ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Advanced FeynRules topics

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Taipei School on MadGraph for LHC physics
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Recap of previous lecture

- Lecture 1 & 2: FeynRules
  - ➡ implement a model into FeynRules.
  - ➡ export the model to MadGraph 5.
  - ➡ check a model implementation.
- Lecture 3: UFO & ALOHA
  - ➡ what happens when going from FeynRules to MadGraph.
- This lecture:
  - ➡ Superfields in FeynRules.
  - ➡ Going beyond tree level: InSurGe & FR@NLO.
  - ➡ Galileo.

Superfields in FeynRules

The lifecycle of SUSY pheno

- Example: SUSY model

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

- Very easy 'theory description'
  - ➡ Choose a gauge group (+ additional internal symmetries).
  - ➡ Choose the matter content (= chiral superfields in some representation).
  - ➡ Write down the most general superpotential.
  - ➡ Write down the soft-SUSY breaking terms.
  - ➡ (+ check validity of the model)

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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!).
  - ➡ Express everything in terms of mass eigenstates.
  - ➡ Integrate out D and F terms.
  - ➡ Implement vertices one-by-one (beware of factors of *i*, *etc*!)

Supersymmetric models

- FeynRules allows to use the superfield formalism for supersymmetric theories.
- The code then
  - ➡ expands the superfields in the Grassmann variables and integrates them out.
  - ➡ Weyl fermions are transformed into 4-component spinors.
  - ➡ auxiliary fields are integrated out.
- As a result, we obtain a Lagrangian that can be exported to matrix element generators!

Supersymmetric models

- Example: SUSY QCD
  - ➡ 1 octet vector superfield $V^a = (\tilde{g}^a, G^a_\mu, D^a)$
  - ➡ 1 triplet left-handed chiral superfield $Q^i_L = (\tilde{q}^i_L, \chi^i, F^i_L)$
  - ➡ 1 triplet right-handed chiral superfield $Q^i_R = (\tilde{q}^i_R, \bar{\xi}^i, F^i_R)$
- The physical spectrum contains
  - ➡ a gauge boson, the gluon
  - ➡ two complex triplet scalars
  - ➡ an octet Majorana fermion
  - ➡ a triplet Dirac fermion, the quark $q^i = (\chi^i, \bar{\xi}^i)$

Supersymmetric models

- Interactions (almost) entirely fixed by SUSY

$$Q_L^\dagger\, e^{-2g_s V}\, Q_L + Q_R^\dagger\, e^{-2g_s V}\, Q_R + \frac{1}{8g_s^2}\mathrm{Tr}(W^\alpha W_\alpha) + \frac{1}{8g_s^2}\mathrm{Tr}(\overline{W}_{\dot\alpha}\overline{W}^{\dot\alpha})$$
$$+W(Q_L, Q_R^\dagger) + W^\star(Q_L^\dagger, Q_R)$$

- The gauge sector is already rather complicated in terms of component fields...

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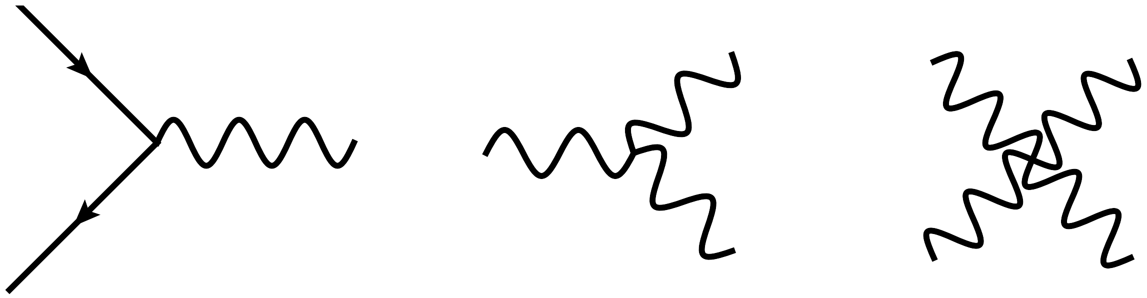

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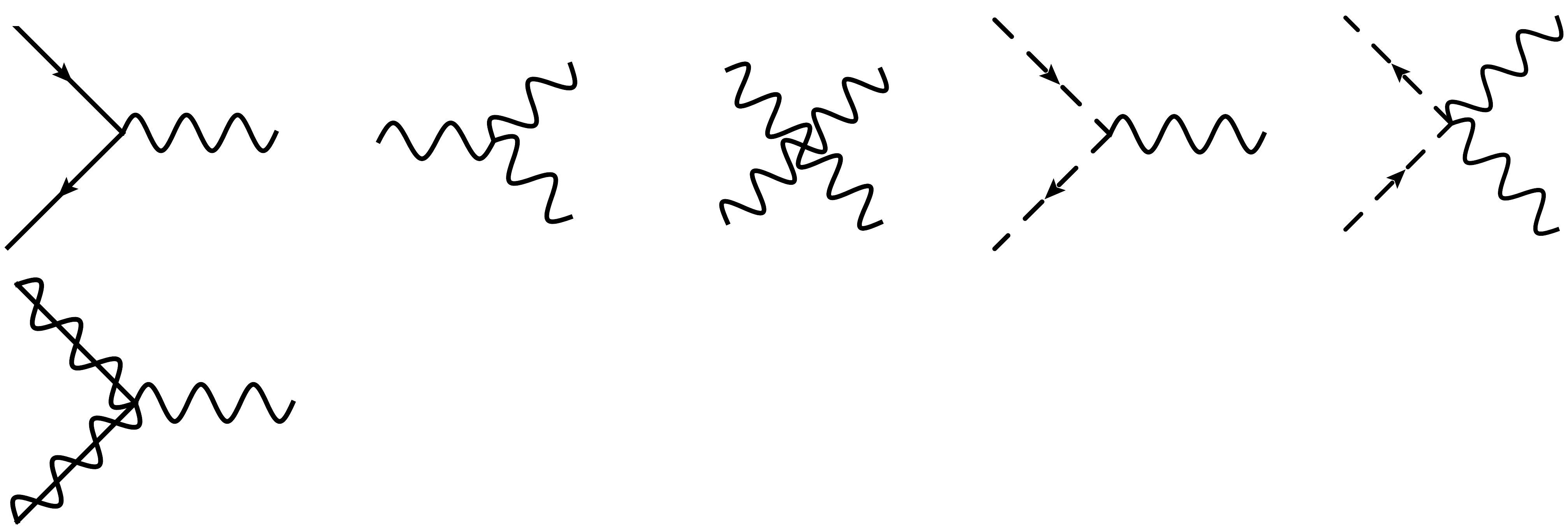

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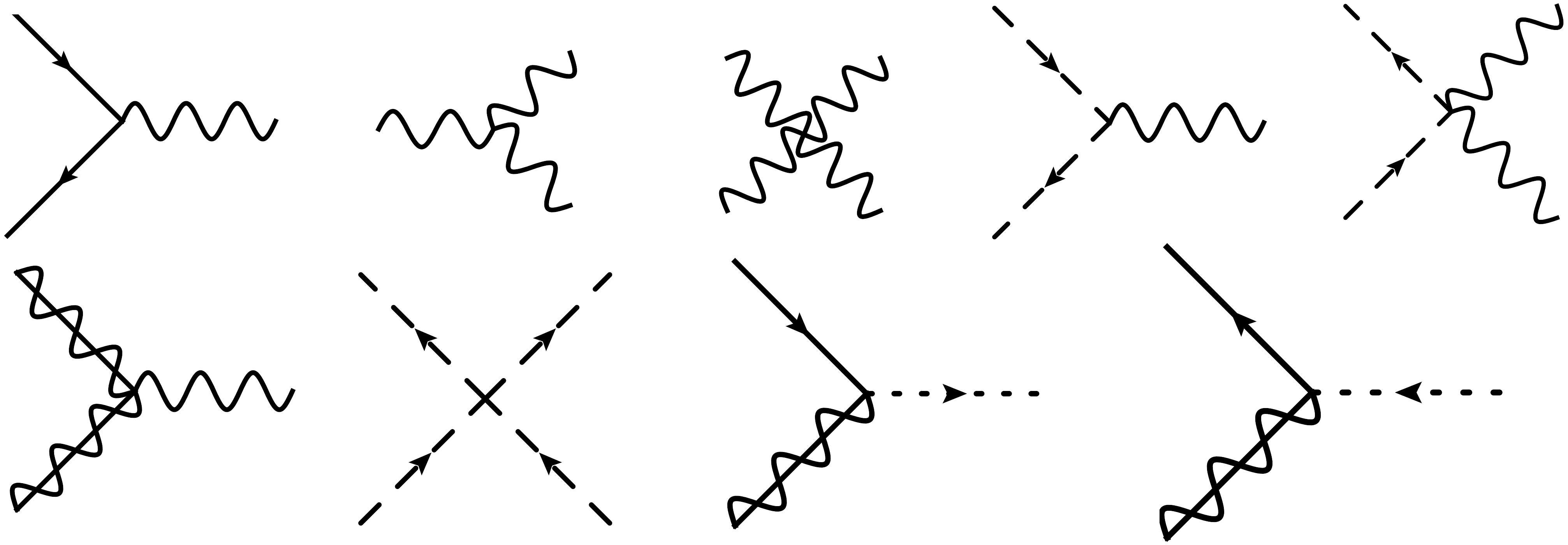

Defining superfields

```
VSF[1] == { ClassName   -> GSF,
            GaugeBoson  -> G,
            Gaugino     -> gow,
            Indices     -> {Index[Gluon]}},

CSF[1] == { ClassName    -> QL,
             Chirality    -> Left,
             Weyl         -> qLw,
             Scalar       -> QLs,
             Indices->{Index[Colour]}},
```

$$V^a = (\tilde{g}^a, G^a_\mu, D^a)$$

$$Q^i_L = (\tilde{q}^i_L, \chi^i, F^i_L)$$

- The component fields are defined separately.
- Auxiliary F and D fields could be added, but can be left out, and are created on the fly.

Using superfields

```
WS = ...
SL = VSFKineticTerms[] + CSFKineticTerms[] + WS + HC[WS];
```

- A set of functions allows to transform the superspace action into a component field Lagrangian.
  - ➡ SF2Components: expansion in the Grassmann parameters
  - ➡ ThetaThetabarComponent etc.: selects the desired coefficient in the Grassmann expansion.
  - ➡ SolveEqMotionF/SolveEqMotionD: solves the equations of motion for the F and D terms.
  - ➡ WeylToDirac: Transforms Weyl fermions into 4-component fermions.

Using superfields

$$-4 f_{\mathrm{Gluon\$1,Gluon\$2,Gluon\$3}} f_{\mathrm{Gluon\$3,Gluon\$4,Gluon\$5}} G_{\mathrm{mu\$1,Gluon\$1}} G_{\mathrm{mu\$1,Gluon\$4}} G_{\mathrm{mu\$2,Gluon\$2}} G_{\mathrm{mu\$2,Gluon\$5}} \mathrm{gs}^4 +$$

$$16 \partial_{\mathrm{mu\$2}}\left(G_{\mathrm{mu\$1,Gluon\$1}}\right) f_{\mathrm{Gluon\$1,Gluon\$2,Gluon\$3}} G_{\mathrm{mu\$1,Gluon\$2}} G_{\mathrm{mu\$2,Gluon\$3}} \mathrm{gs}^3 + 8 i \bar{\mathrm{go}}_{\mathrm{r\$28685,Gluon\$2}} \cdot \mathrm{go}_{\mathrm{r\$28698,Gluon\$1}} f_{\mathrm{Gluon\$1,Gluon\$2,Gluon\$3}} G_{\mathrm{mu\$1,Gluon\$3}} \gamma^{\mathrm{mu\$1}} \cdot P_{-,\mathrm{r\$28685,r\$28698}} \mathrm{gs}^3 -$$

$$8 i \bar{\mathrm{go}}_{\mathrm{r\$28698,Gluon\$1}} \cdot \mathrm{go}_{\mathrm{r\$28685,Gluon\$2}} f_{\mathrm{Gluon\$1,Gluon\$2,Gluon\$3}} G_{\mathrm{mu\$1,Gluon\$3}} \gamma^{\mathrm{mu\$1}} \cdot P_{+,\mathrm{r\$28698,r\$28685}} \mathrm{gs}^3 - 8 \partial_{\mathrm{mu\$2}}\left(G_{\mathrm{mu\$1,Gluon\$1}}\right)^2 \mathrm{gs}^2 +$$

$$8 \partial_{\mathrm{mu\$2}}\left(G_{\mathrm{mu\$1,Gluon\$1}}\right) \partial_{\mathrm{mu\$1}}\left(G_{\mathrm{mu\$2,Gluon\$1}}\right) \mathrm{gs}^2 + G_{\mathrm{mu\$1,Gluon\$1}} G_{\mathrm{mu\$1,Gluon\$2}} \mathrm{QLs}_{\mathrm{Colour\$1}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$3}} T^{\mathrm{Gluon\$2}}_{\mathrm{Colour\$3,Colour\$1}} \mathrm{gs}^2 +$$

$$G_{\mathrm{mu\$1,Gluon\$1}} G_{\mathrm{mu\$1,Gluon\$2}} \mathrm{QRs}_{\mathrm{Colour\$1}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$3}} T^{\mathrm{Gluon\$2}}_{\mathrm{Colour\$3,Colour\$1}} \mathrm{gs}^2 + 4 i \bar{\mathrm{go}}_{\mathrm{r\$28679,Gluon\$1}} \cdot \partial_{\mathrm{mu\$1}}\left(\mathrm{go}_{\mathrm{r\$28692,Gluon\$1}}\right) \gamma^{\mathrm{mu\$1}} \cdot P_{-,\mathrm{r\$28679,r\$28692}} \mathrm{gs}^2 -$$

$$4 i \partial_{\mathrm{mu\$1}}\left(\bar{\mathrm{go}}_{\mathrm{r\$28682,Gluon\$1}}\right) \cdot \mathrm{go}_{\mathrm{r\$28695,Gluon\$1}} \gamma^{\mathrm{mu\$1}} \cdot P_{-,\mathrm{r\$28682,r\$28695}} \mathrm{gs}^2 - 4 i \partial_{\mathrm{mu\$1}}\left(\bar{\mathrm{go}}_{\mathrm{r\$28692,Gluon\$1}}\right) \cdot \mathrm{go}_{\mathrm{r\$28679,Gluon\$1}} \gamma^{\mathrm{mu\$1}} \cdot P_{+,\mathrm{r\$28692,r\$28679}} \mathrm{gs}^2 +$$

$$4 i \bar{\mathrm{go}}_{\mathrm{r\$28695,Gluon\$1}} \cdot \partial_{\mathrm{mu\$1}}\left(\mathrm{go}_{\mathrm{r\$28682,Gluon\$1}}\right) \gamma^{\mathrm{mu\$1}} \cdot P_{+,\mathrm{r\$28695,r\$28682}} \mathrm{gs}^2 - i \partial_{\mathrm{mu\$1}}\left(\mathrm{QLs}^{\dagger}_{\mathrm{Colour\$1}}\right) G_{\mathrm{mu\$1,Gluon\$1}} \mathrm{QLs}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$1,Colour\$2}} \mathrm{gs} +$$

$$i \sqrt{2}\, \bar{q}_{\mathrm{r\$28675,Colour\$1}} \cdot \mathrm{go}_{\mathrm{r\$28688,Gluon\$1}} P_{+,\mathrm{r\$28675,r\$28688}} \mathrm{QLs}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$1,Colour\$2}} \mathrm{gs} + i \partial_{\mathrm{mu\$1}}\left(\mathrm{QRs}^{\dagger}_{\mathrm{Colour\$1}}\right) G_{\mathrm{mu\$1,Gluon\$1}} \mathrm{QRs}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$1,Colour\$2}} \mathrm{gs} -$$

$$i \sqrt{2}\, \bar{q}_{\mathrm{r\$28689,Colour\$1}} \cdot \mathrm{go}_{\mathrm{r\$28676,Gluon\$1}} P_{-,\mathrm{r\$28689,r\$28676}} \mathrm{QRs}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$1,Colour\$2}} \mathrm{gs} + i \partial_{\mathrm{mu\$1}}\left(\mathrm{QLs}_{\mathrm{Colour\$1}}\right) G_{\mathrm{mu\$1,Gluon\$1}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$1}} \mathrm{gs} -$$

$$i \sqrt{2}\, \bar{\mathrm{go}}_{\mathrm{r\$28677,Gluon\$1}} \cdot q_{\mathrm{r\$28690,Colour\$1}} P_{-,\mathrm{r\$28677,r\$28690}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$1}} \mathrm{gs} - i \partial_{\mathrm{mu\$1}}\left(\mathrm{QRs}_{\mathrm{Colour\$1}}\right) G_{\mathrm{mu\$1,Gluon\$1}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$1}} \mathrm{gs} +$$

$$i \sqrt{2}\, \bar{\mathrm{go}}_{\mathrm{r\$28691,Gluon\$1}} \cdot q_{\mathrm{r\$28678,Colour\$1}} P_{+,\mathrm{r\$28691,r\$28678}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$1}} \mathrm{gs} + \bar{q}_{\mathrm{r\$28687,Colour\$2}} \cdot q_{\mathrm{r\$28700,Colour\$1}} G_{\mathrm{mu\$1,Gluon\$1}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$1}} \gamma^{\mathrm{mu\$1}} \cdot P_{-,\mathrm{r\$28687,r\$28700}} \mathrm{gs} -$$

$$\bar{q}_{\mathrm{r\$28699,Colour\$1}} \cdot q_{\mathrm{r\$28686,Colour\$2}} G_{\mathrm{mu\$1,Gluon\$1}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$1,Colour\$2}} \gamma^{\mathrm{mu\$1}} \cdot P_{+,\mathrm{r\$28699,r\$28686}} \mathrm{gs} + \frac{1}{2} \partial_{\mathrm{mu\$1}}\left(\mathrm{QLs}_{\mathrm{Colour\$1}}\right) \partial_{\mathrm{mu\$1}}\left(\mathrm{QLs}^{\dagger}_{\mathrm{Colour\$1}}\right) +$$

$$\frac{1}{2} \partial_{\mathrm{mu\$1}}\left(\mathrm{QRs}_{\mathrm{Colour\$1}}\right) \partial_{\mathrm{mu\$1}}\left(\mathrm{QRs}^{\dagger}_{\mathrm{Colour\$1}}\right) - \frac{1}{4} \partial_{\mathrm{mu\$1}}\left(\partial_{\mathrm{mu\$1}}\left(\mathrm{QLs}^{\dagger}_{\mathrm{Colour\$1}}\right)\right) \mathrm{QLs}_{\mathrm{Colour\$1}} - \frac{1}{4} \partial_{\mathrm{mu\$1}}\left(\partial_{\mathrm{mu\$1}}\left(\mathrm{QLs}_{\mathrm{Colour\$1}}\right)\right) \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$1}} - \frac{1}{4} \partial_{\mathrm{mu\$1}}\left(\partial_{\mathrm{mu\$1}}\left(\mathrm{QRs}^{\dagger}_{\mathrm{Colour\$1}}\right)\right) \mathrm{QRs}_{\mathrm{Colour\$1}} -$$

$$\frac{1}{4} \partial_{\mathrm{mu\$1}}\left(\partial_{\mathrm{mu\$1}}\left(\mathrm{QRs}_{\mathrm{Colour\$1}}\right)\right) \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$1}} + \frac{1}{32} \mathrm{QLs}_{\mathrm{Colour\$1\$28637}} \mathrm{QLs}_{\mathrm{Colour\$1\$28639}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2\$28637}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2\$28639}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28637,Colour\$1\$28637}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28639,Colour\$1\$28639}} +$$

$$\frac{1}{32} \mathrm{QLs}_{\mathrm{Colour\$1\$28639}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2\$28639}} \mathrm{QRs}_{\mathrm{Colour\$1\$28638}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2\$28638}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28638,Colour\$1\$28638}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28639,Colour\$1\$28639}} +$$

$$\frac{1}{32} \mathrm{QLs}_{\mathrm{Colour\$1\$28637}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2\$28637}} \mathrm{QRs}_{\mathrm{Colour\$1\$28640}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2\$28640}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28637,Colour\$1\$28637}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28640,Colour\$1\$28640}} +$$

$$\frac{1}{32} \mathrm{QRs}_{\mathrm{Colour\$1\$28638}} \mathrm{QRs}_{\mathrm{Colour\$1\$28640}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2\$28638}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2\$28640}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28638,Colour\$1\$28638}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28640,Colour\$1\$28640}} -$$

$$\frac{1}{16} \mathrm{QLs}_{\mathrm{Colour\$1}} \mathrm{QLs}_{\mathrm{Colour\$1\$28641}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2\$28641}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$1}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28641,Colour\$1\$28641}} -$$

$$\frac{1}{16} \mathrm{QLs}_{\mathrm{Colour\$1}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2}} \mathrm{QRs}_{\mathrm{Colour\$1\$28642}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2\$28642}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$1}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28642,Colour\$1\$28642}} -$$

$$\frac{1}{16} \mathrm{QLs}_{\mathrm{Colour\$1\$28643}} \mathrm{QLs}^{\dagger}_{\mathrm{Colour\$2\$28643}} \mathrm{QRs}_{\mathrm{Colour\$1}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$1}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28643,Colour\$1\$28643}} -$$

$$\frac{1}{16} \mathrm{QRs}_{\mathrm{Colour\$1}} \mathrm{QRs}_{\mathrm{Colour\$1\$28644}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2}} \mathrm{QRs}^{\dagger}_{\mathrm{Colour\$2\$28644}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2,Colour\$1}} T^{\mathrm{Gluon\$1}}_{\mathrm{Colour\$2\$28644,Colour\$1\$28644}} + \frac{1}{2} i \bar{q}_{\mathrm{r\$28680,Colour\$1}} \cdot \partial_{\mathrm{mu\$1}}\left(q_{\mathrm{r\$28693,Colour\$1}}\right) \gamma^{\mathrm{mu\$1}} \cdot P_{-,\mathrm{r\$28680,r\$28693}} -$$

$$\frac{1}{2} i \partial_{\mathrm{mu\$1}}\left(\bar{q}_{\mathrm{r\$28683,Colour\$1}}\right) \cdot q_{\mathrm{r\$28696,Colour\$1}} \gamma^{\mathrm{mu\$1}} \cdot P_{-,\mathrm{r\$28683,r\$28696}} - \frac{1}{2} i \partial_{\mathrm{mu\$1}}\left(\bar{q}_{\mathrm{r\$28694,Colour\$1}}\right) \cdot q_{\mathrm{r\$28681,Colour\$1}} \gamma^{\mathrm{mu\$1}} \cdot P_{+,\mathrm{r\$28694,r\$28681}} + \frac{1}{2} i \bar{q}_{\mathrm{r\$28697,Colour\$1}} \cdot \partial_{\mathrm{mu\$1}}\left(q_{\mathrm{r\$28684,Colour\$1}}\right) \gamma^{\mathrm{mu\$1}} \cdot P_{+,\mathrm{r\$28697,r\$28684}}$$

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)

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

Summary

- FeynRules allows to use the superfield formalism for supersymmetric theories.
  - ➡ expands the superfields in the Grassmann variables and integrates them out.
  - ➡ Weyl fermions are transformed into 4-component spinors.
  - ➡ auxiliary fields are integrated out.
- SUSY phenomenology however has other aspects as well, like solving RG equations to obtain the low energy mass spectrum from some high scale input.
- This needs input beyond tree level.

To infinity and beyond...

- We have reached the point that we have a complete and fully automatized chain from the Lagrangian to the events.
- This chain is however restricted to tree level so far.
- Next goal: extend this chain to beyond-tree-level information.
  - ➡ Development branch 1: InSurGe

    'spectrum generator generator'.
  - ➡ Development branch 2: FR@NLO

    getting ready for automated BSM NLO computation.

Beyond tree-level

InSurGe

SUSY RG equations

- The fully generic MSSM depends on 105 free parameters.
  - ➡ impossible to do phenomenology with such a huge parameter space.
- Very often one assumes an organizing principle are at some high UV scale, where, e.g., couplings and/or masses unify.
- The parameters at the weak scale are then fixed by the renomalization group flow.

$$\beta_g^{(1)} = g^3\left[S(\mathcal{R}) - 3C(G)\right] \qquad \beta_M^{(1)} = 2g^2 M\left[S(\mathcal{R}) - 3C(G)\right]$$

- Classical example: mSUGRA

$$m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}(\mu)$$

InSurGe

- The development version of FeynRules allows to extract the one-loop renormalization group equations for generic SUSY models. [A. Alloul, K. de Causmaecker, B. Fuks]

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```
RGE[LSoft, SuperW]
```

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RGE[LSoft, SuperW]

$$\frac{\mathrm{d}\mu}{\mathrm{d}t} = \mu\Big[-\frac{3g'^2}{80\pi^2} - \frac{3g_w^2}{16\pi^2} + \frac{3}{16\pi^2}\mathrm{Tr}\big[\mathbf{y^d}^\dagger\mathbf{y^d}\big] + \frac{3}{16\pi^2}\mathrm{Tr}\big[\mathbf{y^u}^\dagger\mathbf{y^u}\big] + \frac{1}{16\pi^2}\mathrm{Tr}\big[\mathbf{y^e}^\dagger\mathbf{y^e}\big]\Big]$$

$$\frac{\mathrm{d}b}{\mathrm{d}t} = b\Big[-\frac{3g'^2}{80\pi^2} - \frac{3g_w^2}{16\pi^2} + \frac{3}{16\pi^2}\mathrm{Tr}\big[\mathbf{y^d}^\dagger\mathbf{y^d}\big] + \frac{3}{16\pi^2}\mathrm{Tr}\big[\mathbf{y^u}^\dagger\mathbf{y^u}\big] + \frac{1}{16\pi^2}\mathrm{Tr}\big[\mathbf{y^e}^\dagger\mathbf{y^e}\big]\Big]$$
$$+ \mu\Big[\frac{3g'^2 M_1}{40\pi^2} + \frac{3g_w^2 M_2}{8\pi^2} + \frac{3}{8\pi^2}\mathrm{Tr}\big[\mathbf{y^d}^\dagger\mathbf{T^d}\big] + \frac{3}{8\pi^2}\mathrm{Tr}\big[\mathbf{y^u}^\dagger\mathbf{T^u}\big] + \frac{1}{8\pi^2}\mathrm{Tr}\big[\mathbf{y^e}^\dagger\mathbf{T^e}\big]\Big]$$

InSurGe

```
ScaSoftRGE[SoftMS, SPMS, NLoop → 2][[8]]
```

$$\frac{\partial}{\partial t}\left[m^2_{\tilde{e}\,\text{ff1\$5668,ff2\$5668}}\right] = \frac{243\,(g')^4\, m^2_{H_d}\, \delta_{\text{ff1\$5668,ff2\$5668}}}{16\,000\,\pi^4} - \frac{81\,(g')^2 g_w^2\, m^2_{H_d}\, \delta_{\text{ff1\$5668,ff2\$5668}}}{3200\,\pi^4} + \frac{81\,(g')^4\, m^2_{H_u}\, \delta_{\text{ff1\$5668,ff2\$5668}}}{3200\,\pi^4} + \frac{81\,(g')^2 g_w^2\, m^2_{H_u}\, \delta_{\text{ff1\$5668,ff2\$5668}}}{3200\,\pi^4} - \frac{3\,(g')^2\, m^2_{H_d}\, \delta_{\text{ff1\$5668,ff2\$5668}}}{40\,\pi^2} + \frac{3\,(g')^2\, m^2_{H_u}\, \delta_{\text{ff1\$5668,ff2\$5668}}}{40\,\pi^2} +$$

$$\frac{1647\,(g')^4 M_1 M_1^*\, \delta_{\text{ff1\$5668,ff2\$5668}}}{1280\,\pi^4} - \frac{3\,(g')^2 M_1 M_1^*\, \delta_{\text{ff1\$5668,ff2\$5668}}}{10\,\pi^2} + \frac{63\,(g')^4\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{D}\,\text{GEN\$1,GEN\$1}}}{1000\,\pi^4} + \frac{9\,(g')^2 g_s^2\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{D}\,\text{GEN\$1,GEN\$1}}}{200\,\pi^4} + \frac{3\,(g')^2\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{D}\,\text{GEN\$1,GEN\$1}}}{40\,\pi^2} + \frac{81\,(g')^4\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{e}\,\text{GEN\$1,GEN\$1}}}{1000\,\pi^4} +$$

$$\frac{3\,(g')^2\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{e}\,\text{GEN\$1,GEN\$1}}}{40\,\pi^2} + \frac{891\,(g')^4\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{L}\,\text{GEN\$1,GEN\$1}}}{16\,000\,\pi^4} - \frac{81\,(g')^2 g_w^2\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{L}\,\text{GEN\$1,GEN\$1}}}{3200\,\pi^4} - \frac{3\,(g')^2\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{L}\,\text{GEN\$1,GEN\$1}}}{40\,\pi^2} + \frac{981\,(g')^4\, m^2_{\tilde{Q}\,\text{ff1\$5668,ff3\$5668}}}{16\,000\,\pi^4} + \frac{9\,(g')^2 g_s^2\, m^2_{\tilde{Q}\,\text{ff1\$5668,ff3\$5668}}}{200\,\pi^4} +$$

$$\frac{81\,(g')^2 g_w^2\, m^2_{\tilde{Q}\,\text{ff1\$5668,ff3\$5668}}}{3200\,\pi^4} + \frac{3\,(g')^2\, m^2_{\tilde{Q}\,\text{ff1\$5668,ff3\$5668}}}{40\,\pi^2} + \frac{9\,(g')^4\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{U}\,\text{GEN\$1,GEN\$1}}}{40\,\pi^4} - \frac{9\,(g')^2 g_s^2\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{U}\,\text{GEN\$1,GEN\$1}}}{100\,\pi^4} - \frac{3\,(g')^2\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{U}\,\text{GEN\$1,GEN\$1}}}{20\,\pi^2} - \frac{9\,(g')^2\, (T_e)^*_{\text{ff2\$5668,GEN\$1}}\, T_{e\,\text{ff1\$5668,GEN\$1}}}{160\,\pi^4} +$$

$$\frac{9\,g_w^2\, (T_e)^*_{\text{ff2\$5668,GEN\$1}}\, T_{e\,\text{ff1\$5668,GEN\$1}}}{32\,\pi^4} - \frac{9\,(g')^2 M_1^*\, (y^e)^*_{\text{ff2\$5668,GEN\$1}}\, T_{e\,\text{ff1\$5668,GEN\$1}}}{160\,\pi^4} + \frac{9\,g_w^2 M_2^*\, (y^e)^*_{\text{ff2\$5668,GEN\$1}}\, T_{e\,\text{ff1\$5668,GEN\$1}}}{32\,\pi^4} + \frac{(T_e)^*_{\text{ff1\$5668,GEN\$1}}\, T_{e\,\text{ff2\$5668,GEN\$1}}}{4\,\pi^2} - \frac{9\,(g')^2\, m^2_{H_d}\, (y^d)^*_{\text{GEN\$1,GEN\$2}}\, \delta_{\text{ff1\$5668,ff2\$5668}}\, y^d_{\text{GEN\$1,GEN\$2}}}{40\,\pi^4} -$$

$$\frac{9\,(T_d)^*_{\text{GEN\$1,GEN\$2}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, T_{e\,\text{ff1\$5668,GEN\$3}}\, y^d_{\text{GEN\$1,index1071}}}{128\,\pi^4} - \frac{9\,(T_d)^*_{\text{GEN\$1,GEN\$2}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, T_{e\,\text{ff1\$5668,GEN\$3}}\, y^d_{\text{GEN\$1,index1084}}}{128\,\pi^4} - \frac{9\,(g')^2\, (y^d)^*_{\text{GEN\$1,index1058}}\, m^2_{\tilde{Q}\,\text{ff1\$5668,ff3\$5668}}\, y^d_{\text{GEN\$1,index1097}}}{40\,\pi^4} - \frac{9\,(T_e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^d)^*_{\text{GEN\$2,GEN\$3}}\, T_{e\,\text{ff1\$5668,GEN\$1}}\, y^d_{\text{GEN\$2,GEN\$3}}}{64\,\pi^4} -$$

$$\frac{9\,(g')^2\, (y^d)^*_{\text{GEN\$1,GEN\$2}}\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{D}\,\text{GEN\$1,GEN\$3}}\, y^d_{\text{GEN\$3,GEN\$2}}}{80\,\pi^4} - \frac{9\,(g')^2 M_1\, (T_e)^*_{\text{ff2\$5668,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$1}}}{160\,\pi^4} + \frac{9\,g_w^2 M_2\, (T_e)^*_{\text{ff2\$5668,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$1}}}{32\,\pi^4} - \frac{9\,(g')^2 M_1 M_1^*\, (y^e)^*_{\text{ff2\$5668,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$1}}}{80\,\pi^4} + \frac{9\,g_w^2 M_2 M_2^*\, (y^e)^*_{\text{ff2\$5668,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$1}}}{16\,\pi^4} -$$

$$\frac{3\,(T_e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, T_{e\,\text{GEN\$2,GEN\$3}}\, y^e_{\text{ff1\$5668,GEN\$1}}}{64\,\pi^4} - \frac{9\,(g')^2\, (y^e)^*_{\text{GEN\$1,GEN\$2}}\, m^2_{\tilde{e}\,\text{ff2\$5668,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$2}}}{320\,\pi^4} + \frac{9\,g_w^2\, (y^e)^*_{\text{GEN\$1,GEN\$2}}\, m^2_{\tilde{e}\,\text{ff2\$5668,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$2}}}{64\,\pi^4} - \frac{9\,(T_d)^*_{\text{GEN\$1,ff2\$5668}}\, (y^e)^*_{\text{ff2\$5668,GEN\$2}}\, T_{d\,\text{GEN\$1,ff2\$5668}}\, y^e_{\text{ff1\$5668,GEN\$2}}}{64\,\pi^4} -$$

$$\frac{9\,(T_e)^*_{\text{GEN\$1,GEN\$2}}\, (y^d)^*_{\text{GEN\$3,index1071}}\, T_{d\,\text{GEN\$3,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$2}}}{128\,\pi^4} - \frac{9\,(T_e)^*_{\text{GEN\$1,GEN\$2}}\, (y^d)^*_{\text{GEN\$3,index1084}}\, T_{d\,\text{GEN\$3,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$2}}}{128\,\pi^4} - \frac{3\,(T_e)^*_{\text{GEN\$1,GEN\$2}}\, (y^e)^*_{\text{ff2\$5668,GEN\$3}}\, T_{e\,\text{GEN\$1,GEN\$3}}\, y^e_{\text{ff1\$5668,GEN\$2}}}{64\,\pi^4} -$$

$$\frac{3\,(T_e)^*_{\text{GEN\$1,GEN\$2}}\, (y^e)^*_{\text{ff2\$5668,GEN\$3}}\, T_{e\,\text{GEN\$1,GEN\$2}}\, y^e_{\text{ff1\$5668,GEN\$3}}}{64\,\pi^4} - \frac{3\,(T_e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, T_{e\,\text{GEN\$2,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$3}}}{64\,\pi^4} - \frac{9\,m^2_{H_d}\, (y^d)^*_{\text{GEN\$1,GEN\$2}}\, (y^e)^*_{\text{ff2\$5668,GEN\$3}}\, y^d_{\text{GEN\$1,GEN\$2}}\, y^e_{\text{ff1\$5668,GEN\$3}}}{32\,\pi^4} -$$

$$\frac{9\,(y^d)^*_{\text{GEN\$1,GEN\$2}}\, (y^e)^*_{\text{ff2\$5668,GEN\$3}}\, m^2_{\tilde{L}\,\text{GEN\$3,GEN\$4}}\, y^d_{\text{GEN\$1,GEN\$2}}\, y^e_{\text{ff1\$5668,GEN\$4}}}{64\,\pi^4} + \frac{m^2_{H_d}\, (y^e)^*_{\text{ff1\$5668,GEN\$1}}\, y^e_{\text{ff2\$5668,GEN\$1}}}{4\,\pi^2} + \frac{(y^e)^*_{\text{ff1\$5668,GEN\$1}}\, m^2_{\tilde{L}\,\text{GEN\$2,GEN\$1}}\, y^e_{\text{ff2\$5668,GEN\$2}}}{4\,\pi^2} - \frac{3\,(g')^2\, m^2_{H_d}\, (y^e)^*_{\text{GEN\$1,GEN\$2}}\, \delta_{\text{ff1\$5668,ff2\$5668}}\, y^e_{\text{GEN\$1,GEN\$2}}}{40\,\pi^4} -$$

$$\frac{3\,(T_e)^*_{\text{GEN\$1,GEN\$2}}\, (y^e)^*_{\text{ff2\$5668,GEN\$3}}\, T_{e\,\text{ff1\$5668,GEN\$3}}\, y^e_{\text{GEN\$1,GEN\$2}}}{64\,\pi^4} - \frac{3\,(g')^2\, (y^e)^*_{\text{GEN\$1,GEN\$2}}\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{L}\,\text{GEN\$2,GEN\$3}}\, y^e_{\text{GEN\$1,GEN\$3}}}{80\,\pi^4} - \frac{3\,(T_e)^*_{\text{GEN\$1,GEN\$2}}\, (y^e)^*_{\text{ff2\$5668,GEN\$3}}\, T_{e\,\text{ff1\$5668,GEN\$2}}\, y^e_{\text{GEN\$1,GEN\$3}}}{64\,\pi^4} - \frac{9\,(g')^2\, (y^e)^*_{\text{ff2\$5668,GEN\$1}}\, m^2_{\tilde{e}\,\text{ff1\$5668,GEN\$2}}\, y^e_{\text{GEN\$2,GEN\$1}}}{320\,\pi^4} +$$

$$\frac{9\,g_w^2\, (y^e)^*_{\text{ff2\$5668,GEN\$1}}\, m^2_{\tilde{e}\,\text{ff1\$5668,GEN\$2}}\, y^e_{\text{GEN\$2,GEN\$1}}}{64\,\pi^4} + \frac{(y^e)^*_{\text{ff1\$5668,GEN\$1}}\, m^2_{\tilde{e}\,\text{GEN\$2,ff2\$5668}}\, y^e_{\text{GEN\$2,GEN\$1}}}{8\,\pi^2} - \frac{3\,(T_e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, T_{e\,\text{ff1\$5668,GEN\$3}}\, y^e_{\text{GEN\$2,GEN\$1}}}{64\,\pi^4} - \frac{3\,m^2_{H_d}\, (y^e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, y^e_{\text{ff1\$5668,GEN\$3}}\, y^e_{\text{GEN\$2,GEN\$1}}}{64\,\pi^4} -$$

$$\frac{3\,(y^e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, m^2_{\tilde{L}\,\text{GEN\$3,GEN\$4}}\, y^e_{\text{ff1\$5668,GEN\$4}}\, y^e_{\text{GEN\$2,GEN\$1}}}{64\,\pi^4} - \frac{3\,(T_e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, T_{e\,\text{ff1\$5668,GEN\$1}}\, y^e_{\text{GEN\$2,GEN\$3}}}{64\,\pi^4} - \frac{3\,m^2_{H_d}\, (y^e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, y^e_{\text{ff1\$5668,GEN\$1}}\, y^e_{\text{GEN\$2,GEN\$3}}}{32\,\pi^4} -$$

$$\frac{3\,(y^e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, m^2_{\tilde{L}\,\text{GEN\$1,GEN\$4}}\, y^e_{\text{ff1\$5668,GEN\$4}}\, y^e_{\text{GEN\$2,GEN\$3}}}{64\,\pi^4} - \frac{3\,(y^e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, m^2_{\tilde{L}\,\text{GEN\$4,GEN\$1}}\, y^e_{\text{ff1\$5668,GEN\$3}}\, y^e_{\text{GEN\$2,GEN\$4}}}{64\,\pi^4} - \frac{3\,(g')^2\, (y^e)^*_{\text{GEN\$1,GEN\$2}}\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{e}\,\text{GEN\$1,GEN\$3}}\, y^e_{\text{GEN\$3,GEN\$2}}}{80\,\pi^4} -$$

$$\frac{3\,(y^e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, m^2_{\tilde{e}\,\text{ff1\$5668,GEN\$4}}\, y^e_{\text{GEN\$2,GEN\$3}}\, y^e_{\text{GEN\$4,GEN\$1}}}{128\,\pi^4} - \frac{9\,(y^d)^*_{\text{GEN\$1,GEN\$2}}\, (y^e)^*_{\text{ff2\$5668,GEN\$3}}\, m^2_{\tilde{e}\,\text{ff1\$5668,GEN\$4}}\, y^d_{\text{GEN\$1,GEN\$2}}\, y^e_{\text{GEN\$4,GEN\$3}}}{128\,\pi^4} - \frac{3\,(y^e)^*_{\text{ff2\$5668,GEN\$1}}\, (y^e)^*_{\text{GEN\$2,GEN\$3}}\, m^2_{\tilde{e}\,\text{ff1\$5668,GEN\$4}}\, y^e_{\text{GEN\$2,GEN\$1}}\, y^e_{\text{GEN\$4,GEN\$3}}}{128\,\pi^4} -$$

$$\frac{9\,(g')^2\, m^2_{H_u}\, (y^u)^*_{\text{GEN\$1,GEN\$2}}\, \delta_{\text{ff1\$5668,ff2\$5668}}\, y^u_{\text{GEN\$1,GEN\$2}}}{80\,\pi^4} - \frac{9\,(g')^2\, (y^u)^*_{\text{GEN\$1,index1058}}\, m^2_{\tilde{Q}\,\text{ff1\$5668,ff3\$5668}}\, y^u_{\text{GEN\$1,index1097}}}{40\,\pi^4} - \frac{9\,(g')^2\, (y^u)^*_{\text{GEN\$1,GEN\$2}}\, \delta_{\text{ff1\$5668,ff2\$5668}}\, m^2_{\tilde{U}\,\text{GEN\$1,GEN\$3}}\, y^u_{\text{GEN\$3,GEN\$2}}}{80\,\pi^4}$$

InSurGe

- Right now, FeynRules/InSurGe can extract the one and two-loop RGE's for arbitrary (renomalizable) SUSY models.
- These RGE's can then be fed into spectrum generators to obtain the mass spectrum for arbitrary SUSY models.
- In this way, FeynRules/InSurGe turns into a 'spectrum generator generator'.

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- These RGE's can then be fed into spectrum generators to obtain the mass spectrum for arbitrary SUSY models.
- In this way, FeynRules/InSurGe turns into a 'spectrum generator generator'.
- As an example, an interface to SuSpect 3 is being developed that will allow to inject the FeynRules/InSurGe RGE's directly into the SuSpect framework.

```
WriteSuSpectOutput[LSoft, SuperW]
```

InSurGe

- In parallel, InSurGe will come with its own RGE solver.
- Under development right now:
  - ➡ Finding the minimum of the Higgs potential.
  - ➡ Diagonalizing the mass matrices.
- At the same time this solves another problem…

InSurGe

- In parallel, InSurGe will come with its own RGE solver.
- Under development right now:
  - ➡ Finding the minimum of the Higgs potential.
  - ➡ Diagonalizing the mass matrices.
- At the same time this solves another problem...
- Remember that FeynRules does not allow to diagonalize the mass matrices automatically.
- InSurGe will solve this problem at the same time (not only for SUSY models).

Mass diagonalization with InSurGe

- In the future, FeynRules will extract the mass matrices automatically from the Lagrangian.

Mass diagonalization with InSurGe

Preliminary results

In[57]:= **GetMassMatrices[lagr]**

```
The Lagrangian you entered contains physical fields, make sure these don't come
  from a previous field rotation. Calculations have been however performed.

Calculations took 35.8097
  seconds to be performed. Results are stored in the variable MassMatrices
```

In[58]:= **MassMatrices[[7, 2]].MatrixForm[MassMatrices[[7, 3]]].MassMatrices[[7, 4]]**

Out[58]= $\{\mathrm{bow}, \mathrm{wow}_3, \mathrm{hdw}_1, \mathrm{huw}_2\}.$

$$\begin{pmatrix} M_1 & 0 & -\frac{1}{2}\, i\, g'\, v_d & \frac{1}{2}\, i\, g'\, v_u \\ 0 & M_2 & \frac{1}{2}\, i\, g_w\, v_d & -\frac{1}{2}\, i\, g_w\, v_u \\ -\frac{1}{2}\, i\, g'\, v_d & \frac{1}{2}\, i\, g_w\, v_d & 0 & -\mu \\ \frac{1}{2}\, i\, g'\, v_u & -\frac{1}{2}\, i\, g_w\, v_u & -\mu & 0 \end{pmatrix} . \{\mathrm{bow}, \mathrm{wow}_3, \mathrm{hdw}_1, \mathrm{huw}_2\}$$

[A. Alloul @ FR2012]

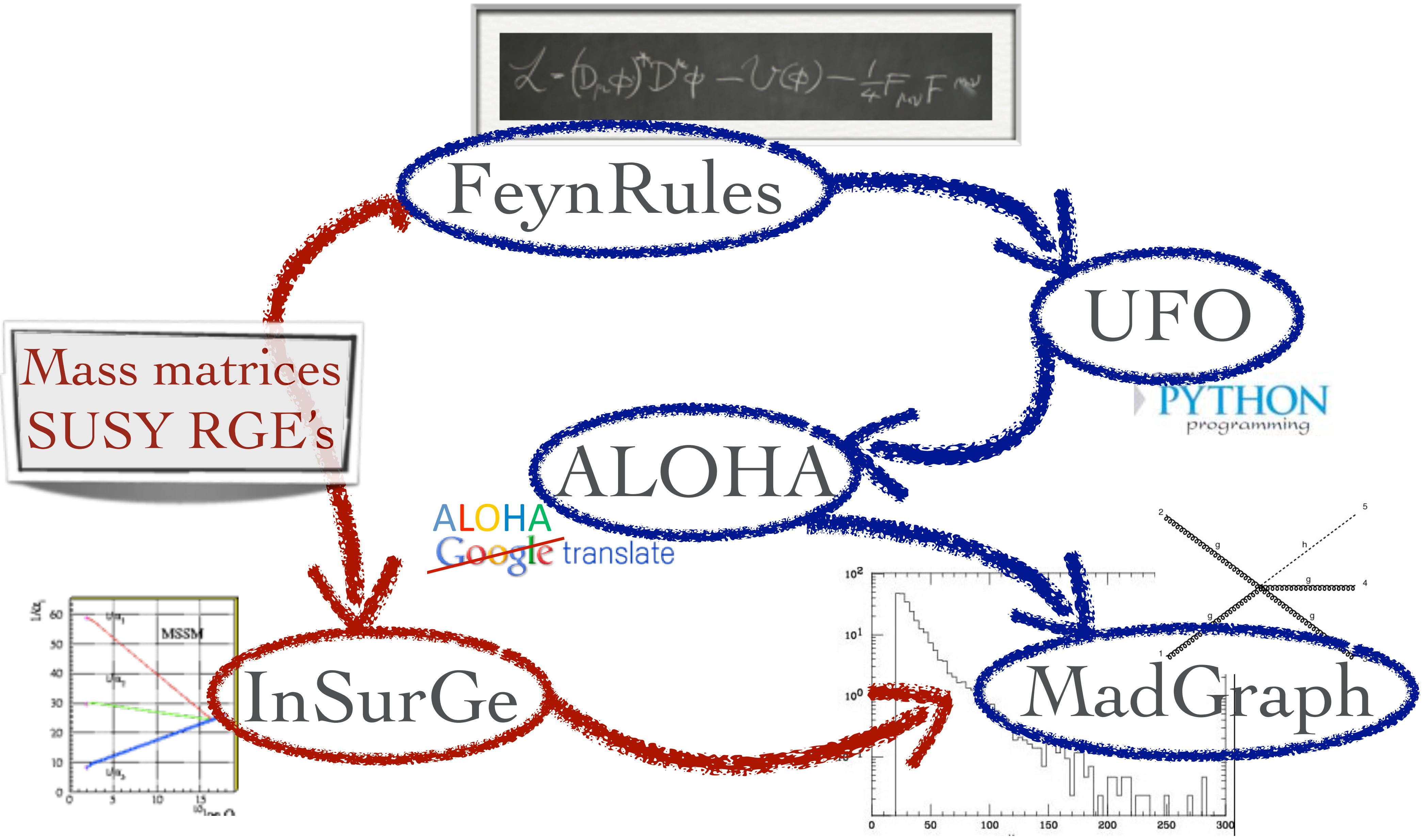
Mass diagonalization with InSurGe

- In the future, FeynRules will extract the mass matrices automatically form the Lagrangian.

- The mass matrix is then passed on to InSurGe:
  - ➡ a C++ code is written out that diagonalizes the mass matrices and returns a `param_card.dat` with the numerical values of the masses and mixing matrices.

- The C++ code is standalone and can be run outside and independently of Mathematica.

Workflow


FeynRules
UFO
PYTHON
programming
ALOHA
ALOHA
Google translate
Mass matrices
SUSY RGE's
InSurGe
MadGraph
MSSM

Beyond tree-level

FR@NLO

Towards NLO

- We are slowly getting to the point that we have automated tools for NLO computations:
  - ➡ Blackhat
  - ➡ GoSam
  - ➡ FeynArts/FormCalc
  - ➡ 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 in addition we need
  - ➡ UV counterterms.
  - ➡ Feynman rules for non cut-constructible part of the amplitude ('R2 terms').

Extraction of UV 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.

- In the future: FeynRules will call FeynArts/FormCalc on the fly to obtain the values of the counterterms.

[C. Degrande, CD, B. Fuks, T. Hahn]

Extraction of counterterms

- First milestone: include counterterms into the FeynArts interface.

Extraction of counterterms

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  - ➡ FeynArts output **without** counterterms:

```
C[ V[1] , V[1] , V[3] , -V[3] ] == {{(-I)*gc8   , 0},
                                     {(-I)*gc8   , 0},
                                     {(2*I)*gc8, 0}}
```

Extraction of counterterms

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  - ➡ FeynArts output **without** counterterms:

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                                    {(-I)*gc8   , 0},
                                    {(2*I)*gc8, 0}}
```

  - ➡ FeynArts output **with** counterterms:

```
C[ V[1] , V[1] , V[3] , -V[3] ] ==
  {{(-I)*gc8, (I*(aEW*deltagw01 + aS*deltagw10)*gw*sw^2)/Pi},
  {(-I)*gc8,  (I*(aEW*deltagw01 + aS*deltagw10)*gw*sw^2)/Pi},
  {(2*I)*gc8, ((-2*I)*(aEW*deltagw01 + aS*deltagw10)*gw*sw^2)/Pi}}
```

Extraction of counterterms

- First milestone: include counterterms into the FeynArts interface.

- Next:
  - ➡ on-the-fly use of FeynArts to compute the analytical values of the independent one-loop coutnerterms.
  - ➡ write counterterms out to the UFO.

Extraction of counterterms

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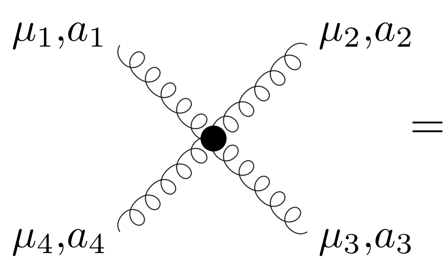
- Next:
  - ➡ on-the-fly use of FeynArts to compute the analytical values of the independent one-loop coutnerterms.
  - ➡ write counterterms out to the UFO.

```
V_R24G = CTVertex(name = 'V_R24G',
             particles = [ P.G, P.G, P.G, P.G ],
             color = [ 'Tr(1,2)*Tr(3,4)' , 'Tr(1,3)*Tr(2,4)' , 'Tr(1,4)*Tr(2,3)', \
                       'd(-1,1,2)*d(-1,3,4)' , 'd(-1,1,3)*d(-1,2,4)' , 'd(-1,1,4)*d(-1,2,3)'],
             lorentz = [  L.R2_4G_1234, L.R2_4G_1324, L.R2_4G_1423 ],
             loop_particles = [ [[P.G]], [[P.u],[P.d],[P.c],[P.s]] ],
             couplings = {(0,0,0):C.GC_4GR2_Gluon_delta5,(0,1,0):C.GC_4GR2_Gluon_delta7,(0,2,0):C.GC_4GR2_Gluon_delta7, \
                          (1,0,0):C.GC_4GR2_Gluon_delta7,(1,1,0):C.GC_4GR2_Gluon_delta5,(1,2,0):C.GC_4GR2_Gluon_delta7, \
                          (2,0,0):C.GC_4GR2_Gluon_delta7,(2,1,0):C.GC_4GR2_Gluon_delta7,(2,2,0):C.GC_4GR2_Gluon_delta5, \
                          (3,0,0):C.GC_4GR2_4Struct,(3,1,0):C.GC_4GR2_2Struct,(3,2,0):C.GC_4GR2_2Struct, \
                          (4,0,0):C.GC_4GR2_2Struct,(4,1,0):C.GC_4GR2_4Struct,(4,2,0):C.GC_4GR2_2Struct, \
                          (5,0,0):C.GC_4GR2_2Struct,(5,1,0):C.GC_4GR2_2Struct,(5,2,0):C.GC_4GR2_4Struct , \
                          (0,0,1):C.GC_4GR2_Fermion_delta11,(0,1,1):C.GC_4GR2_Fermion_delta5,(0,2,1):C.GC_4GR2_Fermion_delta5, \
                          (1,0,1):C.GC_4GR2_Fermion_delta5,(1,1,1):C.GC_4GR2_Fermion_delta11,(1,2,1):C.GC_4GR2_Fermion_delta5, \
                          (2,0,1):C.GC_4GR2_Fermion_delta5,(2,1,1):C.GC_4GR2_Fermion_delta5,(2,2,1):C.GC_4GR2_Fermion_delta11, \
                          (3,0,1):C.GC_4GR2_11Struct,(3,1,1):C.GC_4GR2_5Struct,(3,2,1):C.GC_4GR2_5Struct, \
                          (4,0,1):C.GC_4GR2_5Struct,(4,1,1):C.GC_4GR2_11Struct,(4,2,1):C.GC_4GR2_5Struct, \
                          (5,0,1):C.GC_4GR2_5Struct,(5,1,1):C.GC_4GR2_5Struct,(5,2,1):C.GC_4GR2_11Struct },
             type = 'R2')
```

R2 terms

- All the automatized NLO codes are based, in one way or another, on some unitary-based approach.
- Unitarity, however, does not provide everything, but misses the rational pieces (without cuts).
- Some can be obtained, others (R2) need a different approach.
- R2 terms can be obtained via effective tree-level Feynman rules.



$$
= -\frac{ig^4 N_{col}}{96\pi^2} \sum_{P(234)} \Bigg\{ \Bigg[\frac{\delta_{a_1a_2}\delta_{a_3a_4}+\delta_{a_1a_3}\delta_{a_4a_2}+\delta_{a_1a_4}\delta_{a_2a_3}}{N_{col}}
+ 4\, Tr(t^{a_1}t^{a_3}t^{a_2}t^{a_4}+t^{a_1}t^{a_4}t^{a_2}t^{a_3})\,(3+\lambda_{HV})
- Tr(\{t^{a_1}t^{a_2}\}\{t^{a_3}t^{a_4}\})\,(5+2\lambda_{HV})\Bigg]\, g_{\mu_1\mu_2}g_{\mu_3\mu_4}
+ 12\frac{N_f}{N_{col}} Tr(t^{a_1}t^{a_2}t^{a_3}t^{a_4})\left(\frac{5}{3} g_{\mu_1\mu_3}g_{\mu_2\mu_4} - g_{\mu_1\mu_2}g_{\mu_3\mu_4} - g_{\mu_2\mu_3}g_{\mu_1\mu_4}\right)\Bigg\}
$$

[Draggiotis, Garzelli, Papadopoulos, Pittau;
Garzelli, Malamos, Pittau]

What are the R_2 rational terms?

$$\bar{A}(\bar{q}) = \frac{1}{(2\pi)^4}\int d^d\bar{q}\frac{\bar{N}(\bar{q})}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}}, \qquad \bar{D}_i = (\bar{q}+p_i)^2 - m_i^2$$

$$\bar{N}(\bar{q}) = N(q) + \widetilde{N}(\tilde{q}, q, \epsilon)$$

where $\bar{X}$ lives in d dimension, X in 4, $\widetilde{X}$ in ϵ.

R_2 definition

$$R_2 \equiv \frac{1}{(2\pi)^4}\int d^d\bar{q}\frac{\widetilde{N}(\tilde{q}, q, \epsilon)}{\bar{D}_0\bar{D}_1\ldots\bar{D}_{m-1}}$$

Finite (< 4 legs) set of vertices computed once for all!

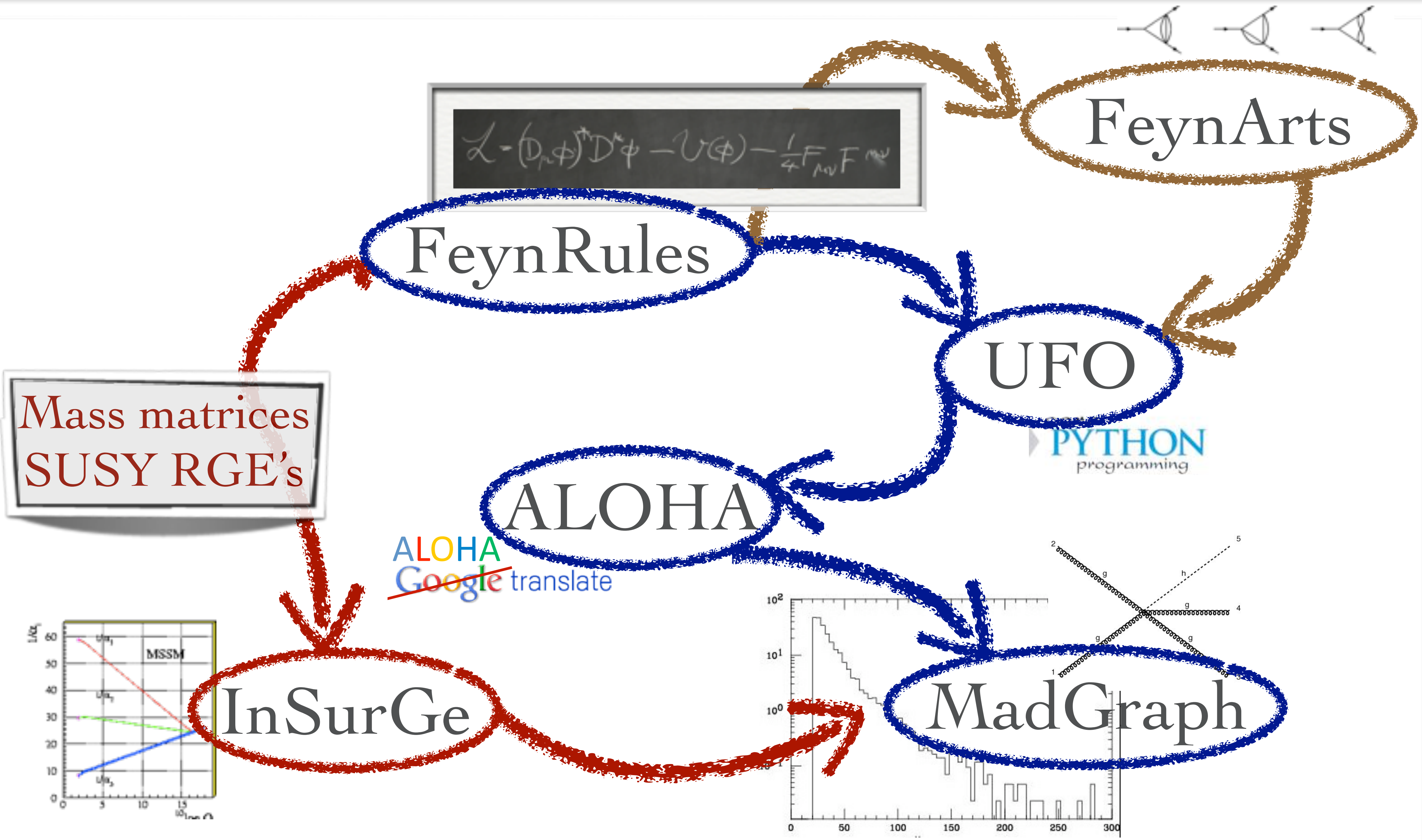
Results from FeynRules

1. SM
   - takes approx. 10min
   - agree up to $-1/i$ factors (definition of $A, \phi^{\pm}$) with

     QCD : Draggiotis, P. et al. JHEP 0904 (2009) 072.

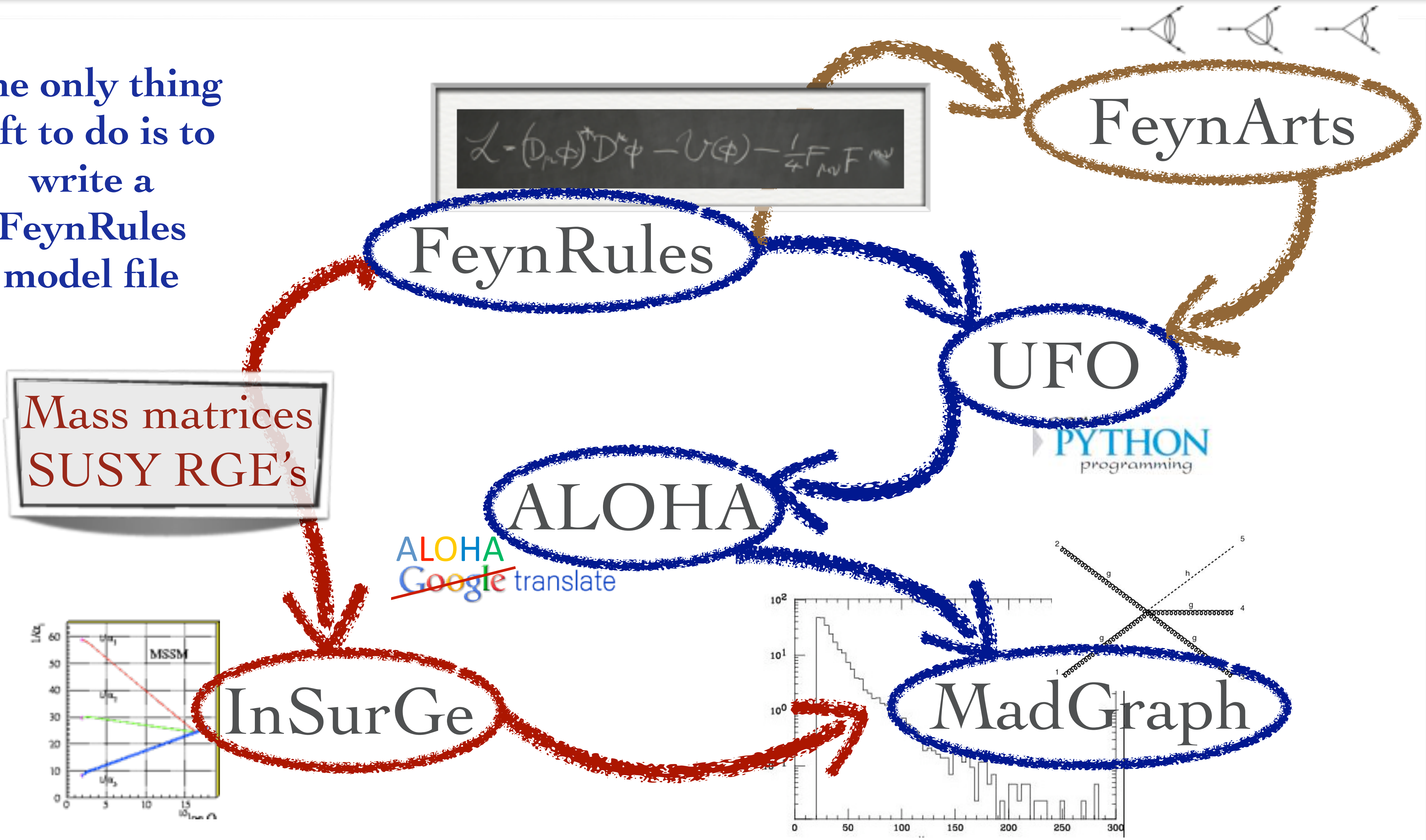
     EW : Garzelli, M.V. et al. JHEP 1001 (2010) 040, Erratum-ibid. 1010 (2010) 097.
2. MSSM : On going

Workflow


FeynArts
FeynRules
UFO
PYTHON
programming
ALOHA
Mass matrices
SUSY RGE's
ALOHA
Google translate
InSurGe
MSSM
MadGraph

Workflow

The only thing left to do is to write a FeynRules model file



Galileo

Model building with FeynRules

- All the steps from the Lagrangian to phenomenology are/will be automatized.
- The only 'bottleneck' right now is the writing of the FeynRules model file.
  - ➡ Avoid typos in the FeynRules syntax.
  - ➡ A lot of information to provide for complicated models.
- In the future, the Galileo package will alleviate this task.

[N. D. Christensen, D. Salmon, N. Setzer C. Speckner, Stefanus]

- Galileo will enable the user to specify the symmetry groups and the particle content of the model, and the FeynRules model file is generated automatically.

Core Components: Compact Lie Algebras

Compact Lie Algebras: Finished and Tested

- Understands any Compact Lie Algebra, $U(1)$, and $\mathbb{Z}_n$
  A_n, B_n, C_n, D_n, G_2, F_4, E_6, E_7, E_8, $U(1)$, $\mathbb{Z}_n$
  - Arbitrary Representations
  - All Generators of any Representations
- Product States
  - Gives Singlets

[N. Setzer @ FR2012]

Galileo

Core Components: Fields

Fields: Mostly Finished and Tested

- Understands Spin 0, $\frac{1}{2}$, and 1 fields (fundamental objects)
- Understands Superfields
  - Implemented as a container
  - Chiral Superfields stored as collection of spin-0 and spin-$\frac{1}{2}$
- Output
  - to MathML
  - NEED to FeynRules

[N. Setzer @ FR2012]

Galileo

Core Components: Model

Model: Mostly Finished and Partly Tested

- Understands any direct product group (of Known Groups)
  - Local or Global ($\mathbb{Z}_n$ only global)
- Lagrangian
  - Completely and automatically generated given fields
  - Handles all operators up to dimension 6
  - For SUSY Generates Kahler potential and Superpotential
  - Output to MathML
- Needs
  - Save/Read Model - XML file
  - Write complet FeynRules `.fr` file

[N. Setzer @ FR2012]

Galileo

SM 1 Higgs (Dim 4)

SM with 1 Higgs up to Dimension 4

$$\overline{Q_l}\gamma^\mu D_\mu Q_l + \overline{U_r}\gamma^\mu D_\mu U_r + \overline{D_r}\gamma^\mu D_\mu D_r + \overline{L_l}\gamma^\mu D_\mu L_l + \overline{E_r}\gamma^\mu D_\mu E_r + D_\mu \Phi^* D^\mu \Phi + G_{C\mu\nu} G_C^{\mu\nu} + \theta_0 \varepsilon_{\alpha\beta\gamma\delta} G_C^{\alpha\beta} G_C^{\gamma\delta}$$
$$+ W_{L\mu\nu} W_L^{\mu\nu} + \theta_1 \varepsilon_{\alpha\beta\gamma\delta} W_L^{\alpha\beta} W_L^{\gamma\delta} + B_{Y\mu\nu} B_Y^{\mu\nu}$$

$$\mu_{r0} \Phi \Phi^*$$

$$\lambda_{r1} \Phi \Phi \Phi^* \Phi^*$$

$$y_2 \Phi \overline{U_r} Q_l + y_2^* \Phi^* \overline{Q_l} U_r + y_3 \Phi^* \overline{D_r} Q_l + y_3^* \Phi \overline{Q_l} D_r + y_4 \Phi^* \overline{E_r} L_l + y_4^* \Phi \overline{L_l} E_r$$

[Stefanus @ MC4BSM2012]

Galileo

SM 1 Higgs (Dim 6)

$\overline{Q_l}\gamma^\mu D_\mu Q_l + \overline{U_r}\gamma^\mu D_\mu U_r + \overline{D_r}\gamma^\mu D_\mu D_r + \overline{L_l}\gamma^\mu D_\mu L_l + \overline{E_r}\gamma^\mu D_\mu E_r + D_\mu \Phi^* D^\mu \Phi + G_{C\mu\nu} G_C^{\mu\nu} + \theta_0 \varepsilon_{\alpha\beta\gamma\delta} G_C^{\alpha\beta} G_C^{\gamma\delta} + W_{L\mu\nu} W_L^{\mu\nu} +$
$\theta_1 \varepsilon_{\alpha\beta\gamma\delta} W_L^{\alpha\beta} W_L^{\gamma\delta} + B_{Y\mu\nu} B_Y^{\mu\nu}$

$\mu_{r0} \Phi \Phi^*$

$\lambda_{r1} \Phi \Phi \Phi^* \Phi^*$

$y_2 \Phi \overline{U_r} Q_l + y_2^* \Phi^* \overline{Q_l} U_r + y_3 \Phi^* \overline{D_r} Q_l + y_3^* \Phi \overline{Q_l} D_r + y_4 \Phi^* \overline{E_r} L_l + y_4^* \Phi \overline{L_l} E_r +$

$y_5 \Phi \Phi \overline{L_l} L_l^c + y_5^* \Phi^* \Phi^* \overline{L_l^c} L_l +$

$y_6 \Phi^* \Phi \Phi \overline{U_r} Q_l + y_6^* \Phi \Phi^* \Phi^* \overline{Q_l} U_r + y_7 \Phi^* \Phi^* \Phi \overline{D_r} Q_l + y_7^* \Phi \Phi \Phi^* \overline{Q_l} D_r + y_8 \Phi^* \Phi^* \Phi \overline{E_r} L_l + y_8^* \Phi \Phi \Phi^* \overline{L_l} E_r$

[Stefanus @ MC4BSM2012]

Galileo

$$g_{r9}\overline{Q_l}\gamma_\mu Q_l\overline{Q_l}\gamma^\mu Q_l + g_{r10}\overline{Q_l^c}\sigma_{\mu\nu}Q_l\overline{Q_l}\sigma^{\mu\nu}Q_l^c + g_{r11}\overline{Q_l^c}Q_l\overline{Q_l}Q_l^c + g_{r12}\overline{Q_l}\gamma_\mu Q_l\overline{U_r}\gamma^\mu U_r + g_{r13}\overline{Q_l^c}\gamma_\mu U_r\overline{U_r}\gamma^\mu Q_l^c + g_{r14}\overline{Q_l}\sigma_{\mu\nu}U_r\overline{U_r}$$

$$\sigma^{\mu\nu}Q_l + g_{r15}\overline{Q_l}U_r\overline{U_r}Q_l + g_{r16}\overline{Q_l}\gamma_\mu Q_l\overline{D_r}\gamma^\mu D_r + g_{r17}\overline{Q_l^c}\gamma_\mu D_r\overline{D_r}\gamma^\mu Q_l^c + g_{r18}\overline{Q_l}\sigma_{\mu\nu}D_r\overline{D_r}\sigma^{\mu\nu}Q_l + g_{r19}\overline{Q_l}D_r\overline{D_r}Q_l + g_{r20}\overline{Q_l}\gamma_\mu L_l$$

$$\overline{L_l}\gamma^\mu Q_l + g_{r21}\overline{Q_l}\gamma_\mu Q_l\overline{L_l}\gamma^\mu L_l + g_{r22}\overline{Q_l^c}\sigma_{\mu\nu}L_l\overline{L_l}\sigma^{\mu\nu}Q_l^c + g_{r23}\overline{Q_l^c}L_l\overline{L_l}Q_l^c + g_{r24}\overline{Q_l}\gamma_\mu Q_l\overline{E_r}\gamma^\mu E_r + g_{r25}\overline{Q_l^c}\gamma_\mu E_r\overline{E_r}\gamma^\mu Q_l^c + g_{r26}\overline{Q_l}$$

$$\sigma_{\mu\nu}E_r\overline{E_r}\sigma^{\mu\nu}Q_l + g_{r27}\overline{Q_l}E_r\overline{E_r}Q_l + g_{28}\overline{Q_l}\sigma_{\mu\nu}Q_l^c\overline{L_l}\sigma^{\mu\nu}Q_l^c + g_{28}^*\overline{Q_l^c}\sigma_{\mu\nu}Q_l\overline{Q_l^c}\sigma^{\mu\nu}L_l + g_{29}\overline{Q_l}Q_l^c\overline{L_l}Q_l^c + g_{29}^*\overline{Q_l^c}Q_l\overline{Q_l^c}L_l + g_{30}\overline{D_r}$$

$$\sigma_{\mu\nu}Q_l\overline{U_r}\sigma^{\mu\nu}Q_l + g_{30}^*\overline{Q_l}\sigma_{\mu\nu}D_r\overline{Q_l}\sigma^{\mu\nu}U_r + g_{31}\overline{D_r}Q_l\overline{U_r}Q_l + g_{31}^*\overline{Q_l}D_r\overline{Q_l}U_r + g_{32}\overline{U_r}\sigma_{\mu\nu}Q_l\overline{D_r}\sigma^{\mu\nu}Q_l + g_{32}^*\overline{Q_l}\sigma_{\mu\nu}U_r\overline{Q_l}\sigma^{\mu\nu}D_r +$$

$$g_{33}\overline{U_r}Q_l\overline{D_r}Q_l + g_{33}^*\overline{Q_l}U_r\overline{Q_l}D_r + g_{34}\overline{Q_l}\sigma_{\mu\nu}Q_l^c\overline{U_r^c}\sigma^{\mu\nu}D_r + g_{34}^*\overline{Q_l^c}\sigma_{\mu\nu}Q_l\overline{D_r}\sigma^{\mu\nu}U_r^c + g_{35}\overline{Q_l}Q_l^c\overline{U_r^c}D_r + g_{35}^*\overline{Q_l^c}Q_l\overline{D_r}U_r^c + g_{36}\overline{E_r}$$

$$\gamma_\mu Q_l^c\overline{U_r}\gamma^\mu Q_l^c + g_{36}^*\overline{Q_l^c}\gamma_\mu E_r\overline{Q_l^c}\gamma^\mu U_r + g_{37}\overline{U_r}\gamma_\mu Q_l^c\overline{E_r}\gamma^\mu Q_l^c + g_{37}^*\overline{Q_l^c}\gamma_\mu U_r\overline{Q_l^c}\gamma^\mu E_r + g_{38}\overline{Q_l}\sigma_{\mu\nu}Q_l^c\overline{E_r}\sigma^{\mu\nu}U_r^c + g_{38}^*\overline{Q_l^c}\sigma_{\mu\nu}Q_l$$

$$\overline{U_r^c}\sigma^{\mu\nu}E_r + g_{39}\overline{Q_l}Q_l^c\overline{E_r}U_r^c + g_{39}^*\overline{Q_l^c}Q_l\overline{U_r^c}E_r + g_{40}\overline{E_r}\sigma_{\mu\nu}Q_l\overline{U_r}\sigma^{\mu\nu}L_l + g_{40}^*\overline{Q_l}\sigma_{\mu\nu}E_r\overline{L_l}\sigma^{\mu\nu}U_r + g_{41}\overline{E_r}Q_l\overline{U_r}L_l + g_{41}^*\overline{Q_l}E_r\overline{L_l}U_r$$

$$+ g_{42}\overline{U_r}\sigma_{\mu\nu}Q_l\overline{E_r}\sigma^{\mu\nu}L_l + g_{42}^*\overline{Q_l}\sigma_{\mu\nu}U_r\overline{L_l}\sigma^{\mu\nu}E_r + g_{43}\overline{U_r}Q_l\overline{E_r}L_l + g_{43}^*\overline{Q_l}U_r\overline{L_l}E_r + g_{44}\overline{L_l}\sigma_{\mu\nu}Q_l^c\overline{U_r^c}\sigma^{\mu\nu}E_r + g_{44}^*\overline{Q_l^c}\sigma_{\mu\nu}L_l\overline{E_r}\sigma^{\mu\nu}$$

$$U_r^c + g_{45}\overline{L_l}Q_l^c\overline{U_r^c}E_r + g_{45}^*\overline{Q_l^c}L_l\overline{E_r}U_r^c + g_{46}\overline{D_r}\gamma_\mu Q_l^c\overline{L_l}\gamma^\mu U_r^c + g_{46}^*\overline{Q_l^c}\gamma_\mu D_r\overline{U_r^c}\gamma^\mu L_l + g_{47}\overline{U_r}\gamma_\mu Q_l^c\overline{L_l}\gamma^\mu D_r^c + g_{47}^*\overline{Q_l^c}\gamma_\mu U_r\overline{D_r^c}\gamma^\mu L_l$$

$$+ g_{48}\overline{L_l}\sigma_{\mu\nu}Q_l^c\overline{D_r}\sigma^{\mu\nu}U_r^c + g_{48}^*\overline{Q_l^c}\sigma_{\mu\nu}L_l\overline{U_r^c}\sigma^{\mu\nu}D_r + g_{49}\overline{L_l}Q_l^c\overline{D_r}U_r^c + g_{49}^*\overline{Q_l^c}L_l\overline{U_r^c}D_r + g_{50}\overline{L_l}\gamma_\mu Q_l\overline{D_r}\gamma^\mu E_r + g_{50}^*\overline{Q_l}\gamma_\mu L_l\overline{E_r}\gamma^\mu D_r$$

$$+ g_{51}\overline{E_r}\gamma_\mu Q_l^c\overline{D_r^c}\gamma^\mu L_l + g_{51}^*\overline{Q_l^c}\gamma_\mu E_r\overline{L_l}\gamma^\mu D_r^c + g_{52}\overline{D_r}\sigma_{\mu\nu}Q_l\overline{L_l}\sigma^{\mu\nu}E_r + g_{52}^*\overline{Q_l}\sigma_{\mu\nu}D_r\overline{E_r}\sigma^{\mu\nu}L_l + g_{53}\overline{D_r}Q_l\overline{L_l}E_r + g_{53}^*\overline{Q_l}D_r\overline{E_r}L_l +$$

$$g_{r54}\overline{U_r}\gamma_\mu U_r\overline{U_r}\gamma^\mu U_r + g_{r55}\overline{U_r^c}\sigma_{\mu\nu}U_r\overline{U_r}\sigma^{\mu\nu}U_r^c + g_{r56}\overline{U_r^c}U_r\overline{U_r}U_r^c + g_{r57}\overline{U_r}\gamma_\mu D_r\overline{D_r}\gamma^\mu U_r + g_{r58}\overline{U_r}\gamma_\mu U_r\overline{D_r}\gamma^\mu D_r + g_{r59}$$

$$\overline{U_r^c}\sigma_{\mu\nu}D_r\overline{D_r}\sigma^{\mu\nu}U_r^c + g_{r60}\overline{U_r^c}D_r\overline{D_r}U_r^c + g_{r61}\overline{U_r}\gamma_\mu U_r\overline{L_l}\gamma^\mu L_l + g_{r62}\overline{U_r^c}\gamma_\mu L_l\overline{L_l}\gamma^\mu U_r^c + g_{r63}\overline{U_r}\sigma_{\mu\nu}L_l\overline{L_l}\sigma^{\mu\nu}U_r + g_{r64}\overline{U_r}L_l\overline{L_l}U_r +$$

$$g_{r65}\overline{U_r}\gamma_\mu E_r\overline{E_r}\gamma^\mu U_r + g_{r66}\overline{U_r}\gamma_\mu U_r\overline{E_r}\gamma^\mu E_r + g_{r67}\overline{U_r^c}\sigma_{\mu\nu}E_r\overline{E_r}\sigma^{\mu\nu}U_r^c + g_{r68}\overline{U_r^c}E_r\overline{E_r}U_r^c + g_{69}\overline{E_r}\sigma_{\mu\nu}U_r^c\overline{D_r}\sigma^{\mu\nu}U_r^c + g_{69}^*\overline{U_r^c}\sigma_{\mu\nu}E_r$$

$$\overline{U_r^c}\sigma^{\mu\nu}D_r + g_{70}\overline{E_r}U_r^c\overline{D_r}U_r^c + g_{70}^*\overline{U_r^c}E_r\overline{U_r^c}D_r + g_{71}\overline{D_r}\sigma_{\mu\nu}U_r^c\overline{E_r}\sigma^{\mu\nu}U_r^c + g_{71}^*\overline{U_r^c}\sigma_{\mu\nu}D_r\overline{U_r^c}\sigma^{\mu\nu}E_r + g_{72}\overline{D_r}U_r^c\overline{E_r}U_r^c + g_{72}^*\overline{U_r^c}D_r$$

$$\overline{U_r^c}E_r + g_{73}\overline{U_r}\sigma_{\mu\nu}U_r^c\overline{E_r}\sigma^{\mu\nu}D_r^c + g_{73}^*\overline{U_r^c}\sigma_{\mu\nu}U_r\overline{D_r^c}\sigma^{\mu\nu}E_r + g_{74}\overline{U_r}U_r^c\overline{E_r}D_r^c + g_{74}^*\overline{U_r^c}U_r\overline{D_r^c}E_r + g_{r75}\overline{D_r}\gamma_\mu D_r\overline{D_r}\gamma^\mu D_r + g_{r76}$$

$$\overline{D_r^c}\sigma_{\mu\nu}D_r\overline{D_r}\sigma^{\mu\nu}D_r^c + g_{r77}\overline{D_r^c}D_r\overline{D_r}D_r^c + g_{r78}\overline{D_r}\gamma_\mu D_r\overline{L_l}\gamma^\mu L_l + g_{r79}\overline{D_r^c}\gamma_\mu L_l\overline{L_l}\gamma^\mu D_r^c + g_{r80}\overline{D_r}\sigma_{\mu\nu}L_l\overline{L_l}\sigma^{\mu\nu}D_r + g_{r81}\overline{D_r}L_l\overline{L_l}D_r +$$

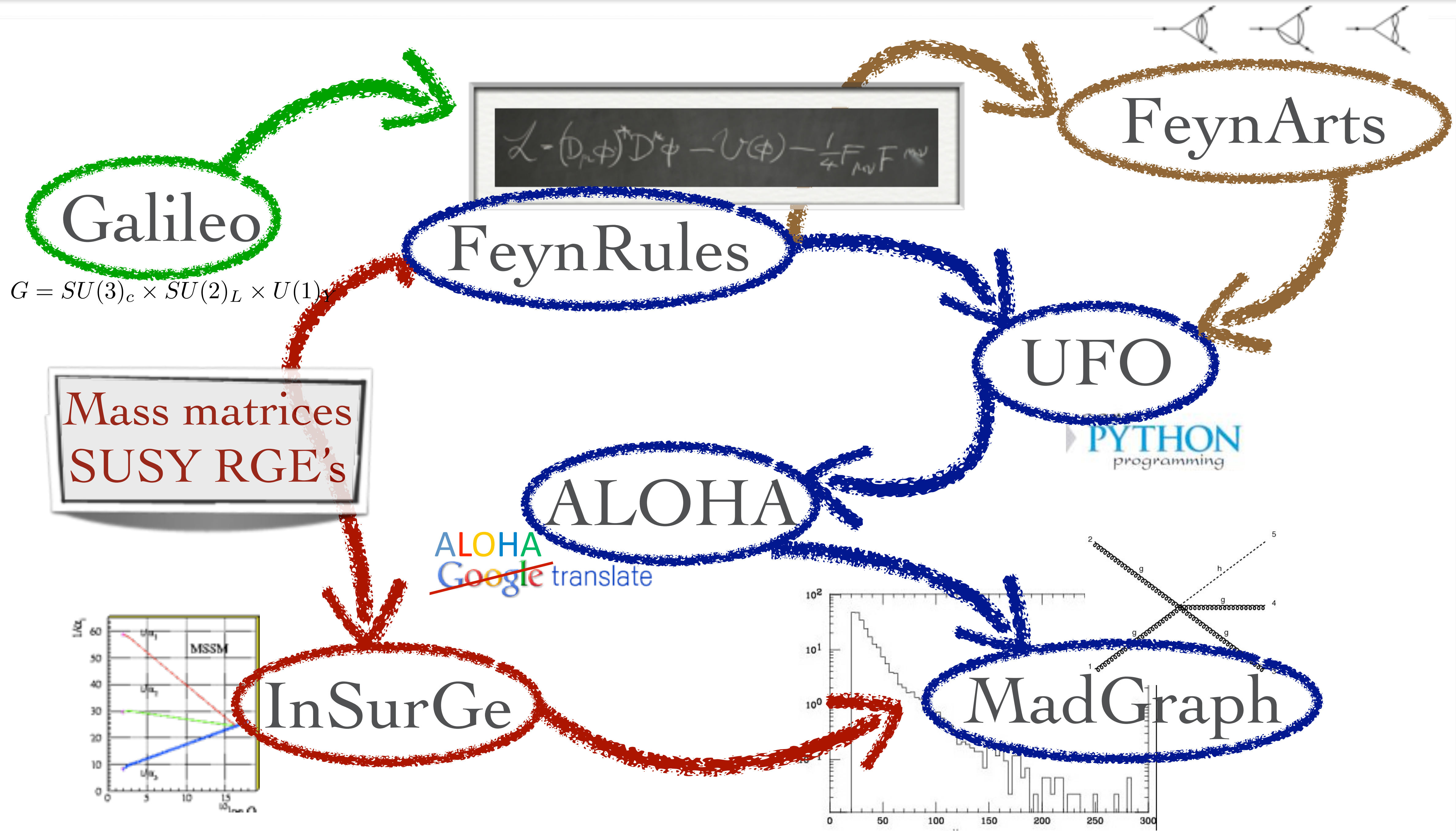
$$g_{r82}\overline{D_r}\gamma_\mu E_r\overline{E_r}\gamma^\mu D_r + g_{r83}\overline{D_r}\gamma_\mu D_r\overline{E_r}\gamma^\mu E_r + g_{r84}\overline{D_r^c}\sigma_{\mu\nu}E_r\overline{E_r}\sigma^{\mu\nu}D_r^c + g_{r85}\overline{D_r^c}E_r\overline{E_r}D_r^c + g_{r86}\overline{L_l}\gamma_\mu L_l\overline{L_l}\gamma^\mu L_l + g_{r87}\overline{L_l^c}\sigma_{\mu\nu}L_l\overline{L_l}\sigma^{\mu\nu}$$

$$L_l^c + g_{r88}\overline{L_l^c}L_l\overline{L_l}L_l^c + g_{r89}\overline{L_l}\gamma_\mu L_l\overline{E_r}\gamma^\mu E_r + g_{r90}\overline{L_l^c}\gamma_\mu E_r\overline{E_r}\gamma^\mu L_l^c + g_{r91}\overline{L_l}\sigma_{\mu\nu}E_r\overline{E_r}\sigma^{\mu\nu}L_l + g_{r92}\overline{L_l}E_r\overline{E_r}L_l + g_{r93}\overline{E_r}\gamma_\mu E_r\overline{E_r}\gamma^\mu E_r +$$

$$g_{r94}\overline{E_r^c}\sigma_{\mu\nu}E_r\overline{E_r}\sigma^{\mu\nu}E_r^c + g_{r95}\overline{E_r^c}E_r\overline{E_r}E_r^c + g_{r96}\Phi\Phi\Phi\Phi^*\Phi^*\Phi^*$$

[Stefanus @ MC4BSM2012]

Workflow


Galileo
$G = SU(3)_c \times SU(2)_L \times U(1)_Y$
FeynRules
FeynArts
UFO
PYTHON
programming
ALOHA
ALOHA
Google translate
Mass matrices
SUSY RGE's
InSurGe
MSSM
MadGraph