Beyond the Standard Model phenomenology with FEYNRULES

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MADGRAPH5_aMC@NLO Femto workshop

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Outline

1. FEYNRULES in a nutshell

2. Main features of FEYNRULES 2.0

3. On the way to automated NLO calculations

4. Summary

Monte Carlo tools and discoveries at the LHC (I)

Assumption

There is some new physics to be discovered

A BSM LHC story

- *A priori* preparation
  - Viable model building
  - Phenomenological studies
  - Prospective collider analyses
- *A posteriori* reactions to announcements
  - Model building
  - Recasting experimental analyses
  - Measurements (precision predictions)

Predictions for the LHC

- Option 1: handmade calculations
  - Factorial growth of the number of diagrams
  - Tedious and error prone
- Option 2: Monte Carlo simulations
  - Easy to use
  - Can include the collision environment

Monte Carlo tools and discoveries at the LHC (2)

Predictions for the LHC

- ~~Option 1: handmade calculations~~
  - ~~Factorial growth of the number of diagrams~~
  - ~~Tedious and error prone~~
- Option 2: Monte Carlo simulations
  - Easy to use
  - Can include the collision environment

- How to implement a new physics model in a Monte Carlo program?
  - Model definition: particles, parameters & vertices (≡ Lagrangian)
  - To be translated in a programming language, following some conventions, *etc*.
  - Tedious, time-consuming, error prone
  - Iterations for all considered tools and models
  - Beware of the restrictions of each tool (Lorentz structures, color structures)

★ **Highly redundant** (each tool, each model)
★ **No-brainer task** (from Feymman rules to code)

→

FEYNRULES

Systematization & automation

FEYNRULES in a nutshell

[Christensen, Duhr (CPC '09); Alloul, Christensen, Degrande, Duhr, BF (CPC'14)]

✦ What is FEYNRULES?

- ✤ A framework to develop new physics models
- ✤ Automatic export to several Monte Carlo event generators

➡ Facilitate phenomenological investigations of the models
➡ Facilitate the confrontation of the models against data

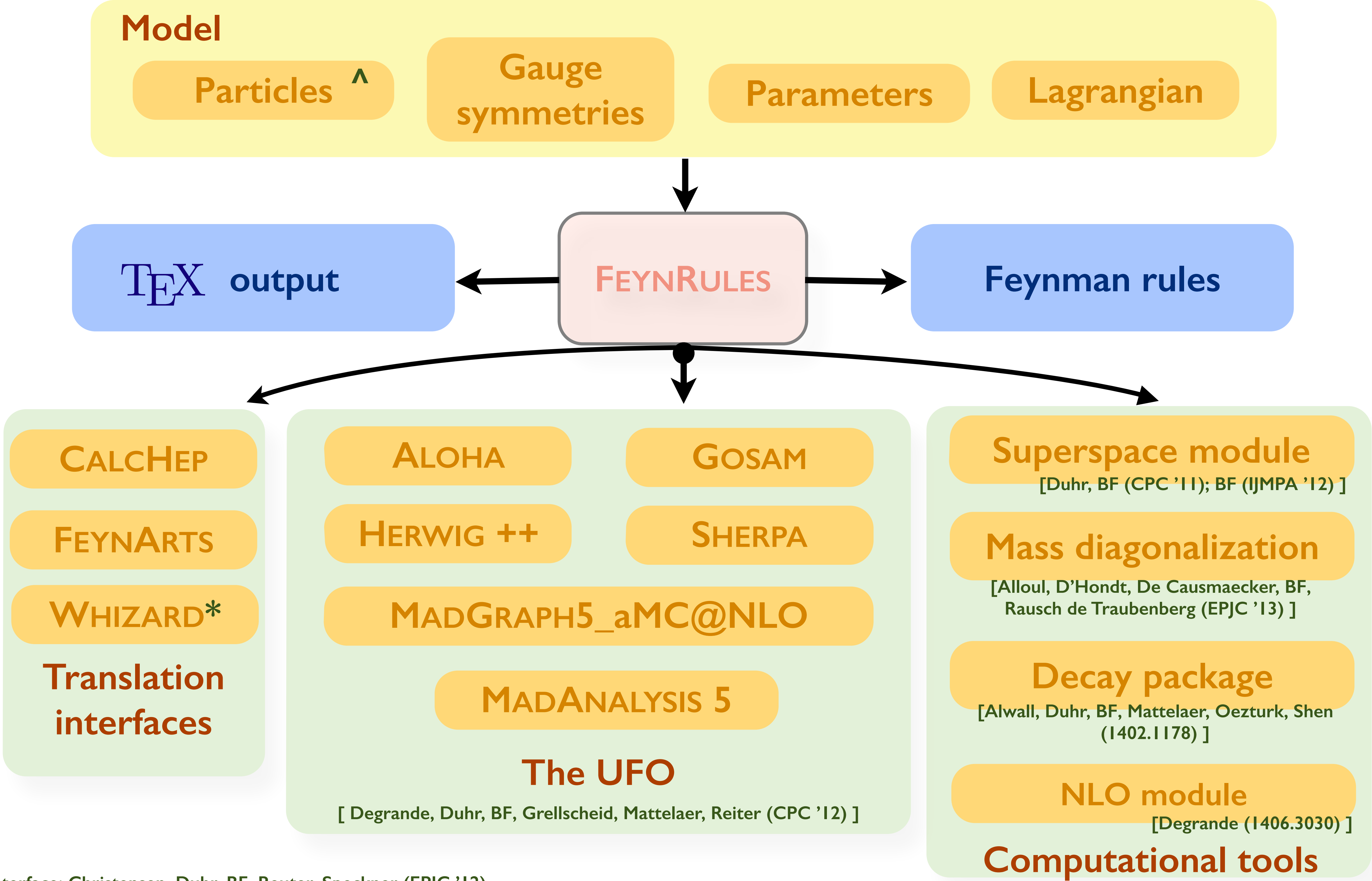
- ✤ Validation of the implementation using several programs

✦ Main features (FEYNRULES 2.0)

- ✤ MATHEMATICA package
- ✤ Core function: derives Feynman rules from a Lagrangian
- ✤ Requirements: locality, Lorentz and gauge invariance
- ✤ Supported fields: scalar, (two- and four-component) fermion, vector, ghost, spin-3/2 field, tensor, superfield

From FeynRules to Monte Carlo tools...

[Christensen, Duhr (CPC '09); Alloul, Christensen, Degrande, Duhr, BF (CPC'14)]



Model

Particles ^

Gauge symmetries

Parameters

Lagrangian

FeynRules

TeX output

Feynman rules

CalcHep

FeynArts

Whizard*

Translation interfaces

Aloha

GoSam

Herwig ++

Sherpa

MadGraph5_aMC@NLO

MadAnalysis 5

The UFO

[Degrande, Duhr, BF, Grellscheid, Mattelaer, Reiter (CPC '12)]

Superspace module

[Duhr, BF (CPC '11); BF (IJMPA '12)]

Mass diagonalization

[Alloul, D'Hondt, De Causmaecker, BF, Rausch de Traubenberg (EPJC '13)]

Decay package

[Alwall, Duhr, BF, Mattelaer, Oezturk, Shen (1402.1178)]

NLO module

[Degrande (1406.3030)]

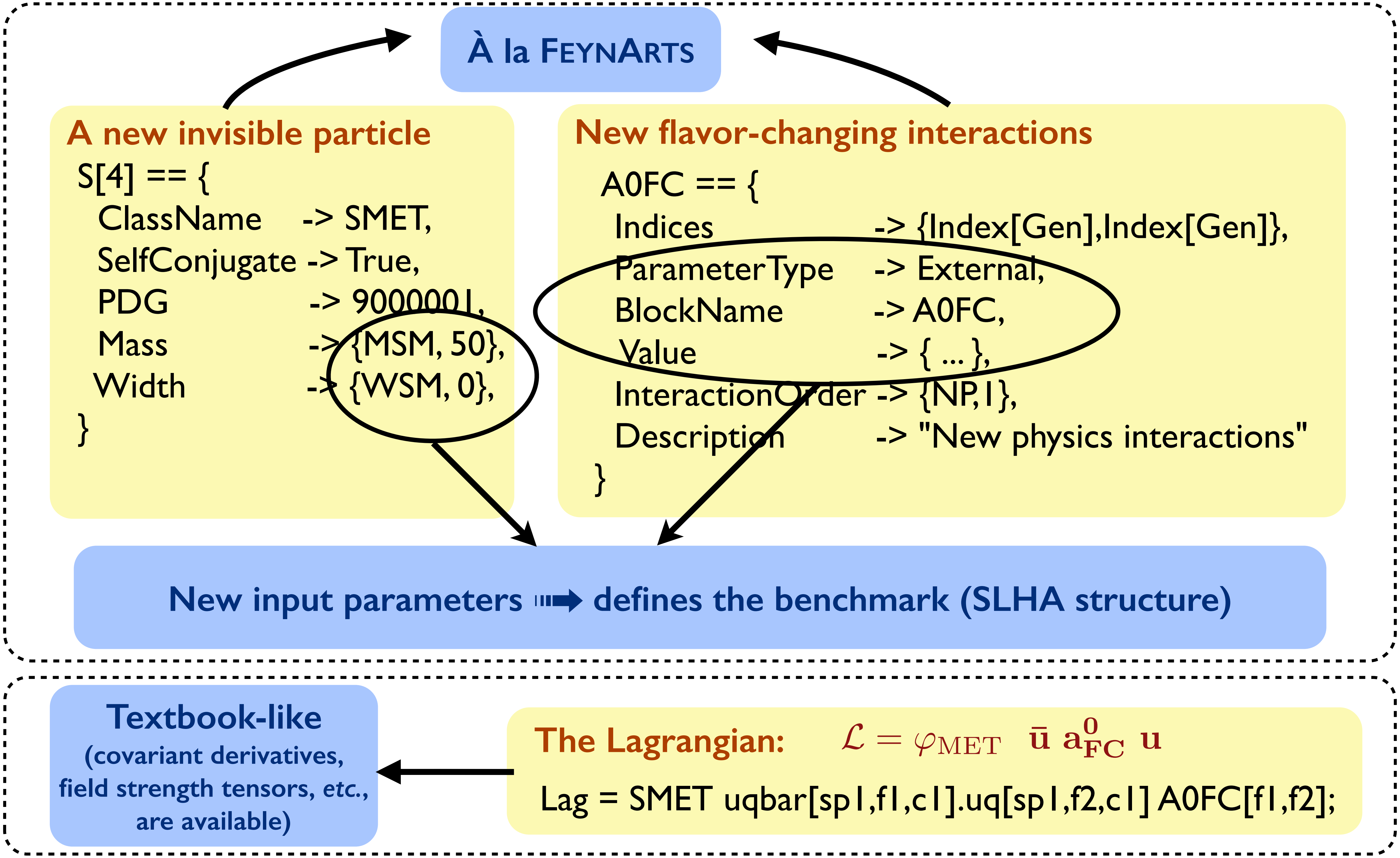
Computational tools

* Whizard interface: Christensen, Duhr, BF, Reuter, Speckner (EPJC '12)

^ Support for spin 3/2: Christensen, de Aquino, Deutschmann, Duhr, BF, Garcia-Cely, Mattelaer, Mawatari, Oexl, Takaesu (EPJC '13)

Example: Yukawa interactions with a new scalar φ (1)

See the manual for more details, gauge groups, *etc.*



À la FEYNARTS

A new invisible particle

```
S[4] == {
  ClassName     -> SMET,
  SelfConjugate -> True,
  PDG           -> 9000001,
  Mass          -> {MSM, 50},
  Width         -> {WSM, 0},
}
```

New flavor-changing interactions

```
A0FC == {
  Indices          -> {Index[Gen],Index[Gen]},
  ParameterType    -> External,
  BlockName        -> A0FC,
  Value            -> { ... },
  InteractionOrder -> {NP,1},
  Description      -> "New physics interactions"
}
```

New input parameters ➠ defines the benchmark (SLHA structure)

Textbook-like

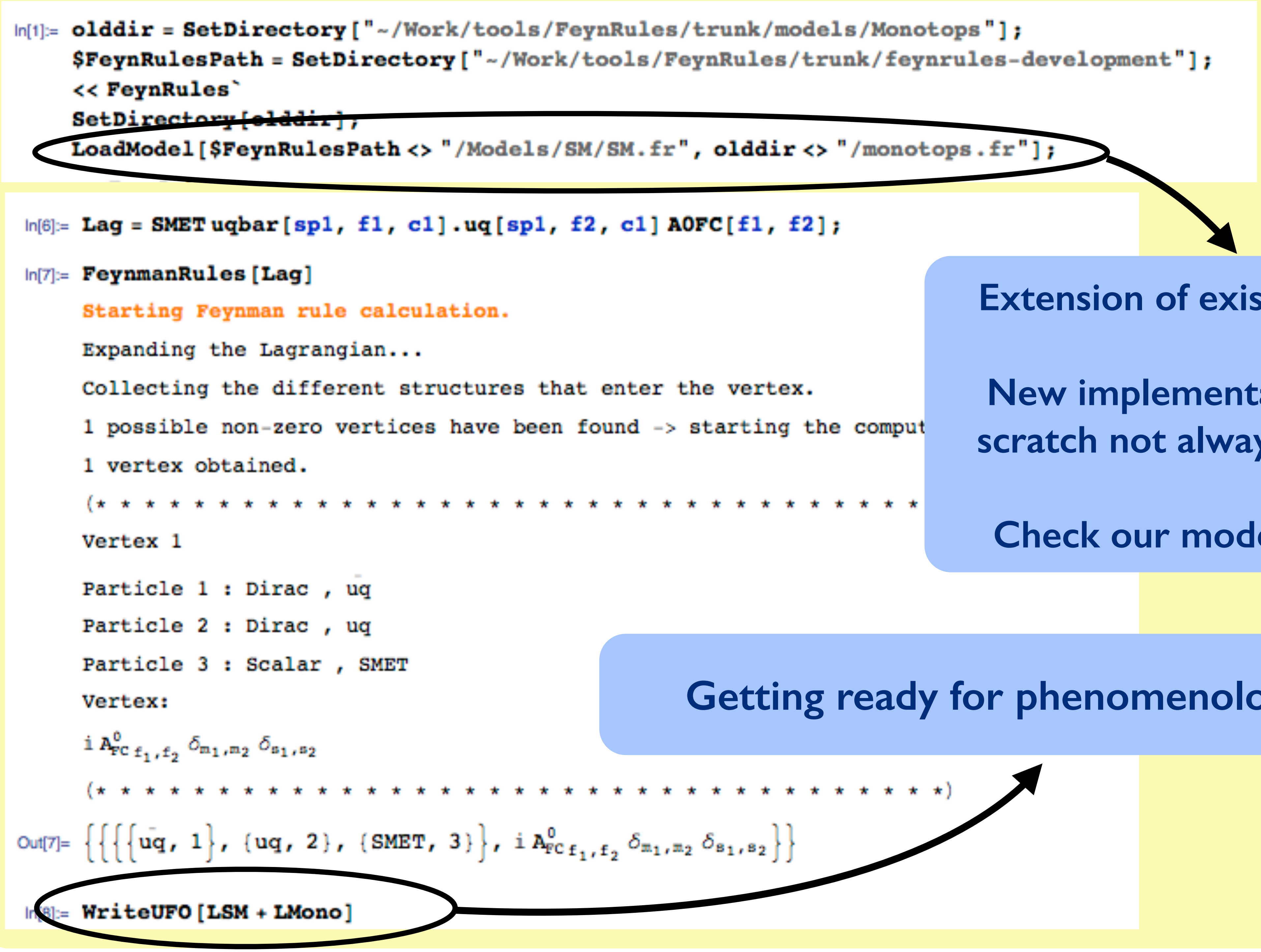
(covariant derivatives, field strength tensors, *etc.*, are available)

The Lagrangian: $\mathcal{L} = \varphi_{\rm MET}\ \bar{\bf u}\ {\bf a}^{\bf 0}_{\bf FC}\ {\bf u}$

```
Lag = SMET uqbar[sp1,f1,c1].uq[sp1,f2,c1] A0FC[f1,f2];
```

Example: Yukawa interactions with a new scalar φ (2)

MATHEMATICA screenshot



```
In[1]:= olddir = SetDirectory["~/Work/tools/FeynRules/trunk/models/Monotops"];
        $FeynRulesPath = SetDirectory["~/Work/tools/FeynRules/trunk/feynrules-development"];
        << FeynRules`
        SetDirectory[olddir];
        LoadModel[$FeynRulesPath <> "/Models/SM/SM.fr", olddir <> "/monotops.fr"];
```

```
In[6]:= Lag = SMET uqbar[sp1, f1, c1].uq[sp1, f2, c1] A0FC[f1, f2];

In[7]:= FeynmanRules[Lag]

        Starting Feynman rule calculation.

        Expanding the Lagrangian...

        Collecting the different structures that enter the vertex.

        1 possible non-zero vertices have been found -> starting the comput

        1 vertex obtained.

        (* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

        Vertex 1

        Particle 1 : Dirac , ūq

        Particle 2 : Dirac , uq

        Particle 3 : Scalar , SMET

        Vertex:
```

$$i\, A^{0}_{\mathrm{FC}\, f_1,f_2}\, \delta_{m_1,m_2}\, \delta_{s_1,s_2}$$

```
        (* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)
```

Out[7]= $\{\{\{\{\bar{u}q, 1\}, \{uq, 2\}, \{SMET, 3\}\}, i\, A^{0}_{\mathrm{FC}\, f_1,f_2}\, \delta_{m_1,m_2}\, \delta_{s_1,s_2}\}\}$

```
In[8]:= WriteUFO[LSM + LMono]
```

Extension of existing models

New implementations from scratch not always necessary

Check our model database

Getting ready for phenomenology

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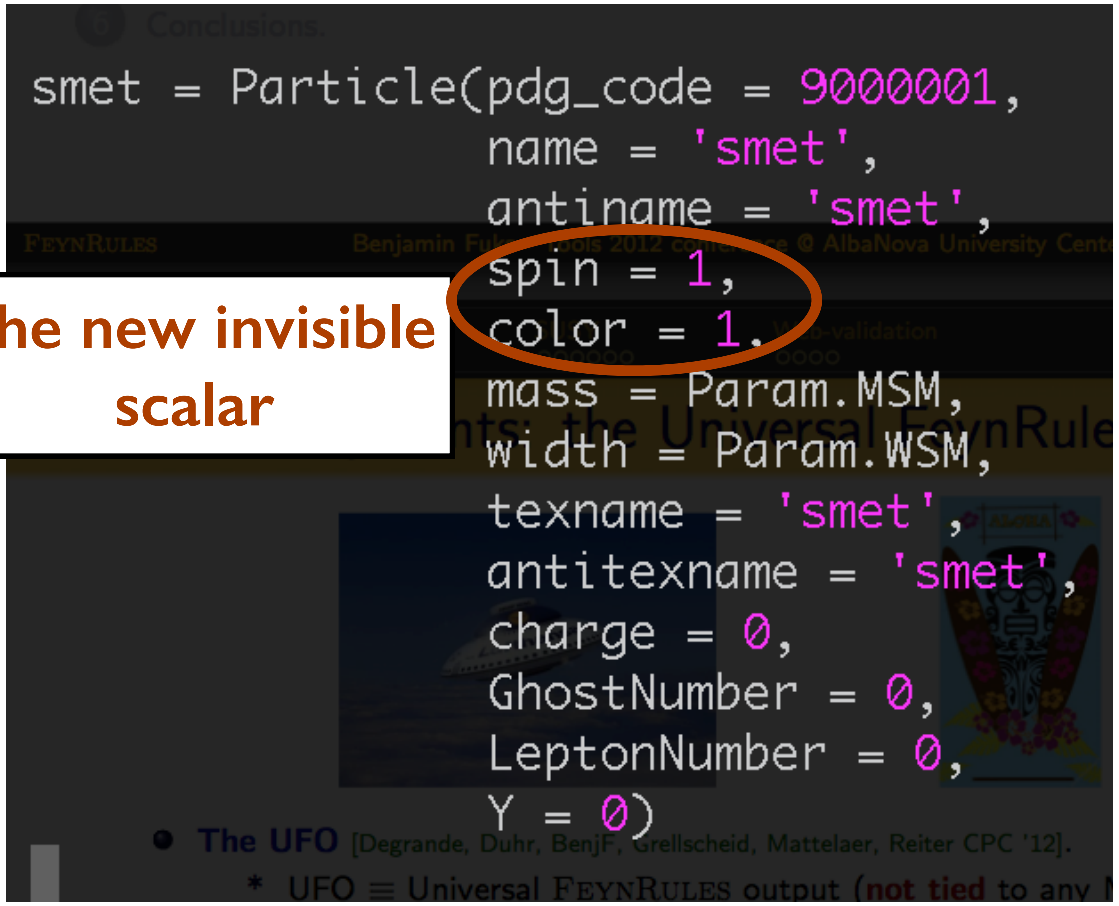
The Universal FEYNRULES Output format (I)

[Degrande, Duhr, BF, Grellscheid, Mattelaer, Reiter (CPC '12)]

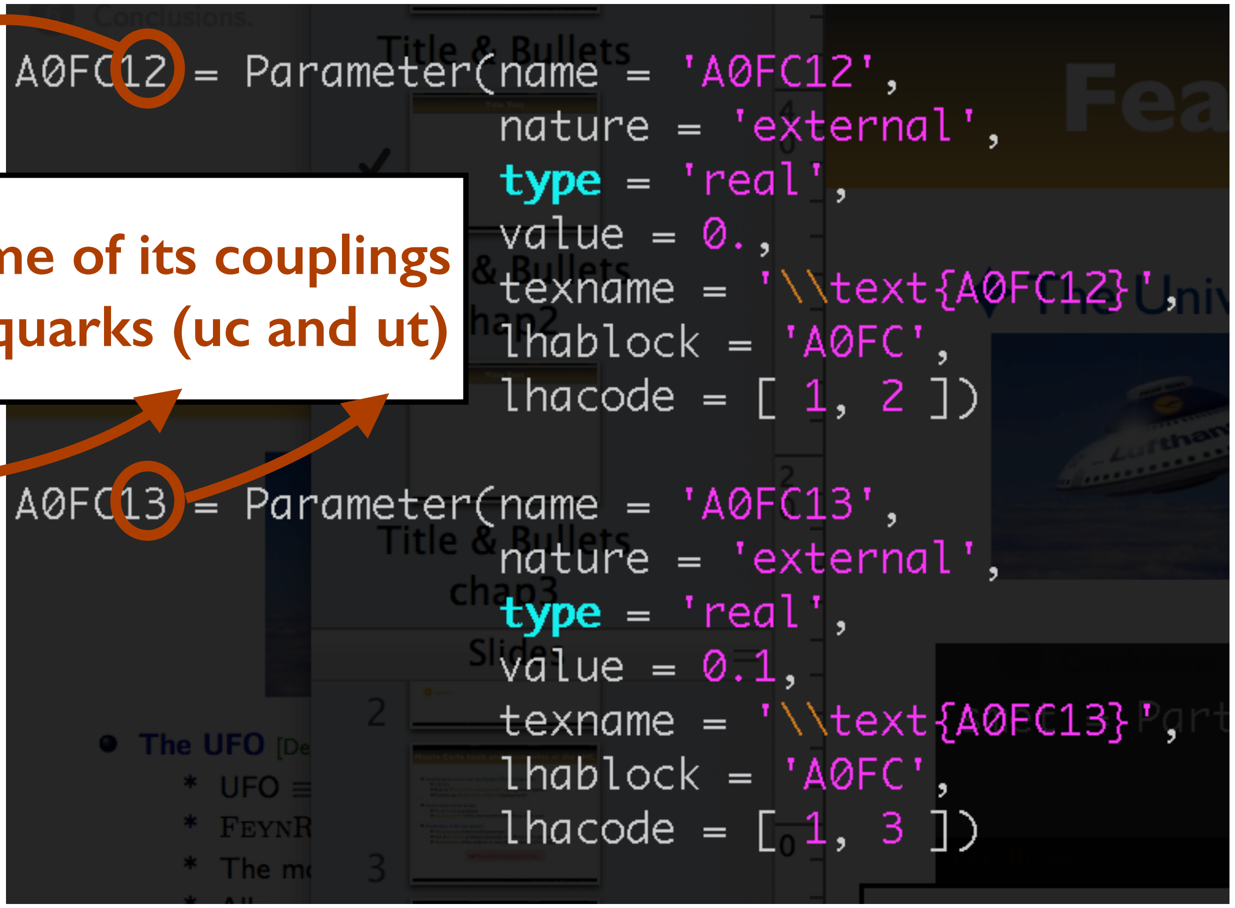
✦ The Universal FEYNRULES Output, a.k.a. the UFO

- ✤ A PYTHON module to be linked to any code
- ✤ All model information is included
- ✤ No restriction on the vertices (e.g., Lorentz and color structures)



```
smet = Particle(pdg_code = 9000001,
                name = 'smet',
                antiname = 'smet',
                spin = 1,
                color = 1,
                mass = Param.MSM,
                width = Param.WSM,
                texname = 'smet',
                antitexname = 'smet',
                charge = 0,
                GhostNumber = 0,
                LeptonNumber = 0,
                Y = 0)
```

The new invisible scalar



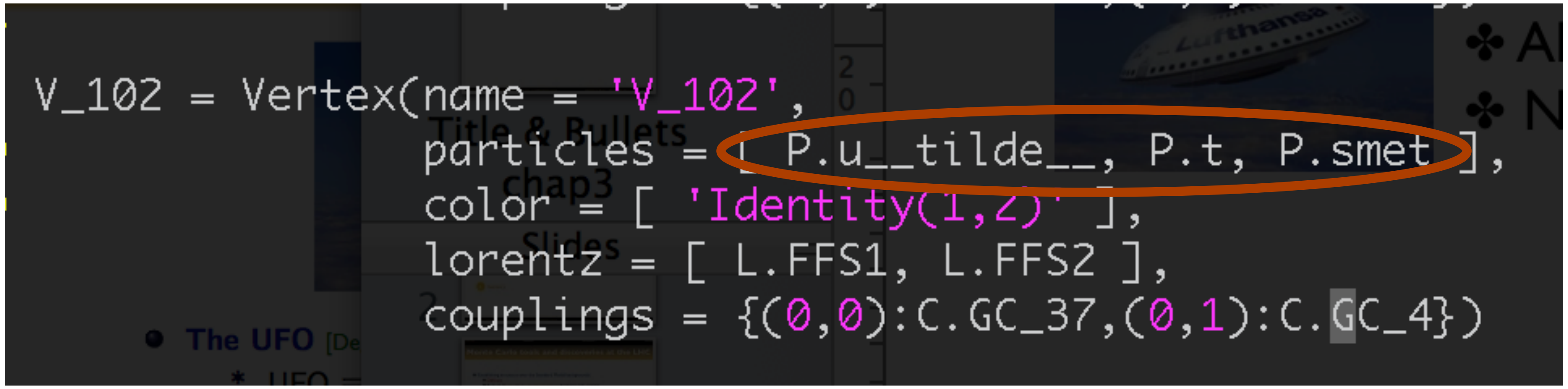
```
A0FC12 = Parameter(name = 'A0FC12',
                   nature = 'external',
                   type = 'real',
                   value = 0.,
                   texname = '\\text{A0FC12}',
                   lhablock = 'A0FC',
                   lhacode = [ 1, 2 ])

A0FC13 = Parameter(name = 'A0FC13',
                   nature = 'external',
                   type = 'real',
                   value = 0.1,
                   texname = '\\text{A0FC13}',
                   lhablock = 'A0FC',
                   lhacode = [ 1, 3 ])
```

Some of its couplings to quarks (uc and ut)

The Universal FEYNRULES Output format (2)

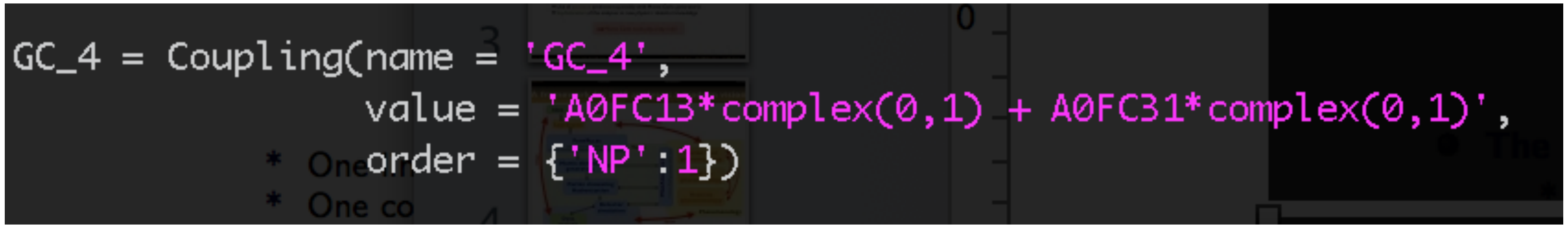
[Degrande, Duhr, BF, Grellscheid, Mattelaer, Reiter (CPC '12)]

- The Lagrangian: $\mathcal{L} = \varphi_{\rm MET}\quad \bar{\mathbf{u}}\ \mathbf{a}^{\mathbf{0}}_{\mathbf{FC}}\ \mathbf{u}$
  - Factorization of the vertices in spin x color space
  - Lorentz/color bases
  - Coupling strengths ↔ coordinates in the spin x color basis



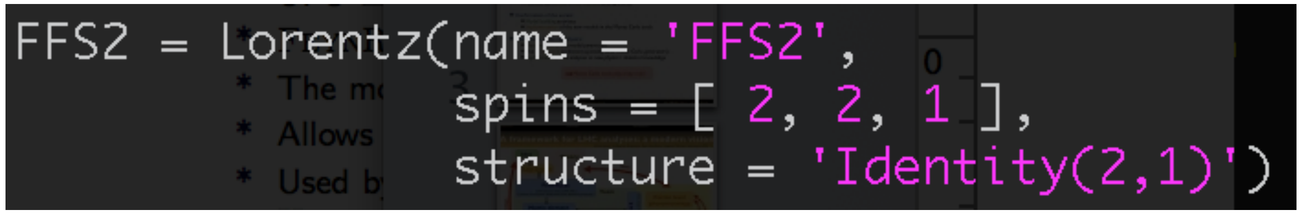
```
V_102 = Vertex(name = 'V_102',
               particles = [ P.u__tilde__, P.t, P.smet ],
               color = [ 'Identity(1,2)' ],
               lorentz = [ L.FFS1, L.FFS2 ],
               couplings = {(0,0):C.GC_37,(0,1):C.GC_4})
```

→ **u-t- $\varphi_{\rm MET}$**



```
GC_4 = Coupling(name = 'GC_4',
                value = 'A0FC13*complex(0,1) + A0FC31*complex(0,1)',
                order = {'NP':1})
```

Coupling strength



```
FFS2 = Lorentz(name = 'FFS2',
               spins = [ 2, 2, 1 ],
               structure = 'Identity(2,1)')
```

Lorentz structure

The supersymmetry module

[Duhr, BF (CPC '11); Alloul, Duhr, BF, Rausch de Traubenberg (LH '11); BF (IJMPA '12)]

✦ A module dedicated to calculations in superspace

- ✤ Superfield declaration and links to the component fields
- ✤ Series expansion in terms of component fields
- ✤ Automatic derivation of supersymmetric Lagrangians
- ✤ Automatic solution to the equations of motion of the unphysical fields
- ✤ Many built-in functions

```
Lag = LSoft + Theta2Thetabar2Component[ CSFKineticTerms[ ] ] +
  Theta2Component[VSFKineticTerms[ ] + SuperPot ] +
  Thetabar2Component[VSFKineticTerms[ ] + HC[SuperPot] ]
```

See the manual for more details

A MSSM Higgs superfield

```
CSF[1] == {
 ClassName          -> HU,
 Chirality          -> Left,
 Weyl               -> huw,
 Scalar             -> hus,
 QuantumNumbers -> {Y-> 1/2},
 Indices            -> {Index[SU2D]}
}
```

✦ Supersymmetric renormalization group equations

- ✤ Extraction at the two-loop level
- ✤ Export to a numerical module (possible development)

```
RGE[ LSoft, SuperW, NLoops->1 ] ;
```

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

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

Other leading order features

✦ Automatic mass diagonalization [Alloul, D'Hondt, De Causmaecker, BF, Rausch de Traubenberg (EPJC '13)]

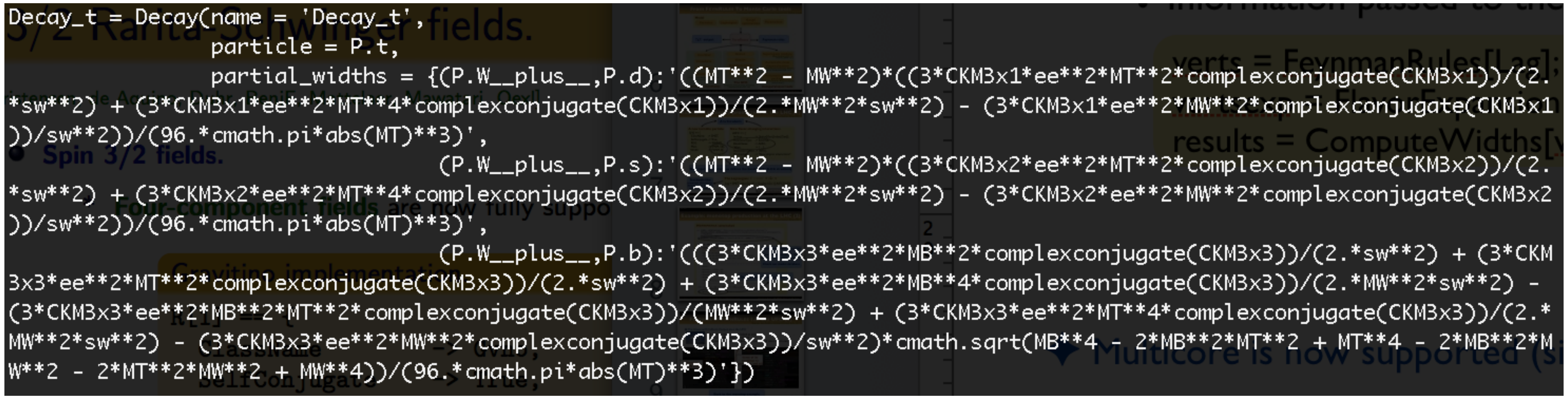
- Computation of the model mass matrices from the Lagrangian
- Numerical diagonalization ➠ spectrum generation ➠ MADGRAPH
- Extension to the one-loop level: possible development

✦ Automatic decay width computations [Alwall, Duhr, BF, Mattelaer, Oezturk, Shen (1402.1178)]

- Computation of all two-body decay widths from the Lagrangian

```
verts    = FeynmanRules[Lag];
vertsexp = FlavorExpansion[verts];
results  = ComputeWidths[vertsexp];
```

- Analytical results without any hypothesis on the masses (benchmark independent)
- Information passed to the UFO (used by MADGRAPH 5)



```
Decay_t = Decay(name = 'Decay_t',
                particle = P.t,
                partial_widths = {(P.W__plus__,P.d):'((MT**2 - MW**2)*((3*CKM3x1*ee**2*MT**2*complexconjugate(CKM3x1))/(2.
*sw**2) + (3*CKM3x1*ee**2*MT**4*complexconjugate(CKM3x1))/(2.*MW**2*sw**2) - (3*CKM3x1*ee**2*MW**2*complexconjugate(CKM3x1
))/sw**2))/(96.*cmath.pi*abs(MT)**3)',
                                      (P.W__plus__,P.s):'((MT**2 - MW**2)*((3*CKM3x2*ee**2*MT**2*complexconjugate(CKM3x2))/(2.
*sw**2) + (3*CKM3x2*ee**2*MT**4*complexconjugate(CKM3x2))/(2.*MW**2*sw**2) - (3*CKM3x2*ee**2*MW**2*complexconjugate(CKM3x2
))/sw**2))/(96.*cmath.pi*abs(MT)**3)',
                                      (P.W__plus__,P.b):'(((3*CKM3x3*ee**2*MB**2*complexconjugate(CKM3x3))/(2.*sw**2) + (3*CKM
3x3*ee**2*MT**2*complexconjugate(CKM3x3))/(2.*sw**2) + (3*CKM3x3*ee**2*MB**4*complexconjugate(CKM3x3))/(2.*MW**2*sw**2) -
(3*CKM3x3*ee**2*MB**2*MT**2*complexconjugate(CKM3x3))/(MW**2*sw**2) + (3*CKM3x3*ee**2*MT**4*complexconjugate(CKM3x3))/(2.*
MW**2*sw**2) - (3*CKM3x3*ee**2*MW**2*complexconjugate(CKM3x3))/sw**2)*cmath.sqrt(MB**4 - 2*MB**2*MT**2 + MT**4 - 2*MB**2*M
W**2 - 2*MT**2*MW**2 + MW**4))/(96.*cmath.pi*abs(MT)**3)'})
```

✦ Multicore is now supported (significant speed increase)

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On the way to next-to-leading order

[Degrande (1406.3030)]

✦ Ingredients of a next-to-leading order model file for MadGraph5_aMC@NLO

- ✤ Tree-level vertices
- ✤ UV counterterms
- ✤ R_2 counterterms

✦ Technical details at the FeynRules level

- ✤ Automatic renormalization of the Lagrangian
- ✤ Use of the FeynArts-FormCalc interface of FeynRules
- ✤ Generation of a FeynArts-FormCalc script for NLO vertex generation
- ✤ Script execution → R_2 and UV counterterms
- ✤ Inclusion of the R_2 and UV counterterms in a UFO@NLO model file

NLOCT

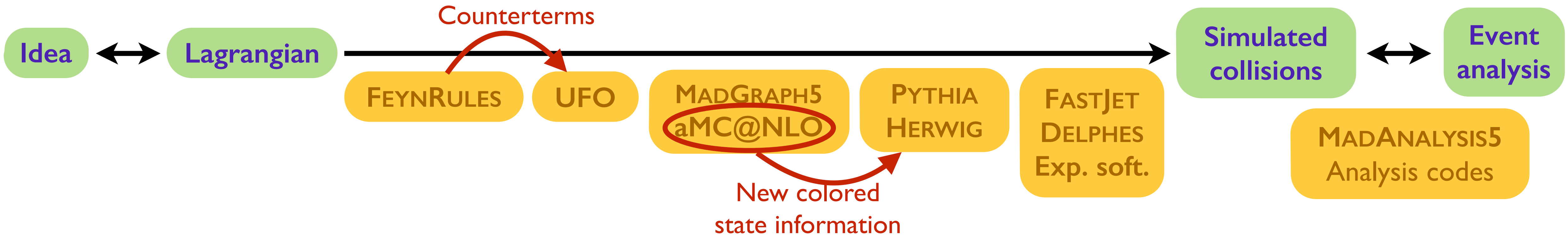
✦ New physics with MadGraph5_aMC@NLO

- ✤ Proof of principle: automatic via the NLOCT package
- ✤ The machinery is ready for event generation at NLO in any framework
  - ★ Including higher-dimensional operators
  - ★ Fancy color structures
  - ★ Only the Lagrangian has to be provided by the user (as for the leading-order case)

Automated NLO calculations with MADGRAPH5_aMC@NLO

[Degrande, BF, Hirschi, Proudom & Shao (1412.5589)]

✦ A comprehensive approach to Monte Carlo simulations



✦ Streamline the chain from the model Lagrangian to analyzed simulated collisions

- ✤ FEYNRULES is linked to the NLOCT module
  - ★ Calculation of UV and R_2 counterterms
  - ★ Export of the information to the UFO

- ✤ Matching to parton showers
  - ★ Monte Carlo counterterms associated with the new colored states are included
  - ★ Restrictions on the parton shower code to employ (PYTHIA 8, HERWIG++)

✦ Analytical and numerical validation: on-going

[http://feynrules.irmp.ucl.ac.be/wiki/NLOModels]

- ✤ BSM models will be released as soon as validated:
  - ★ Some simplified models (stops and sgluons) are available
  - ★ A model dedicated to the characterization of the Higgs is available
  - ★ A Two-Higgs-Doublet-Model implementation is available

The stop simplified model: description

[Degrande, BF, Hirschi, Proudom & Shao (1412.5589)]

✦ The stop (σ_3) / bino (χ) model

$$\mathcal{L}_3 = \underbrace{D_\mu\sigma_3^\dagger D^\mu\sigma_3 - m_3^2\sigma_3^\dagger\sigma_3}_{\text{Production}} + \underbrace{\frac{i}{2}\bar{\chi}\not{\partial}\chi - \frac{1}{2}m_\chi\bar{\chi}\chi + \Big[\sigma_3\bar{t}\big(\tilde{g}_L P_L + \tilde{g}_R P_R\big)\chi + \text{h.c.}\Big]}_{\text{Decay}}$$

- ✤ One scalar field in the fundamental representation (σ_3)
- ✤ One gauge-singlet Majorana fermion (χ) coupling the stop to the top

✦ UV behavior (on-shell scheme, zero-momentum subtraction for α_s)

✤ Analytical checks

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{96\pi^2}\left[\frac{1}{\bar{\epsilon}} - \log\frac{m_3^2}{\mu_R^2}\right]$$

$$\delta Z_{\sigma_3} = 0 \quad \text{and} \quad \delta m_3^2 = -\frac{g_s^2 m_3^2}{12\pi^2}\left[\frac{3}{\bar{\epsilon}} + 7 - 3\log\frac{m_3^2}{\mu_R^2}\right]$$

$$\frac{\delta\alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi\bar{\epsilon}}\left[\frac{n_f}{3} - \frac{11}{2}\right] + \frac{\alpha_s}{6\pi}\left[\frac{1}{\bar{\epsilon}} - \log\frac{m_t^2}{\mu_R^2}\right] + \frac{\alpha_s}{24\pi}\left[\frac{1}{\bar{\epsilon}} - \log\frac{m_3^2}{\mu_R^2}\right]$$

$$R_2^{\sigma_3^\dagger\sigma_3} = \frac{ig_s^2}{72\pi^2}\delta_{c_1c_2}\left[3m_3^2 - p^2\right]$$

$$R_2^{g\sigma_3^\dagger\sigma_3} = \frac{53ig_s^3}{576\pi^2}T^{a_1}_{c_2c_3}\left(p_2 - p_3\right)^{\mu_1}$$

$$R_2^{gg\sigma_3^\dagger\sigma_3} = \frac{ig_s^4}{1152\pi^2}\eta^{\mu_1\mu_2}\left[3\delta^{a_1a_2} - 187\{T^{a_1}, T^{a_2}\}\right]_{c_3c_4}$$

Neutralino couplings also checked
Unlike in full models, non-trivial behavior

Stops in MADGRAPH5_aMC@NLO: results

[Degrande, BF, Hirschi, Proudom & Shao (1412.5589)]

✦ Total rates at 8 TeV

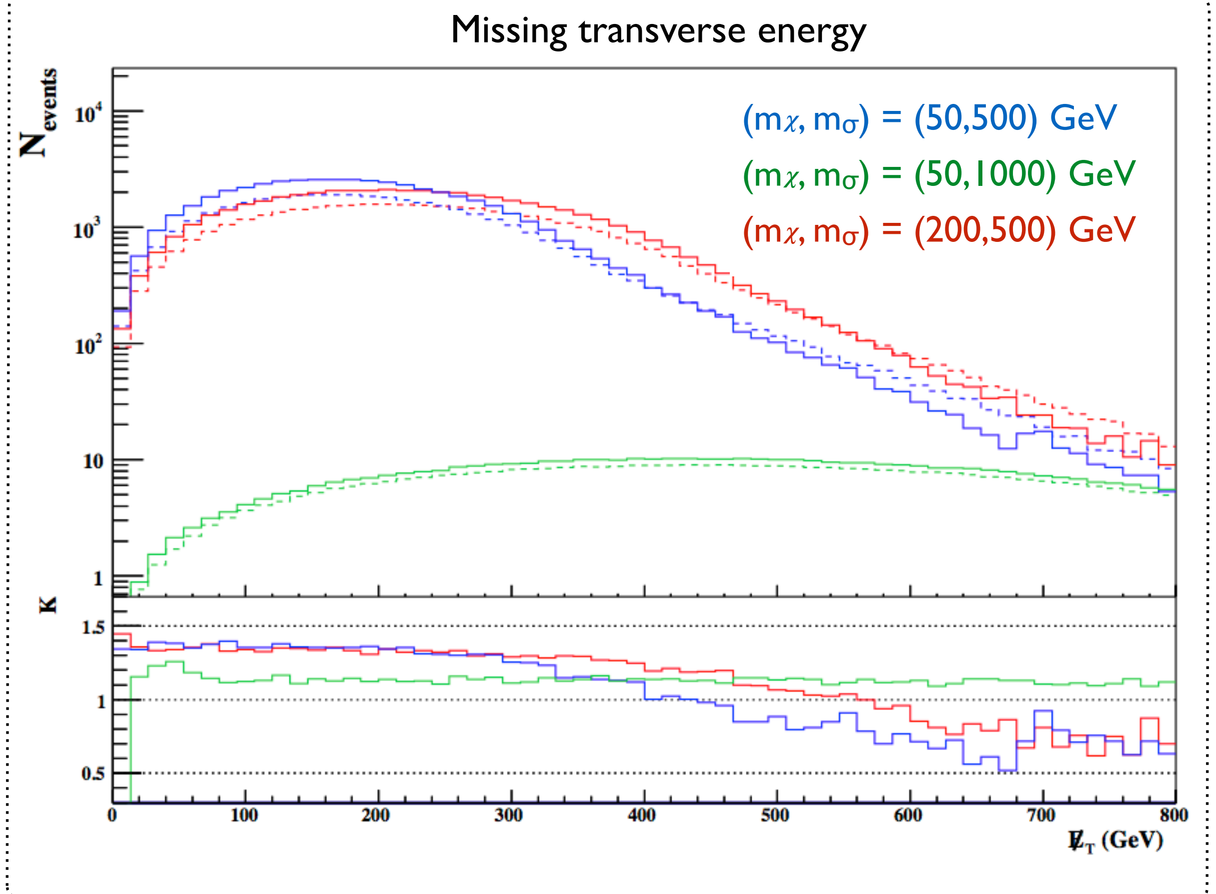
- ✤ NNPDF2.3
- ✤ Scales set to the stop mass
- ✤ Agrees with PROSPINO

m_3 [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
100	$3.893 \pm 0.0095 \cdot 10^2$ $^{+34.2\%}_{-23.9\%}$	$5.548 \pm 0.018 \cdot 10^2$ $^{+14.9\%}_{-13.5\%}$ $^{+1.6\%}_{-1.6\%}$
250	$4.118 \pm 0.0096 \cdot 10^0$ $^{+40.4\%}_{-27.2\%}$	$5.503 \pm 0.017 \cdot 10^0$ $^{+13.1\%}_{-13.7\%}$ $^{+3.7\%}_{-3.7\%}$
500	$6.594 \pm 0.016 \cdot 10^{-2}$ $^{+45.5\%}_{-29.1\%}$	$7.764 \pm 0.025 \cdot 10^{-2}$ $^{+12.1\%}_{-14.1\%}$ $^{+6.7\%}_{-6.7\%}$
750	$3.504 \pm 0.0084 \cdot 10^{-3}$ $^{+48.8\%}_{-30.5\%}$	$3.699 \pm 0.012 \cdot 10^{-3}$ $^{+12.3\%}_{-14.6\%}$ $^{+10.2\%}_{-10.2\%}$
1000	$2.875 \pm 0.0067 \cdot 10^{-4}$ $^{+51.5\%}_{-31.5\%}$	$2.775 \pm 0.0087 \cdot 10^{-4}$ $^{+13.1\%}_{-15.2\%}$ $^{+15.5\%}_{-15.5\%}$

- ★ Scale varied by a factor of two up and down
- ★ PDF variations with the 100 NNPDF replica

✦ Differential distributions at NLO

- ✤ 500/1000 GeV stop; 50/200 GeV bino; LHC-13
- ✤ Couplings: maximally mixing stop and a bino
- ✤ Shower: PYTHIA 8.2
- ✤ Analysis (single lepton case): MADANALYSIS 5



Missing transverse energy

Outline

1. A new physics story at the LHC: when tools meet phenomenology

2. FEYNRULES in a nutshell

3. Main features of FEYNRULES 2.0

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Final words

✦ The quest for new physics at the LHC has started

  - ✤ Rely on Monte Carlo event generators for background and signal modeling
  - ✤ Satellite tools have also been intensively developed (like FEYNRULES)

✦ FEYNRULES: http://feynrules.irmp.ucl.ac.be

- ✤ Straightforward implementation of new physics model in Monte Carlo tools
  - ★ Interfaces to many programs (in particular the UFO)
- ✤ FEYNRULES is shipped with its own computational modules
  - ★ A superspace module
  - ★ A decay package
  - ★ A mass diagonalization module
  - ★ A new NLO module

✦ NLO models: be ready for the LHC run-II

- ✤ Simplified models
- ✤ Full MSSM
- ✤ Higgs effective field theories
- ✤ Top quark effective field theories