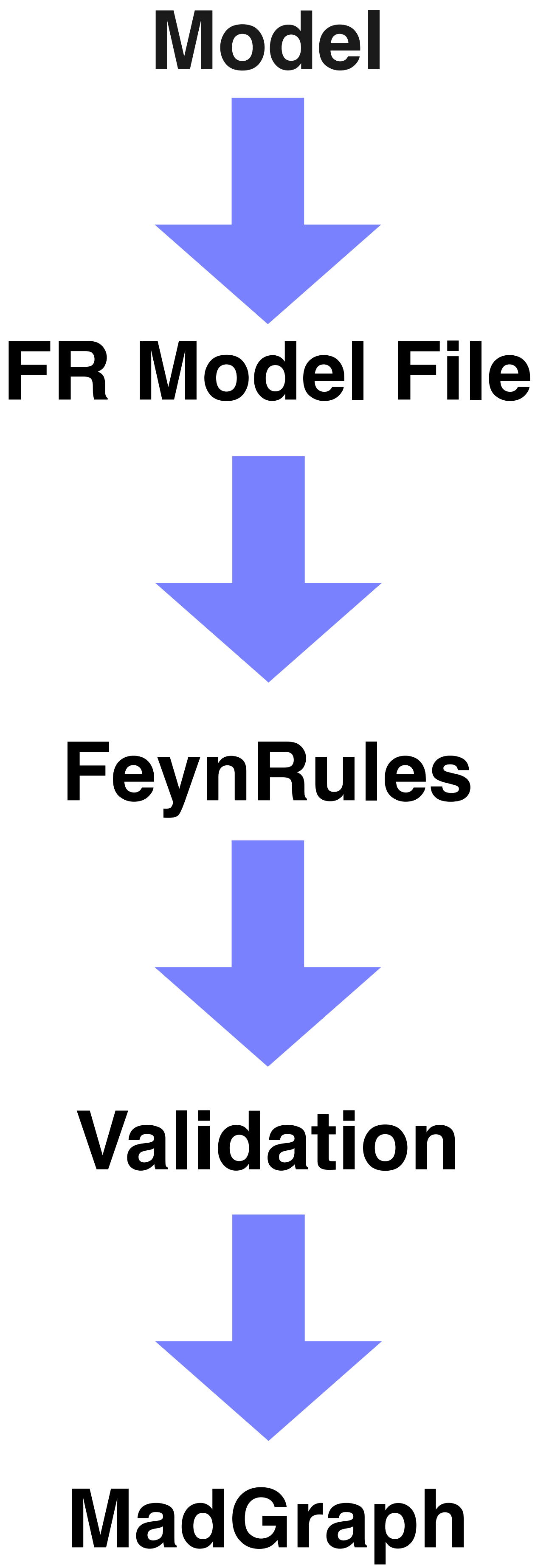


UFO & ALOHA

- UFO
- ALOHA



Model
FR Model File
FeynRules
Validation
MadGraph
•Load **UFO** into MG5
•Run MG5 Tests
•Run Simulations
•Enjoy!


Model
FR Model File
FeynRules
Validation
MadGraph

FeynRules Future

- InSurGe
- FR@NLO
- Galileo

- One-loop renormalization equations
  - Alloul, de Causmaecker and Fuks
  - Generic SUSY models

FeynRules Future

- InSurGe
- FR@NLO
- Galileo

- Automatic Counterterms
  - Degrande, Duhr, Fuks and Hahn

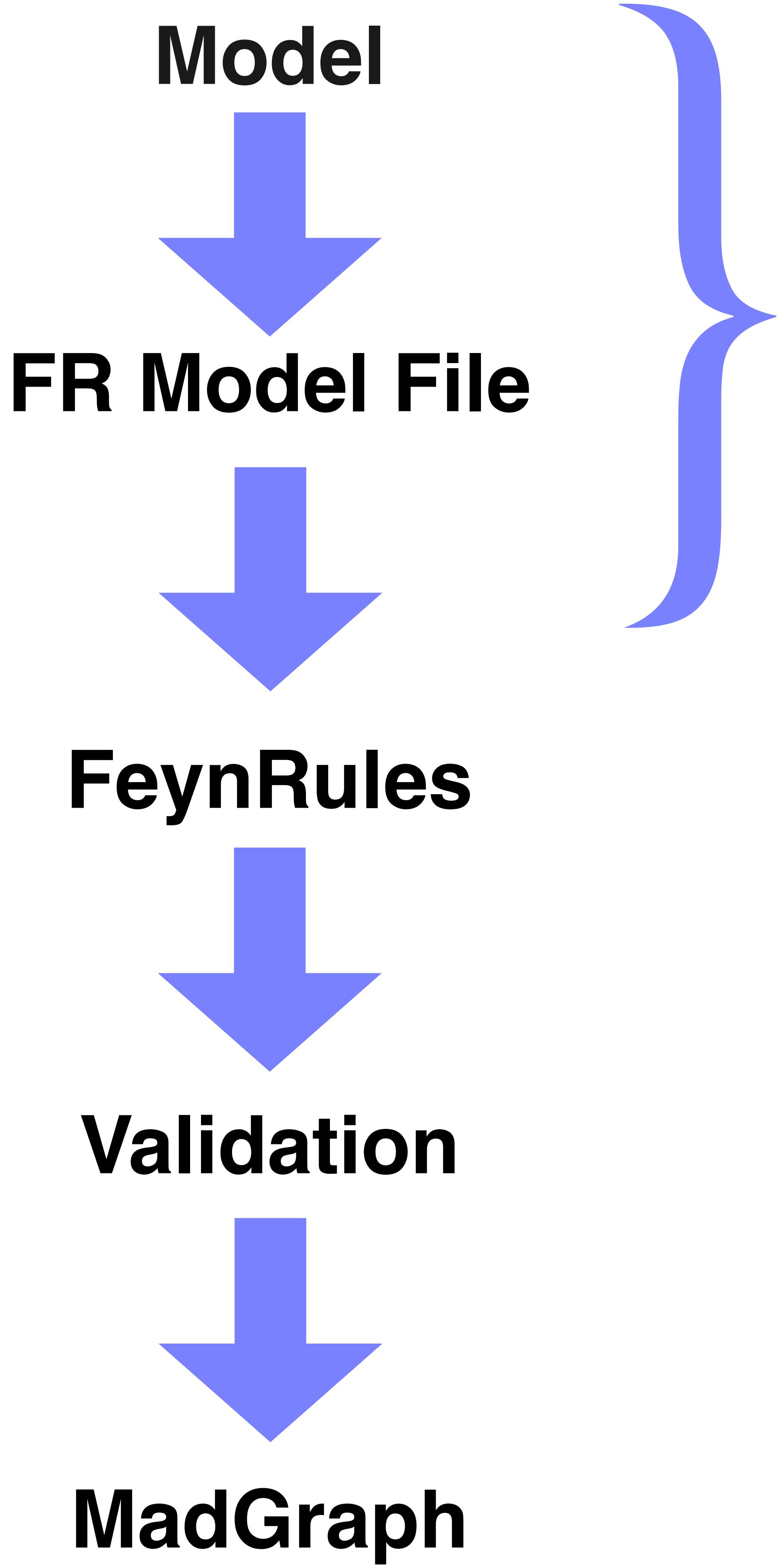
FeynRules Future

- InSurGe
- FR@NLO
- Galileo
    - Models from symmetry
        - Christensen, Salmon, Setzer, Stefanus

FeynRules Future

- InSurGe
- FR@NLO
- **Galileo**

- Models from symmetry
  - Christensen, Salmon, Setzer, Stefanus



Galileo

- Models from symmetry
  - Christensen, Salmon, Setzer, Stefanus

	$SU(3)_c$	$\times SU(2)_W$	$\times U(1)_Y$
Q_L	3	2	$1/6$
u_R	3	1	$2/3$
d_R	3	1	$-1/3$
L_L	1	2	$-1/2$
e_R	1	1	-1
Φ	1	2	$1/2$

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
Q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
L_L	1	2	-1/2
e_R	1	1	-1
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{W\mu\nu} F_W^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$

$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$

$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

$$SU(3)_c \times SU(2)_W \times U(1)_Y$$

Q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
L_L	1	2	-1/2
e_R	1	1	-1
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\,\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
Q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
L_L	1	2	-1/2
e_R	1	1	-1
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{W\mu\nu} F_W^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \tilde{\Phi} \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian

$SU(3)_c \times SU(2)_W \times U(1)_Y$

Q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
L_L	1	2	-1/2
e_R	1	1	-1
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms

	$SU(3)_c$	$\times SU(2)_W$	$\times U(1)_Y$
Q_L	3	2	$1/6$
u_R	3	1	$2/3$
d_R	3	1	$-1/3$
L_L	1	2	$-1/2$
e_R	1	1	-1
Φ	1	2	$1/2$

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{W\mu\nu} F_W^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices

	$SU(3)_c$	$\times SU(2)_W$	$\times U(1)_Y$
Q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
L_L	1	2	-1/2
e_R	1	1	-1
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\,\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
Q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
L_L	1	2	-1/2
e_R	1	1	-1
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\,\mu\nu} F_Y^{\mu\nu}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis
- Calculate Feynman diagrams

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
Q_L	3	2	$1/6$
u_R	3	1	$2/3$
d_R	3	1	$-1/3$
L_L	1	2	$-1/2$
e_R	1	1	-1
Φ	1	2	$1/2$

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu}$$
$$+ i \bar{Q}_L \not{D} Q_L + i \bar{u}_R \not{D} u_R + i \bar{d}_R \not{D} d_R + i \bar{L}_L \not{D} L_L + i \bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \tilde{\Phi} \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis
- Calculate Feynman diagrams
- Implement Feynman rules into CH, FA, MG, SH, WO

	$SU(3)_c$	$\times SU(2)_W$	$\times U(1)_Y$
Q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
L_L	1	2	-1/2
e_R	1	1	-1
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{w\,\mu\nu} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\,\mu\nu} F_Y^{\mu\nu}$$

$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$

$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis
- Calculate Feynman diagrams
- Implement Feynman rules into CH, FA, MG, SH, WO
- Implement Lagrangian into FR

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
Q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
L_L	1	2	-1/2
e_R	1	1	-1
Φ	1	2	1/2

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F^a_{c\,\mu\nu} F_c^{a\mu\nu} - \frac{1}{4} F^a_{W\mu\nu} F_W^{a\mu\nu} - \frac{1}{4} F_{Y\mu\nu} F_Y^{\mu\nu} \\
& + i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R \\
& + \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 \\
& - \lambda_u \tilde{\Phi} \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.
\end{aligned}
$$

- Insert vevs
- Expand Lagrangian
- Collect quadratic terms
- Diagonalize mass matrices
- Rotate fields to mass basis
- Calculate Feynman diagrams
- Implement Feynman rules into CH, FA, MG, SH, WO
- Implement Lagrangian into FR
- Do calculations

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
Q_L	3	2	1/6
u_R	3	1	2/3
d_R	3	1	-1/3
L_L	1	2	-1/2
e_R	1	1	-1
Φ	1	2	1/2

$$\mathcal{L} = -\frac{1}{4} F_{c\,\mu\nu}^{a} F_c^{a\mu\nu} - \frac{1}{4} F_{w\,\mu\nu}^{a} F_w^{a\mu\nu} - \frac{1}{4} F_{Y\mu\rho} F_Y^{\mu\rho}$$
$$+ i\bar{Q}_L \not{D} Q_L + i\bar{u}_R \not{D} u_R + i\bar{d}_R \not{D} d_R + i\bar{L}_L \not{D} L_L + i\bar{e}_R \not{D} e_R$$
$$+ \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$
$$- \lambda_u \Phi \bar{u}_R Q_L - \lambda_d \Phi^\dagger \bar{d}_R Q_L - \lambda_e \Phi^\dagger \bar{e}_R L_L + h.c.$$

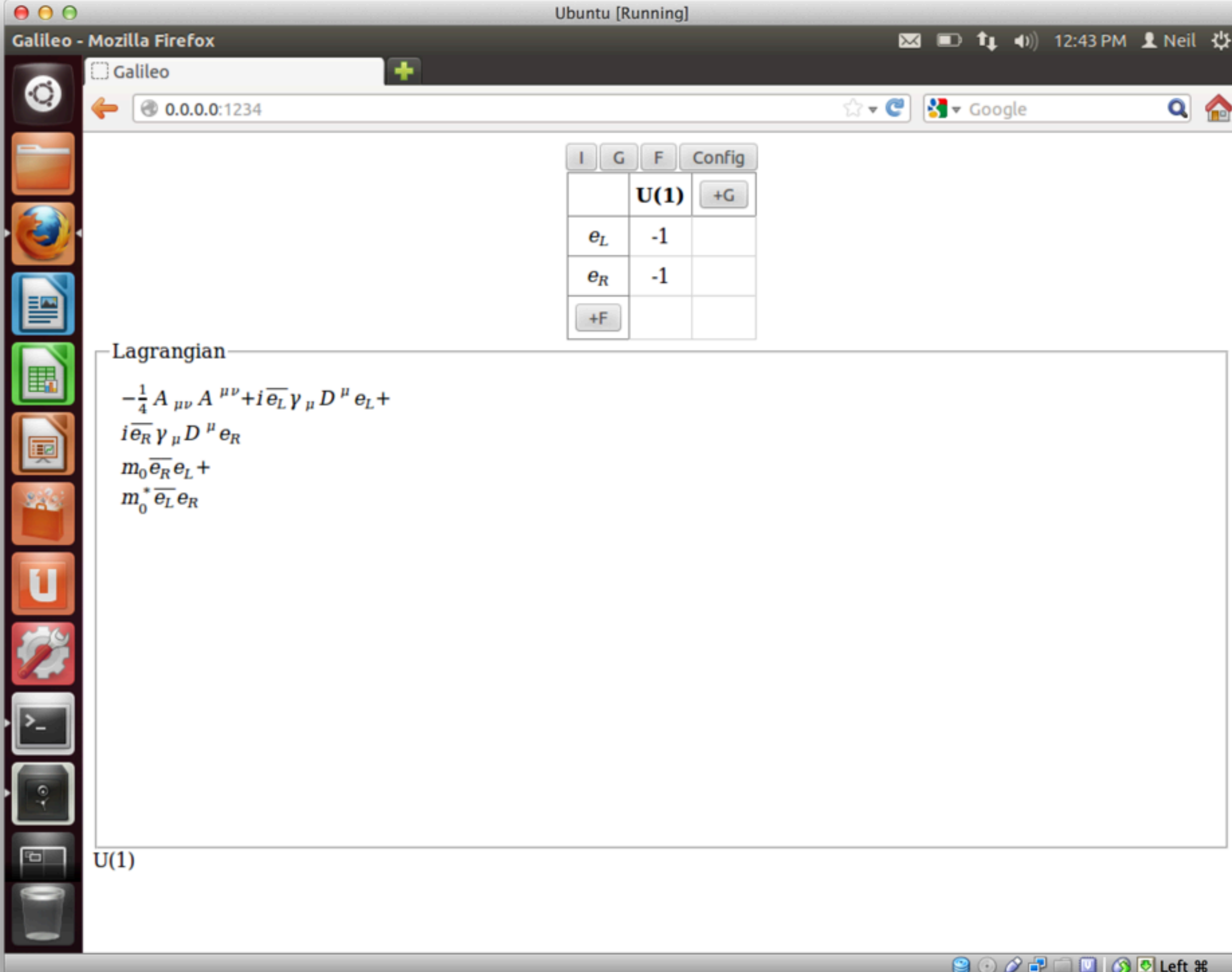
Algorithmic!

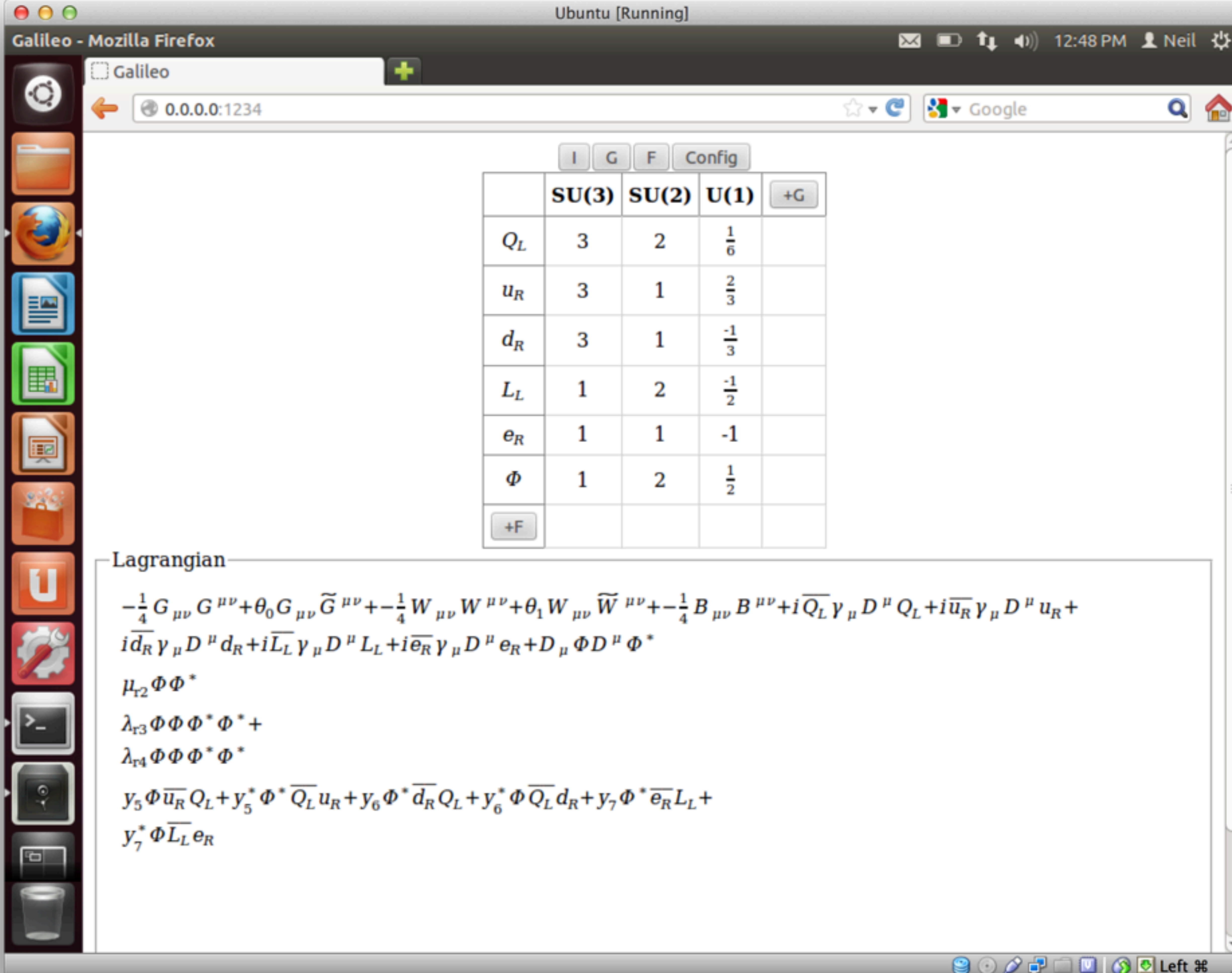
- Insert vevs Algorithmic!
- Expand Lagrangian Algorithmic!
- Collect quadratic terms Algorithmic!
- Diagonalize mass matrices Algorithmic!
- Rotate fields to mass basis Algorithmic!
- Calculate Feynman diagrams Algorithmic!
- Implement Feynman rules into CH, FA, MG, SH, WO Algorithmic!
- Implement Lagrangian into FR Algorithmic!
- Do calculations Some algorithmic!

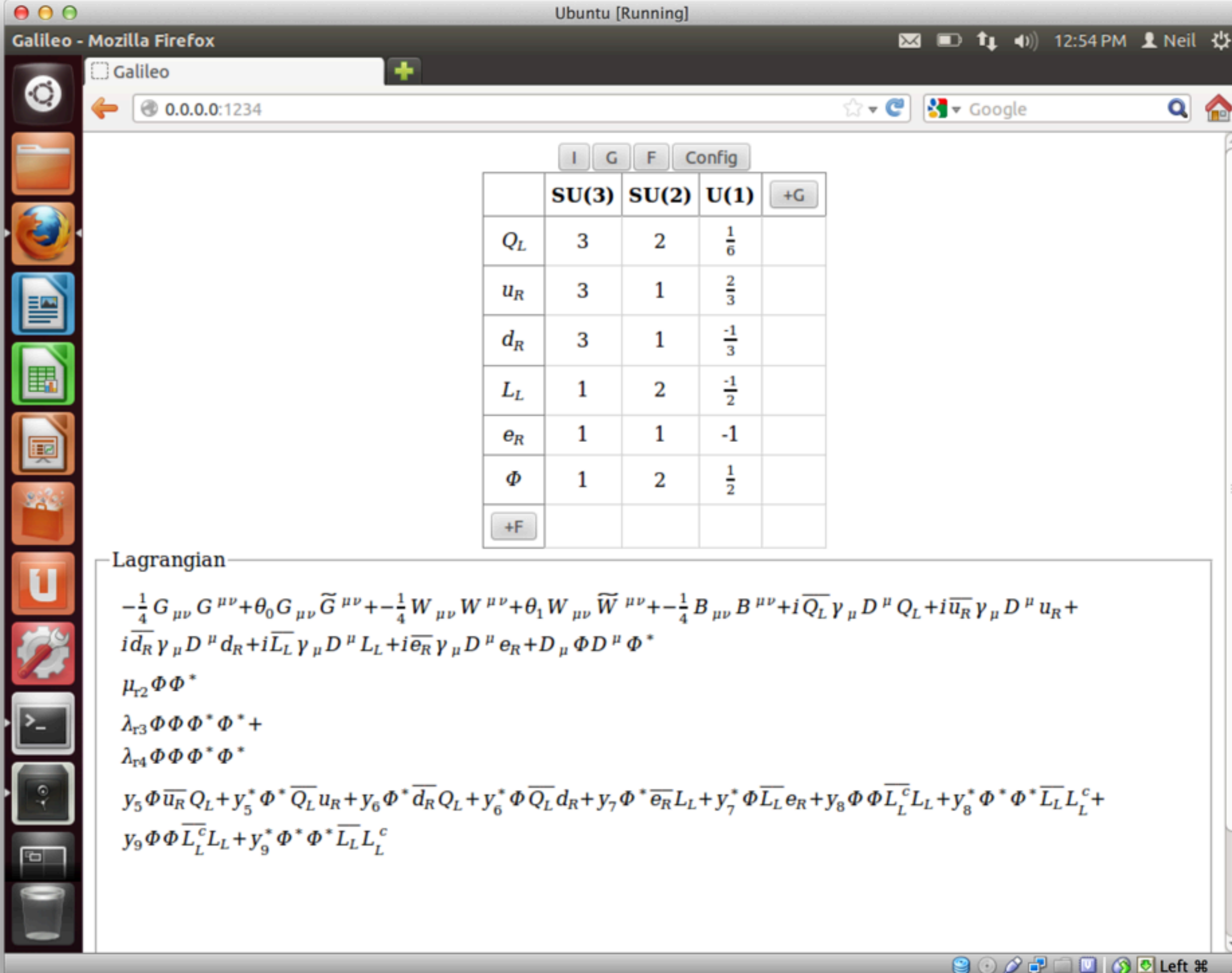
Introducing

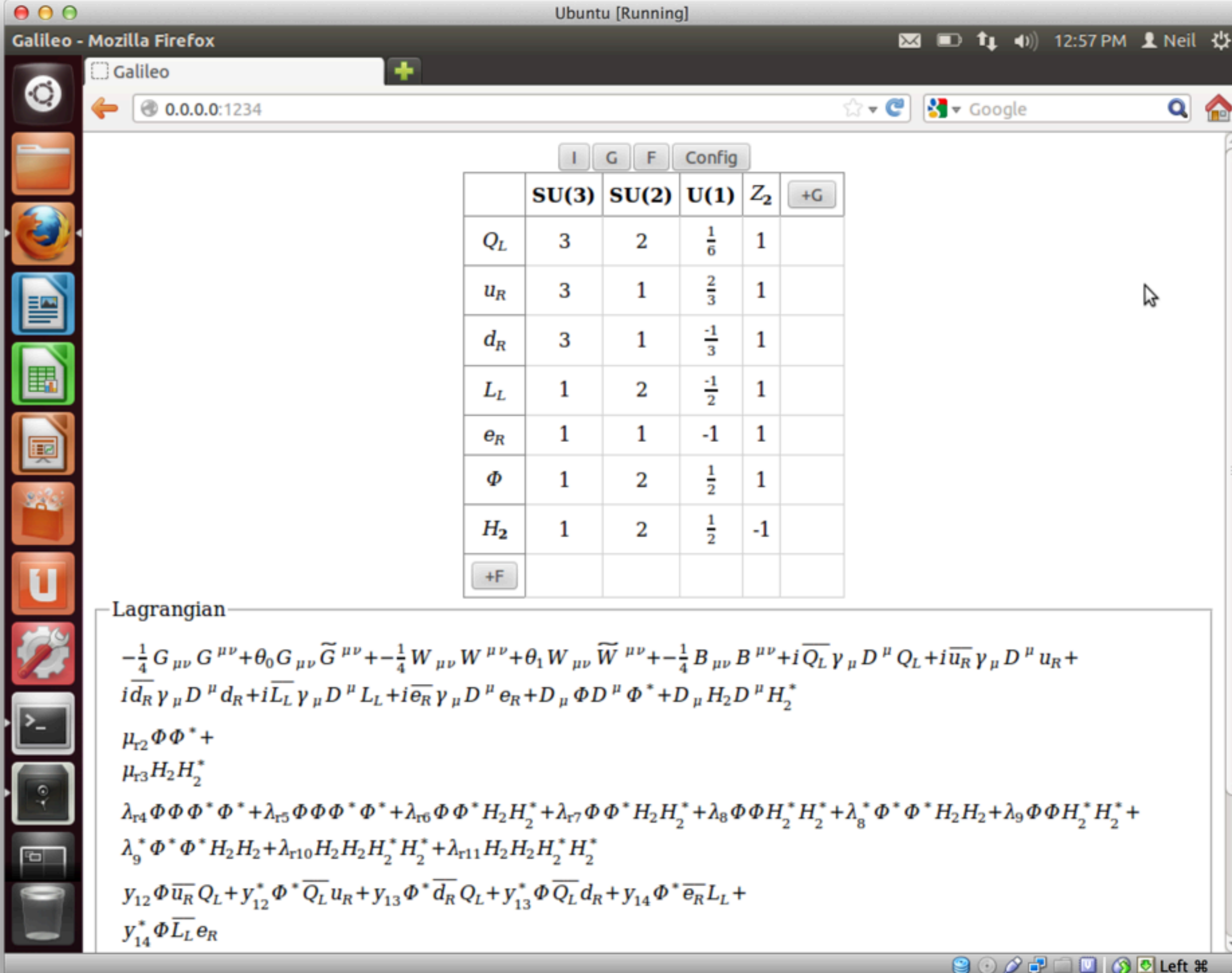
Galileo

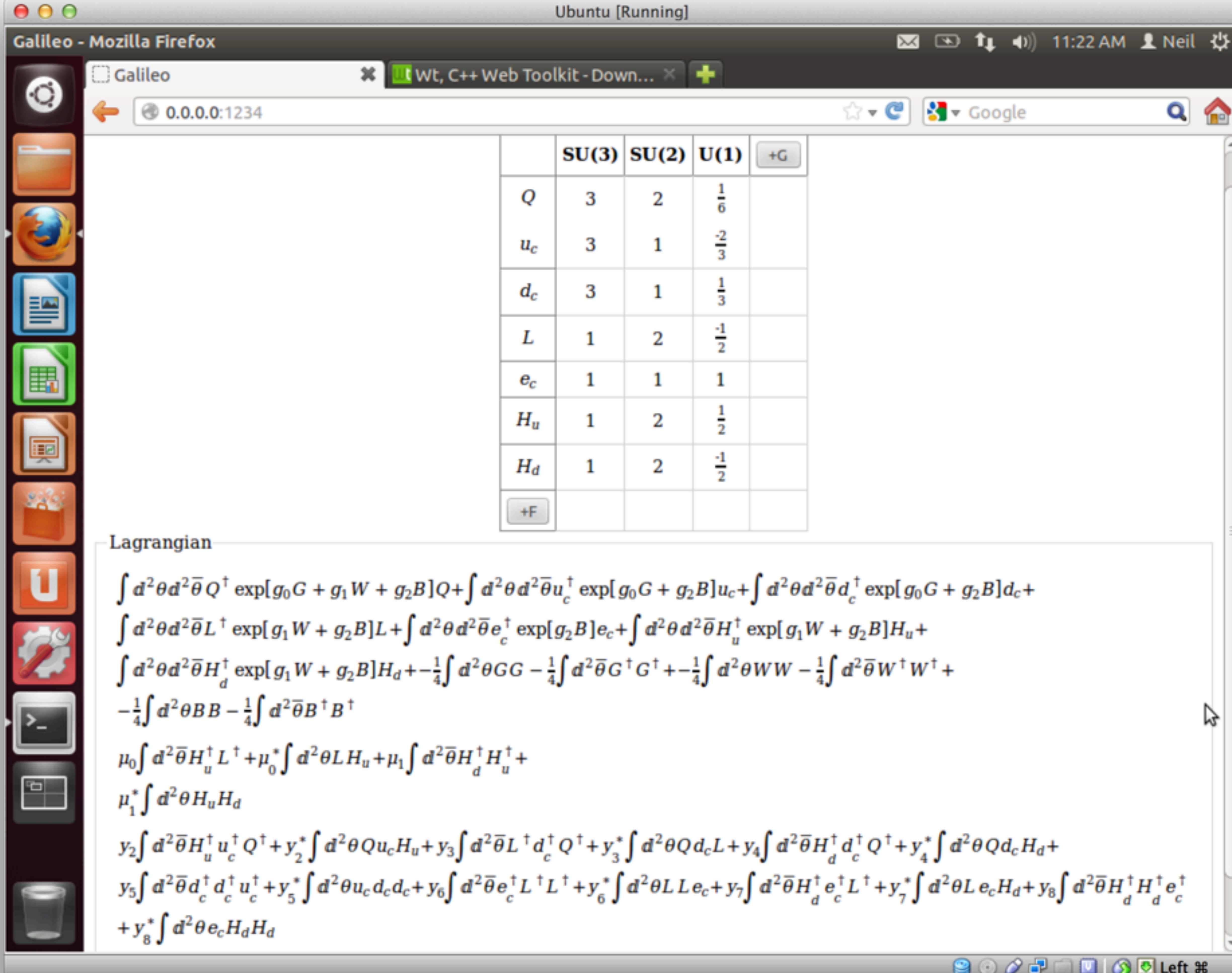
Do more!

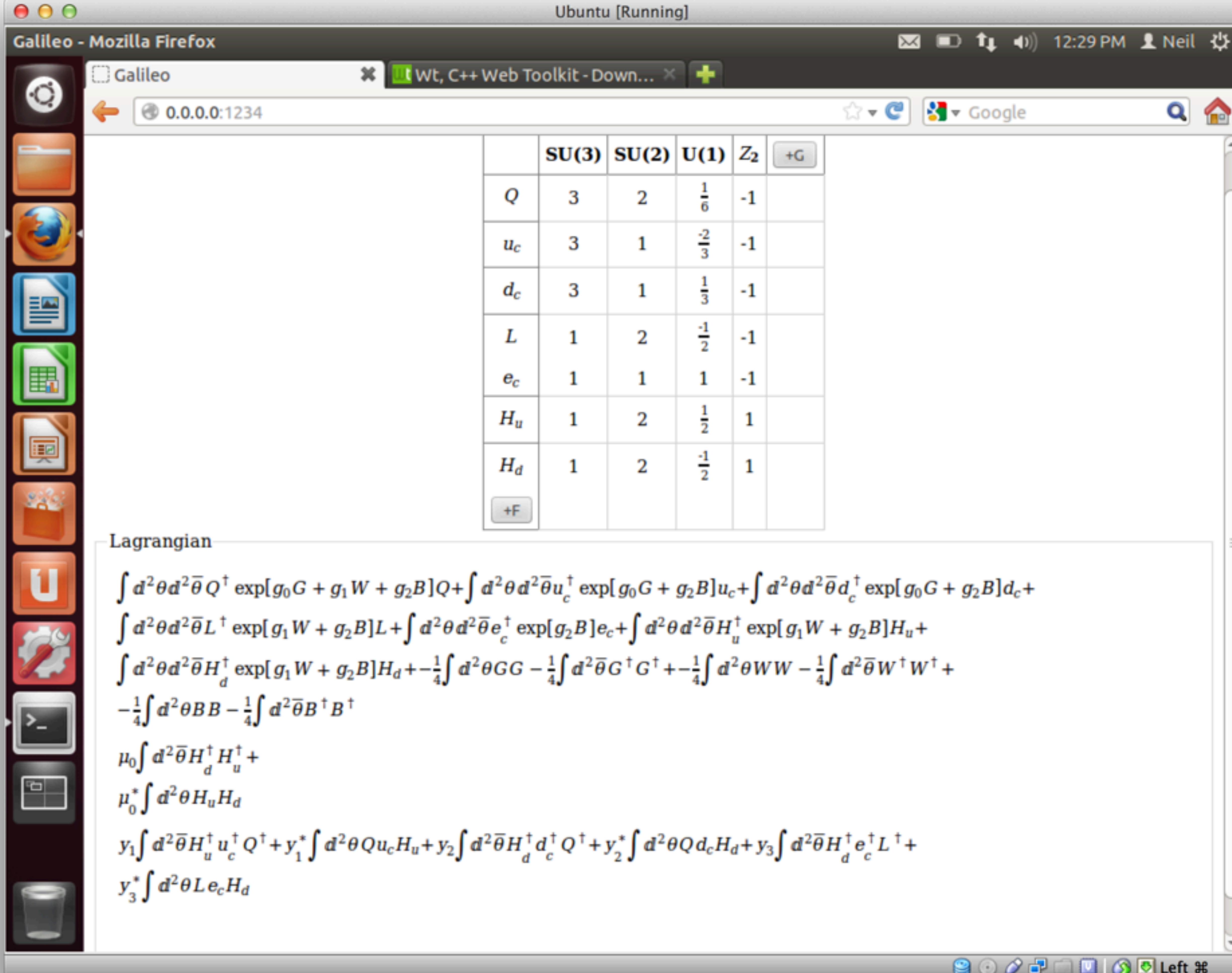

Ubuntu [Running]
Galileo - Mozilla Firefox
12:43 PM
Neil
Galileo
0.0.0.0:1234
Google
I
G
F
Config
U(1)
+G
e_L
-1
e_R
-1
+F
Lagrangian
$-\frac{1}{4} A_{\mu\nu} A^{\mu\nu} + i \overline{e_L} \gamma_\mu D^\mu e_L +$
$i \overline{e_R} \gamma_\mu D^\mu e_R$
$m_0 \overline{e_R} e_L +$
$m_0^* \overline{e_L} e_R$
U(1)
Left ⌘


Ubuntu [Running]
Galileo - Mozilla Firefox
12:48 PM
Neil
Galileo
0.0.0.0:1234
Google
I
G
F
Config
SU(3)
SU(2)
U(1)
+G
Q_L 3 2 $\frac{1}{6}$
u_R 3 1 $\frac{2}{3}$
d_R 3 1 $\frac{-1}{3}$
L_L 1 2 $\frac{-1}{2}$
e_R 1 1 -1
Φ 1 2 $\frac{1}{2}$
+F
Lagrangian
$-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\theta_0 G_{\mu\nu}\widetilde{G}^{\mu\nu}+-\frac{1}{4}W_{\mu\nu}W^{\mu\nu}+\theta_1 W_{\mu\nu}\widetilde{W}^{\mu\nu}+-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}+i\overline{Q_L}\gamma_\mu D^\mu Q_L+i\overline{u_R}\gamma_\mu D^\mu u_R+$
$i\overline{d_R}\gamma_\mu D^\mu d_R+i\overline{L_L}\gamma_\mu D^\mu L_L+i\overline{e_R}\gamma_\mu D^\mu e_R+D_\mu\Phi D^\mu\Phi^*$
$\mu_{r2}\Phi\Phi^*$
$\lambda_{r3}\Phi\Phi\Phi^*\Phi^*+$
$\lambda_{r4}\Phi\Phi\Phi^*\Phi^*$
$y_5\Phi\overline{u_R}Q_L+y_5^*\Phi^*\overline{Q_L}u_R+y_6\Phi^*\overline{d_R}Q_L+y_6^*\Phi\overline{Q_L}d_R+y_7\Phi^*\overline{e_R}L_L+$
$y_7^*\Phi\overline{L_L}e_R$
Left ⌘


Ubuntu [Running]
Galileo - Mozilla Firefox
12:54 PM
Neil
Galileo
0.0.0.0:1234
Google
I
G
F
Config
SU(3)
SU(2)
U(1)
+G
Q_L 3 2 1/6
u_R 3 1 2/3
d_R 3 1 -1/3
L_L 1 2 -1/2
e_R 1 1 -1
Φ 1 2 1/2
+F
Lagrangian
$-\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \theta_0 G_{\mu\nu} \widetilde{G}^{\mu\nu} + -\frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \theta_1 W_{\mu\nu} \widetilde{W}^{\mu\nu} + -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + i\overline{Q_L} \gamma_\mu D^\mu Q_L + i\overline{u_R} \gamma_\mu D^\mu u_R +$
$i\overline{d_R} \gamma_\mu D^\mu d_R + i\overline{L_L} \gamma_\mu D^\mu L_L + i\overline{e_R} \gamma_\mu D^\mu e_R + D_\mu \Phi D^\mu \Phi^*$
$\mu_{r2} \Phi \Phi^*$
$\lambda_{r3} \Phi \Phi \Phi^* \Phi^* +$
$\lambda_{r4} \Phi \Phi \Phi^* \Phi^*$
$y_5 \Phi \overline{u_R} Q_L + y_5^* \Phi^* \overline{Q_L} u_R + y_6 \Phi^* \overline{d_R} Q_L + y_6^* \Phi \overline{Q_L} d_R + y_7 \Phi^* \overline{e_R} L_L + y_7^* \Phi \overline{L_L} e_R + y_8 \Phi \Phi \overline{L_L^c} L_L + y_8^* \Phi^* \Phi^* \overline{L_L} L_L^c +$
$y_9 \Phi \Phi \overline{L_L^c} L_L + y_9^* \Phi^* \Phi^* \overline{L_L} L_L^c$
Left ⌘


Ubuntu [Running]
Galileo - Mozilla Firefox
12:57 PM
Neil
Galileo
0.0.0.0:1234
Google
I
G
F
Config
SU(3) SU(2) U(1) Z_2 +G
Q_L 3 2 $\frac{1}{6}$ 1
u_R 3 1 $\frac{2}{3}$ 1
d_R 3 1 $\frac{-1}{3}$ 1
L_L 1 2 $\frac{-1}{2}$ 1
e_R 1 1 -1 1
Φ 1 2 $\frac{1}{2}$ 1
H_2 1 2 $\frac{1}{2}$ -1
+F
Lagrangian
$-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\theta_0 G_{\mu\nu}\widetilde{G}^{\mu\nu}+-\frac{1}{4}W_{\mu\nu}W^{\mu\nu}+\theta_1 W_{\mu\nu}\widetilde{W}^{\mu\nu}+-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}+i\overline{Q_L}\gamma_\mu D^\mu Q_L+i\overline{u_R}\gamma_\mu D^\mu u_R+$
$i\overline{d_R}\gamma_\mu D^\mu d_R+i\overline{L_L}\gamma_\mu D^\mu L_L+i\overline{e_R}\gamma_\mu D^\mu e_R+D_\mu\Phi D^\mu\Phi^*+D_\mu H_2 D^\mu H_2^*$
$\mu_{r2}\Phi\Phi^*+$
$\mu_{r3}H_2H_2^*$
$\lambda_{r4}\Phi\Phi\Phi^*\Phi^*+\lambda_{r5}\Phi\Phi\Phi^*\Phi^*+\lambda_{r6}\Phi\Phi^*H_2H_2^*+\lambda_{r7}\Phi\Phi^*H_2H_2^*+\lambda_8\Phi\Phi H_2^*H_2^*+\lambda_8^*\Phi^*\Phi^*H_2H_2+\lambda_9\Phi\Phi H_2^*H_2^*+$
$\lambda_9^*\Phi^*\Phi^*H_2H_2+\lambda_{r10}H_2H_2H_2^*H_2^*+\lambda_{r11}H_2H_2H_2^*H_2^*$
$y_{12}\Phi\overline{u_R}Q_L+y_{12}^*\Phi^*\overline{Q_L}u_R+y_{13}\Phi^*\overline{d_R}Q_L+y_{13}^*\Phi\overline{Q_L}d_R+y_{14}\Phi^*\overline{e_R}L_L+$
$y_{14}^*\Phi\overline{L_L}e_R$
Left ⌘


Ubuntu [Running]
Galileo - Mozilla Firefox
11:22 AM
Neil
Galileo
Wt, C++ Web Toolkit - Down...
0.0.0.0:1234
Google
	SU(3)	SU(2)	U(1)	+G
Q	3	2	$\frac{1}{6}$	
u_c	3	1	$\frac{-2}{3}$	
d_c	3	1	$\frac{1}{3}$	
L	1	2	$\frac{-1}{2}$	
e_c	1	1	1	
H_u	1	2	$\frac{1}{2}$	
H_d	1	2	$\frac{-1}{2}$	
+F				
Lagrangian
$\int d^2\theta d^2\bar{\theta} Q^\dagger \exp[g_0 G + g_1 W + g_2 B] Q + \int d^2\theta d^2\bar{\theta} u_c^\dagger \exp[g_0 G + g_2 B] u_c + \int d^2\theta d^2\bar{\theta} d_c^\dagger \exp[g_0 G + g_2 B] d_c +$
$\int d^2\theta d^2\bar{\theta} L^\dagger \exp[g_1 W + g_2 B] L + \int d^2\theta d^2\bar{\theta} e_c^\dagger \exp[g_2 B] e_c + \int d^2\theta d^2\bar{\theta} H_u^\dagger \exp[g_1 W + g_2 B] H_u +$
$\int d^2\theta d^2\bar{\theta} H_d^\dagger \exp[g_1 W + g_2 B] H_d + -\frac{1}{4}\int d^2\theta G G - \frac{1}{4}\int d^2\bar{\theta} G^\dagger G^\dagger + -\frac{1}{4}\int d^2\theta W W - \frac{1}{4}\int d^2\bar{\theta} W^\dagger W^\dagger +$
$-\frac{1}{4}\int d^2\theta B B - \frac{1}{4}\int d^2\bar{\theta} B^\dagger B^\dagger$
$\mu_0 \int d^2\bar{\theta} H_u^\dagger L^\dagger + \mu_0^* \int d^2\theta L H_u + \mu_1 \int d^2\bar{\theta} H_d^\dagger H_u^\dagger +$
$\mu_1^* \int d^2\theta H_u H_d$
$y_2 \int d^2\bar{\theta} H_u^\dagger u_c^\dagger Q^\dagger + y_2^* \int d^2\theta Q u_c H_u + y_3 \int d^2\bar{\theta} L^\dagger d_c^\dagger Q^\dagger + y_3^* \int d^2\theta Q d_c L + y_4 \int d^2\bar{\theta} H_d^\dagger d_c^\dagger Q^\dagger + y_4^* \int d^2\theta Q d_c H_d +$
$y_5 \int d^2\bar{\theta} d_c^\dagger d_c^\dagger u_c^\dagger + y_5^* \int d^2\theta u_c d_c d_c + y_6 \int d^2\bar{\theta} e_c^\dagger L^\dagger L^\dagger + y_6^* \int d^2\theta L L e_c + y_7 \int d^2\bar{\theta} H_d^\dagger e_c^\dagger L^\dagger + y_7^* \int d^2\theta L e_c H_d + y_8 \int d^2\bar{\theta} H_d^\dagger H_d^\dagger e_c^\dagger$
$+ y_8^* \int d^2\theta e_c H_d H_d$
Left ⌘



	SU(3)	SU(2)	U(1)	Z_2	+G
Q	3	2	$\frac{1}{6}$	-1	
u_c	3	1	$\frac{-2}{3}$	-1	
d_c	3	1	$\frac{1}{3}$	-1	
L	1	2	$\frac{-1}{2}$	-1	
e_c	1	1	1	-1	
H_u	1	2	$\frac{1}{2}$	1	
H_d	1	2	$\frac{-1}{2}$	1	
+F					

Lagrangian

$$\int d^2\theta d^2\bar{\theta} Q^\dagger \exp[g_0 G + g_1 W + g_2 B]Q + \int d^2\theta d^2\bar{\theta} u_c^\dagger \exp[g_0 G + g_2 B]u_c + \int d^2\theta d^2\bar{\theta} d_c^\dagger \exp[g_0 G + g_2 B]d_c +$$

$$\int d^2\theta d^2\bar{\theta} L^\dagger \exp[g_1 W + g_2 B]L + \int d^2\theta d^2\bar{\theta} e_c^\dagger \exp[g_2 B]e_c + \int d^2\theta d^2\bar{\theta} H_u^\dagger \exp[g_1 W + g_2 B]H_u +$$

$$\int d^2\theta d^2\bar{\theta} H_d^\dagger \exp[g_1 W + g_2 B]H_d + -\frac{1}{4}\int d^2\theta GG - \frac{1}{4}\int d^2\bar{\theta} G^\dagger G^\dagger + -\frac{1}{4}\int d^2\theta WW - \frac{1}{4}\int d^2\bar{\theta} W^\dagger W^\dagger +$$

$$-\frac{1}{4}\int d^2\theta BB - \frac{1}{4}\int d^2\bar{\theta} B^\dagger B^\dagger$$

$$\mu_0 \int d^2\bar{\theta} H_d^\dagger H_u^\dagger +$$

$$\mu_0^* \int d^2\theta H_u H_d$$

$$y_1 \int d^2\bar{\theta} H_u^\dagger u_c^\dagger Q^\dagger + y_1^* \int d^2\theta Q u_c H_u + y_2 \int d^2\bar{\theta} H_d^\dagger d_c^\dagger Q^\dagger + y_2^* \int d^2\theta Q d_c H_d + y_3 \int d^2\bar{\theta} H_d^\dagger e_c^\dagger L^\dagger +$$

$$y_3^* \int d^2\theta L e_c H_d$$

Ubuntu [Running]

Galileo - Mozilla Firefox

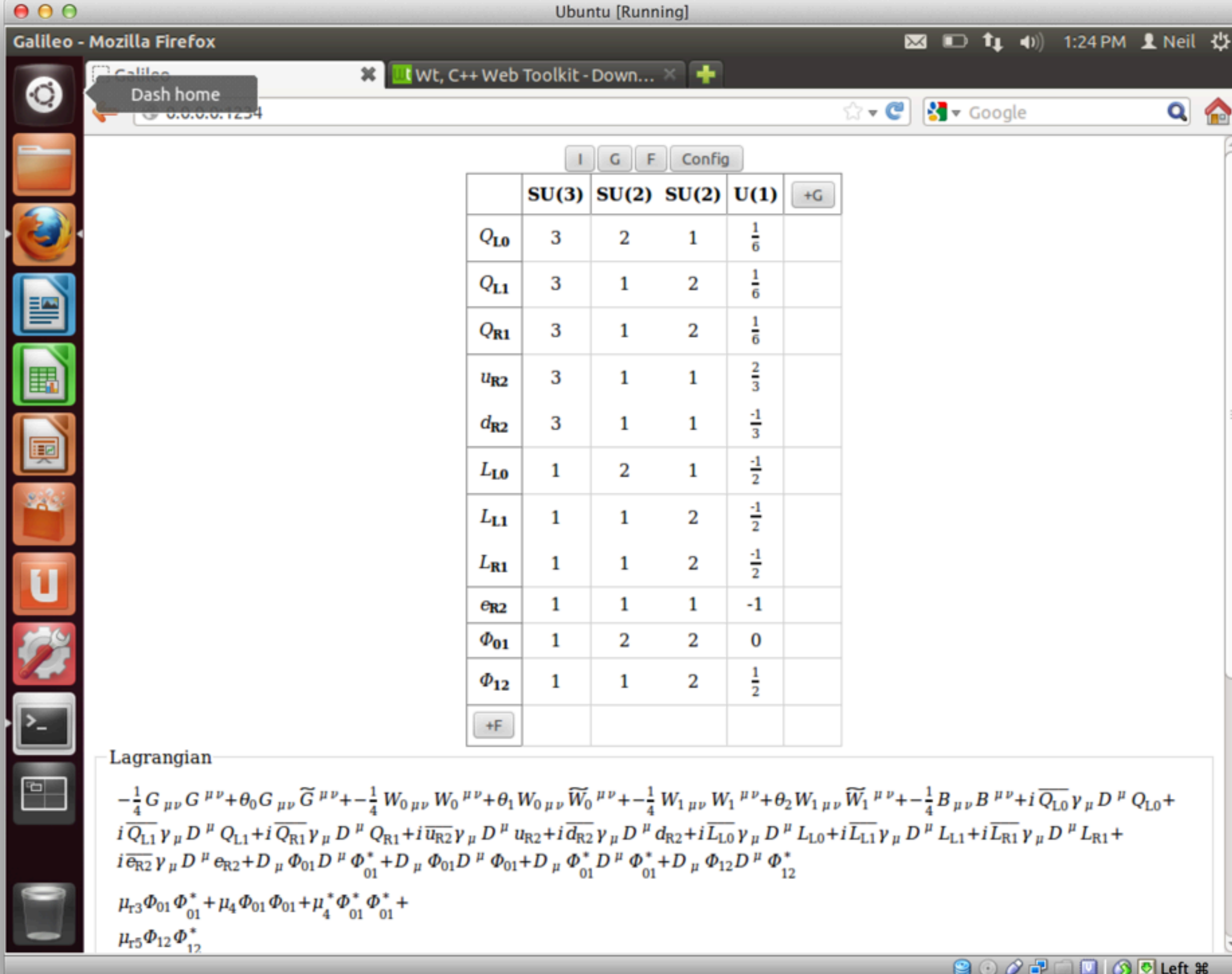
Galileo | Wt, C++ Web Toolkit - Down...

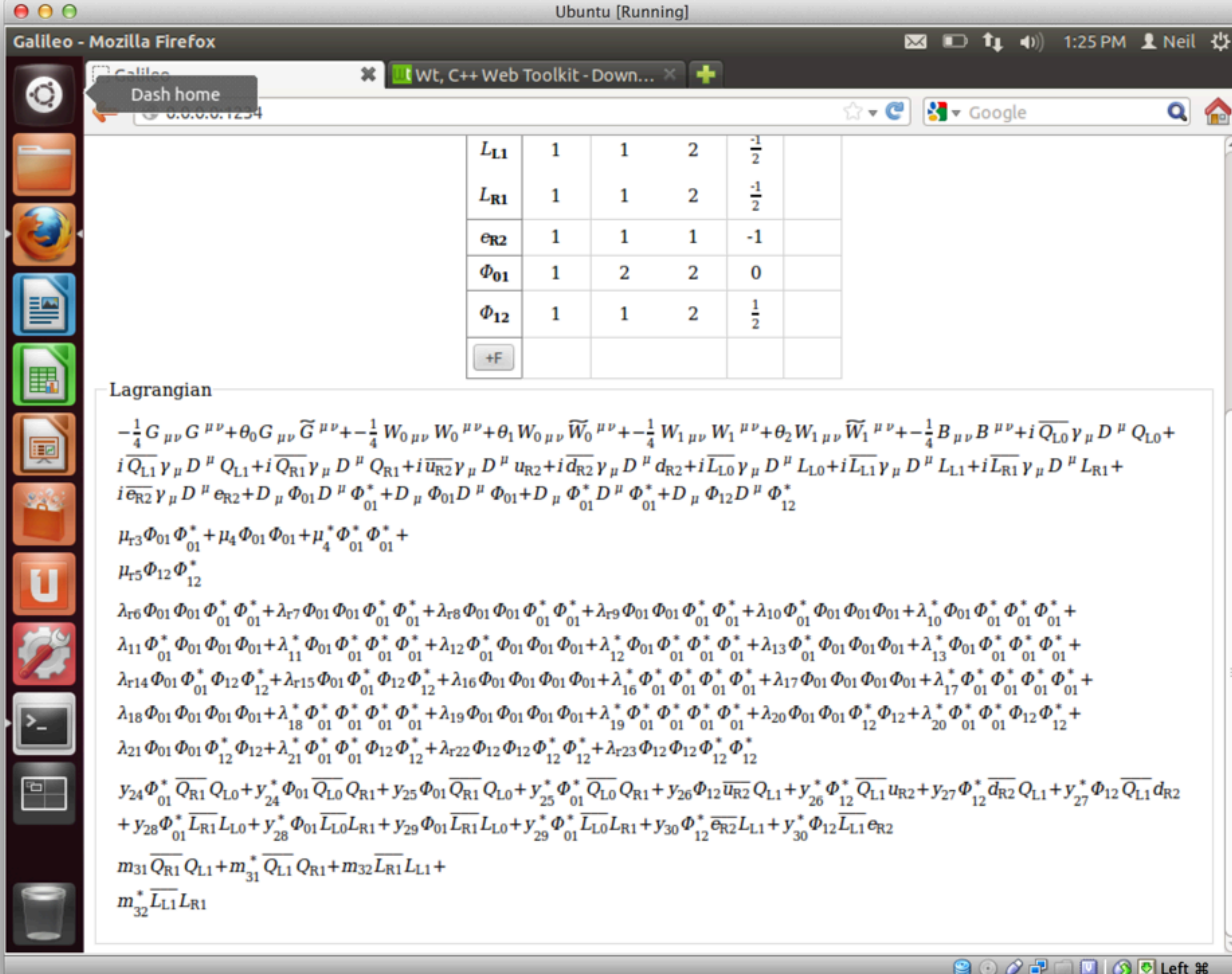
Dash home

	SU(3)	SU(2)	U(1)	Z_2	Z_3	+G
Q	3	2	$\frac{1}{6}$	-1	$e^{\frac{4\pi i}{3}}$	
u_c	3	1	$\frac{-2}{3}$	-1	$e^{\frac{4\pi i}{3}}$	
d_c	3	1	$\frac{1}{3}$	-1	$e^{\frac{4\pi i}{3}}$	
L	1	2	$\frac{-1}{2}$	-1	$e^{\frac{4\pi i}{3}}$	
e_c	1	1	1	-1	$e^{\frac{4\pi i}{3}}$	
H_u	1	2	$\frac{1}{2}$	1	$e^{\frac{4\pi i}{3}}$	
H_d	1	2	$\frac{-1}{2}$	1	$e^{\frac{4\pi i}{3}}$	
S	1	1	0	1	$e^{\frac{4\pi i}{3}}$	
+F						

Lagrangian

$$\int d^2\theta d^2\bar\theta Q^\dagger \exp[g_0 G + g_1 W + g_2 B_3]Q + \int d^2\theta d^2\bar\theta u_c^\dagger \exp[g_0 G + g_2 B_3]u_c + \int d^2\theta d^2\bar\theta d_c^\dagger \exp[g_0 G + g_2 B_3]d_c +$$
$$\int d^2\theta d^2\bar\theta L^\dagger \exp[g_1 W + g_2 B_3]L + \int d^2\theta d^2\bar\theta e_c^\dagger \exp[g_2 B_3]e_c + \int d^2\theta d^2\bar\theta H_u^\dagger \exp[g_1 W + g_2 B_3]H_u +$$
$$\int d^2\theta d^2\bar\theta H_d^\dagger \exp[g_1 W + g_2 B_3]H_d + \int d^2\theta d^2\bar\theta S^\dagger \exp[g_2 B_3]S + -\tfrac{1}{4}\int d^2\theta GG - \tfrac{1}{4}\int d^2\bar\theta G^\dagger G^\dagger + -\tfrac{1}{4}\int d^2\theta WW - \tfrac{1}{4}\int d^2\bar\theta W^\dagger W^\dagger +$$
$$-\tfrac{1}{4}\int d^2\theta B_3 B_3 - \tfrac{1}{4}\int d^2\bar\theta B_3^\dagger B_3^\dagger$$
$$y_0\int d^2\bar\theta H_u^\dagger u_c^\dagger Q^\dagger + y_0^*\int d^2\theta Q u_c H_u + y_1\int d^2\bar\theta H_d^\dagger d_c^\dagger Q^\dagger + y_1^*\int d^2\theta Q d_c H_d + y_2\int d^2\bar\theta H_d^\dagger e_c^\dagger L^\dagger + y_2^*\int d^2\theta L e_c H_d +$$
$$y_3\int d^2\bar\theta S^\dagger H_d^\dagger H_u^\dagger + y_3^*\int d^2\theta H_u H_d S + y_4\int d^2\bar\theta S^\dagger S^\dagger S^\dagger + y_4^*\int d^2\theta SSS$$


Ubuntu [Running]
Galileo - Mozilla Firefox
1:24 PM
Neil
Galileo
Wt, C++ Web Toolkit - Down...
Dash home
Google
I
G
F
Config
SU(3) SU(2) SU(2) U(1) +G
Q_L0 3 2 1 1/6
Q_L1 3 1 2 1/6
Q_R1 3 1 2 1/6
u_R2 3 1 1 2/3
d_R2 3 1 1 -1/3
L_L0 1 2 1 -1/2
L_L1 1 1 2 -1/2
L_R1 1 1 2 -1/2
e_R2 1 1 1 -1
Φ_01 1 2 2 0
Φ_12 1 1 2 1/2
+F
Lagrangian
$-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\theta_0 G_{\mu\nu}\widetilde{G}^{\mu\nu}+-\frac{1}{4}W_{0\,\mu\nu}W_0^{\mu\nu}+\theta_1 W_{0\,\mu\nu}\widetilde{W_0}^{\mu\nu}+-\frac{1}{4}W_{1\,\mu\nu}W_1^{\mu\nu}+\theta_2 W_{1\,\mu\nu}\widetilde{W_1}^{\mu\nu}+-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}+i\overline{Q_{L0}}\gamma_\mu D^\mu Q_{L0}+$
$i\overline{Q_{L1}}\gamma_\mu D^\mu Q_{L1}+i\overline{Q_{R1}}\gamma_\mu D^\mu Q_{R1}+i\overline{u_{R2}}\gamma_\mu D^\mu u_{R2}+i\overline{d_{R2}}\gamma_\mu D^\mu d_{R2}+i\overline{L_{L0}}\gamma_\mu D^\mu L_{L0}+i\overline{L_{L1}}\gamma_\mu D^\mu L_{L1}+i\overline{L_{R1}}\gamma_\mu D^\mu L_{R1}+$
$i\overline{e_{R2}}\gamma_\mu D^\mu e_{R2}+D_\mu\Phi_{01}D^\mu\Phi^*_{01}+D_\mu\Phi_{01}D^\mu\Phi_{01}+D_\mu\Phi^*_{01}D^\mu\Phi^*_{01}+D_\mu\Phi_{12}D^\mu\Phi^*_{12}$
$\mu_{r3}\Phi_{01}\Phi^*_{01}+\mu_4\Phi_{01}\Phi_{01}+\mu^*_4\Phi^*_{01}\Phi^*_{01}+$
$\mu_{r5}\Phi_{12}\Phi^*_{12}$
Left ⌘

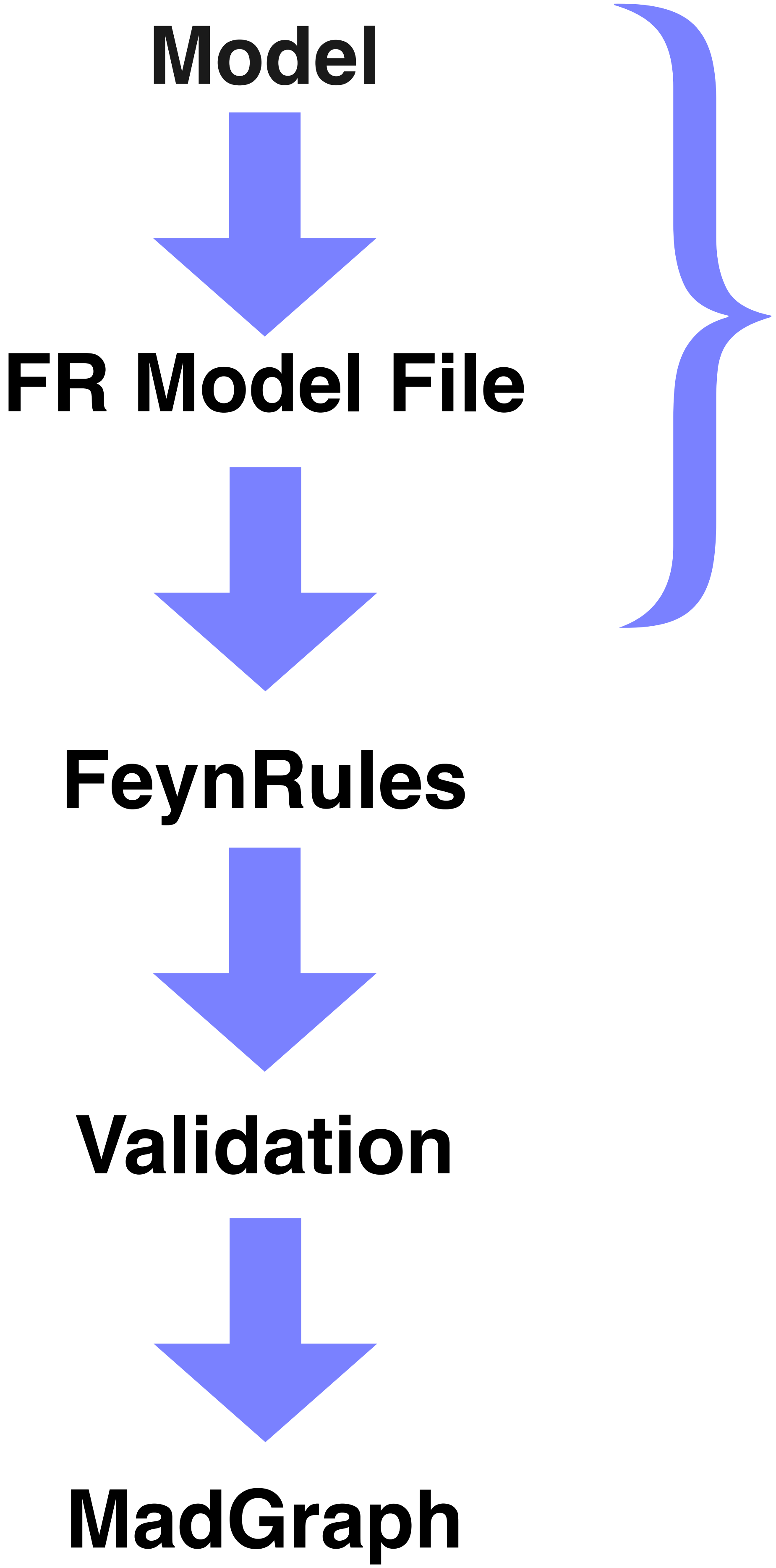

Ubuntu [Running]
Galileo - Mozilla Firefox
1:25 PM
Neil
Galileo
Wt, C++ Web Toolkit - Down...
Dash home
Google
L_{L1} 1 1 2 $\frac{-1}{2}$
L_{R1} 1 1 2 $\frac{-1}{2}$
e_{R2} 1 1 1 -1
Φ_{01} 1 2 2 0
Φ_{12} 1 1 2 $\frac{1}{2}$
+F
Lagrangian
$-\frac{1}{4}G_{\mu\nu}G^{\mu\nu}+\theta_0 G_{\mu\nu}\widetilde{G}^{\mu\nu}+-\frac{1}{4}W_{0\,\mu\nu}W_0^{\mu\nu}+\theta_1 W_{0\,\mu\nu}\widetilde{W_0}^{\mu\nu}+-\frac{1}{4}W_{1\,\mu\nu}W_1^{\mu\nu}+\theta_2 W_{1\,\mu\nu}\widetilde{W_1}^{\mu\nu}+-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}+i\overline{Q_{L0}}\gamma_\mu D^\mu Q_{L0}+$
$i\overline{Q_{L1}}\gamma_\mu D^\mu Q_{L1}+i\overline{Q_{R1}}\gamma_\mu D^\mu Q_{R1}+i\overline{u_{R2}}\gamma_\mu D^\mu u_{R2}+i\overline{d_{R2}}\gamma_\mu D^\mu d_{R2}+i\overline{L_{L0}}\gamma_\mu D^\mu L_{L0}+i\overline{L_{L1}}\gamma_\mu D^\mu L_{L1}+i\overline{L_{R1}}\gamma_\mu D^\mu L_{R1}+$
$i\overline{e_{R2}}\gamma_\mu D^\mu e_{R2}+D_\mu\Phi_{01}D^\mu\Phi^*_{01}+D_\mu\Phi_{01}D^\mu\Phi_{01}+D_\mu\Phi^*_{01}D^\mu\Phi^*_{01}+D_\mu\Phi_{12}D^\mu\Phi^*_{12}$
$\mu_{r3}\Phi_{01}\Phi^*_{01}+\mu_4\Phi_{01}\Phi_{01}+\mu^*_4\Phi^*_{01}\Phi^*_{01}+$
$\mu_{r5}\Phi_{12}\Phi^*_{12}$
$\lambda_{r6}\Phi_{01}\Phi_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{r7}\Phi_{01}\Phi_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{r8}\Phi_{01}\Phi_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{r9}\Phi_{01}\Phi_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{10}\Phi^*_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{10}\Phi_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+$
$\lambda_{11}\Phi^*_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{11}\Phi_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{12}\Phi^*_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{12}\Phi_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{13}\Phi^*_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{13}\Phi_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+$
$\lambda_{r14}\Phi_{01}\Phi^*_{01}\Phi_{12}\Phi^*_{12}+\lambda_{r15}\Phi_{01}\Phi^*_{01}\Phi_{12}\Phi^*_{12}+\lambda_{16}\Phi_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{16}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{17}\Phi_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{17}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+$
$\lambda_{18}\Phi_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{18}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{19}\Phi_{01}\Phi_{01}\Phi_{01}\Phi_{01}+\lambda^*_{19}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}\Phi^*_{01}+\lambda_{20}\Phi_{01}\Phi_{01}\Phi^*_{12}\Phi_{12}+\lambda^*_{20}\Phi^*_{01}\Phi^*_{01}\Phi_{12}\Phi^*_{12}+$
$\lambda_{21}\Phi_{01}\Phi_{01}\Phi^*_{12}\Phi_{12}+\lambda^*_{21}\Phi^*_{01}\Phi^*_{01}\Phi_{12}\Phi^*_{12}+\lambda_{r22}\Phi_{12}\Phi_{12}\Phi^*_{12}\Phi^*_{12}+\lambda_{r23}\Phi_{12}\Phi_{12}\Phi^*_{12}\Phi^*_{12}$
$y_{24}\Phi^*_{01}\overline{Q_{R1}}Q_{L0}+y^*_{24}\Phi_{01}\overline{Q_{L0}}Q_{R1}+y_{25}\Phi_{01}\overline{Q_{R1}}Q_{L0}+y^*_{25}\Phi^*_{01}\overline{Q_{L0}}Q_{R1}+y_{26}\Phi_{12}\overline{u_{R2}}Q_{L1}+y^*_{26}\Phi^*_{12}\overline{Q_{L1}}u_{R2}+y_{27}\Phi^*_{12}\overline{d_{R2}}Q_{L1}+y^*_{27}\Phi_{12}\overline{Q_{L1}}d_{R2}$
$+y_{28}\Phi^*_{01}\overline{L_{R1}}L_{L0}+y^*_{28}\Phi_{01}\overline{L_{L0}}L_{R1}+y_{29}\Phi_{01}\overline{L_{R1}}L_{L0}+y^*_{29}\Phi^*_{01}\overline{L_{L0}}L_{R1}+y_{30}\Phi^*_{12}\overline{e_{R2}}L_{L1}+y^*_{30}\Phi_{12}\overline{L_{L1}}e_{R2}$
$m_{31}\overline{Q_{R1}}Q_{L1}+m^*_{31}\overline{Q_{L1}}Q_{R1}+m_{32}\overline{L_{R1}}L_{L1}+$
$m^*_{32}\overline{L_{L1}}L_{R1}$
Left ⌘

Galileo

- Core library with thin GUI wrapper
  - C++ library linkable to other codes
  - Thorough API documentation
- Any rep of any semisimple compact Lie algebra
  - Including finding singlets
  - Many, many automated tests
- Rewriting Lorentz part of core to be more general
  - Want solid foundation for later development

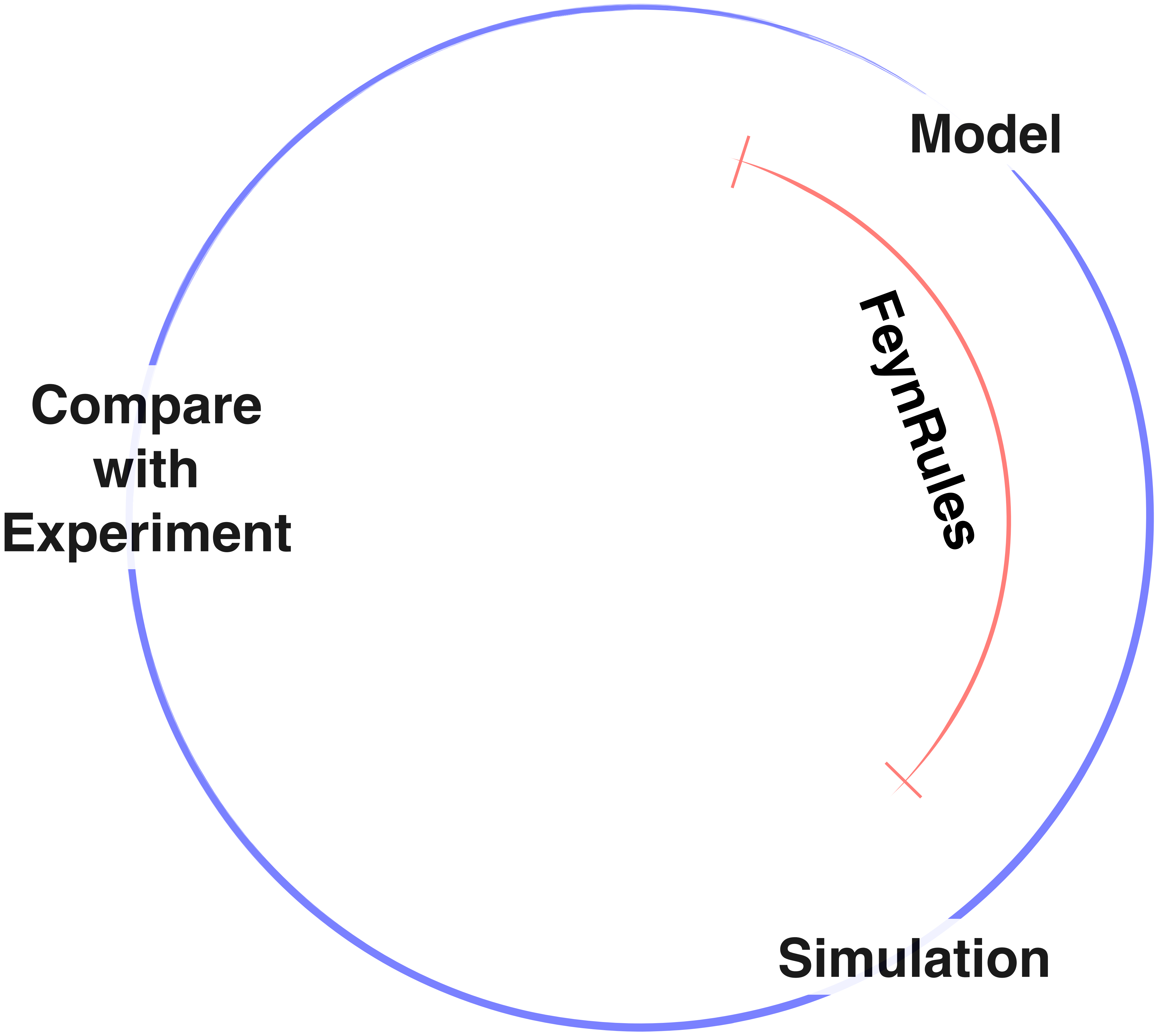
Galileo

- Under construction
  - Lorentz symmetry
  - Symmetry breaking
  - Expansion of Lagrangian
  - Save/Read
  - Output to FeynRules
  - ...



Galileo

- Models from symmetry
  - Christensen, Salmon, Setzer, Stefanus



Model
FeynRules
Compare
with
Experiment
Simulation