



From theory to phenomenology with FeynRules and MadAnalysis 5

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A new physics story at colliders

Assumption

There is some new physics to be discovered

Phase I

◆ A *priori* preparation

- ❖ Viable model building (top-down & bottom-up)
- ❖ Phenomenological studies
- ❖ Prospective collider analyses

◆ A *posteriori* reactions to announcements

- ❖ Model building (top-down & bottom-up)
- ❖ Recasting experimental analyses
- ❖ Designing new analyses to probe new ideas

Phase 2

◆ Option 1: new physics clarification

- ❖ Precision predictions \leftrightarrow parameter extractions
- ❖ Higher order computations
- ❖ Soft gluon resummation

◆ Option 2: no new physics at colliders

- ❖ Flavor physics
- ❖ Dark matter
- ❖ Electroweak precision tests

A modern vision for physics @ colliders (I)

The (past &) present

- ◆ A *priori* preparation
 - ❖ Viable model building (top-down & bottom-up)
 - ❖ Phenomenological studies
 - ❖ Prospective collider analyses

- ◆ A *posteriori* reactions to announcements
 - ❖ Model building (top-down & bottom-up)
 - ❖ Recasting experimental analyses
 - ❖ Designing new analyses to probe new ideas

◆ To-do list to achieve those goals (designed for the LHC; can be applied to any collider)

★ Model building: Lagrangian constructions, etc.

★ Implementation (and validation) of new physics models in simulation tools

★ Design of new analyses / recasting of existing analyses

★ Using the tools for physics studies ⇒ nice novelties to search for

★ Lots of redundancies
(across analyses)
★ Heavy programming

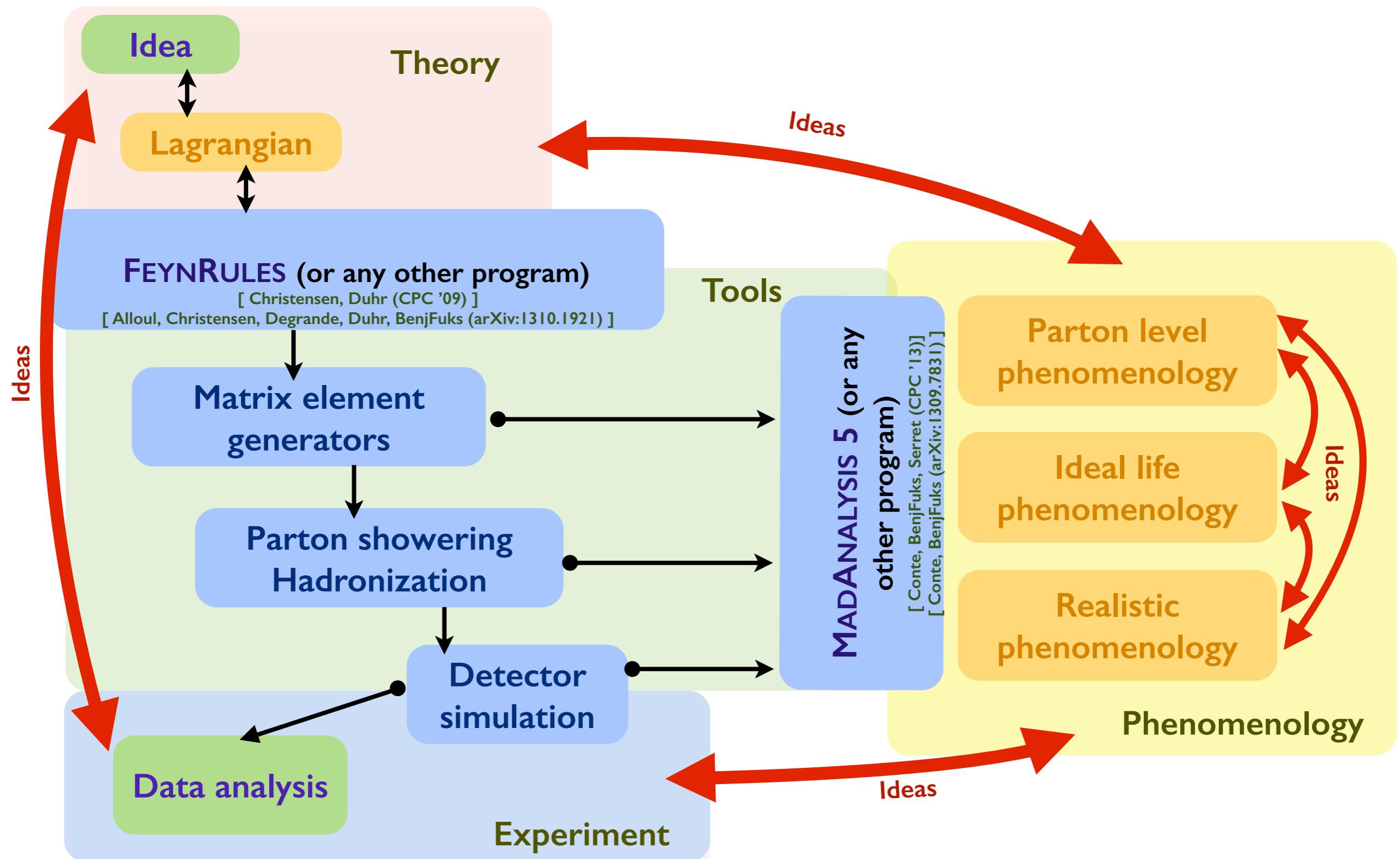
★ The interesting part

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

Systematization and
automation are possible

A modern vision for physics @ colliders (I)

[Christensen, de Aquino, Degrande, Duhr, BenjFuks, Herquet, Maltoni, Schumann (EPJC '11)]



FEYNRULES in a nutshell

[Christensen, Duhr (CPC '09); Alloul, Christensen, Degrande, Duhr, BenjFuks (arXiv:1310.1921)]

◆ 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

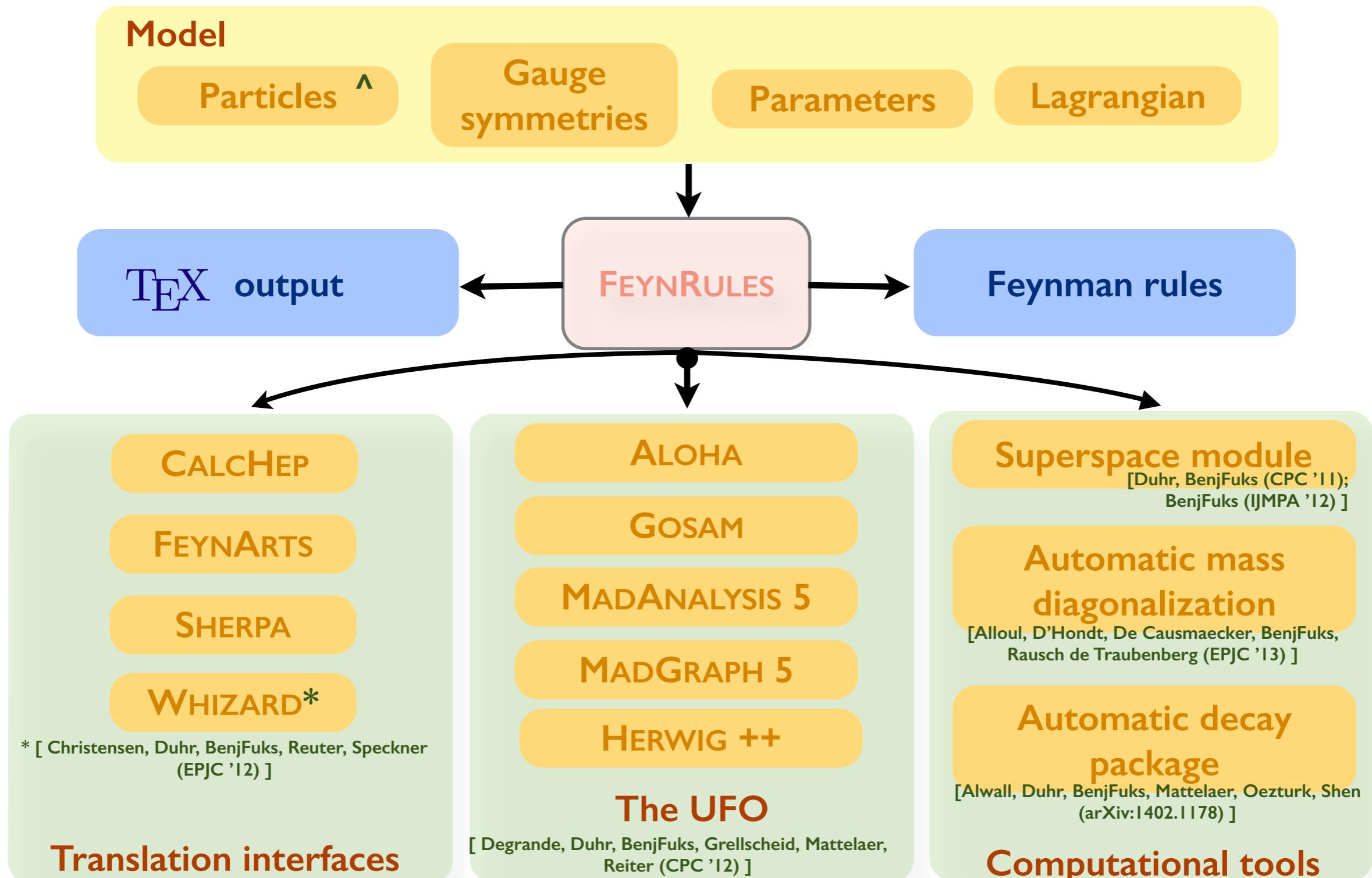
- ❖ Validation of the implementation using several programs

◆ 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...

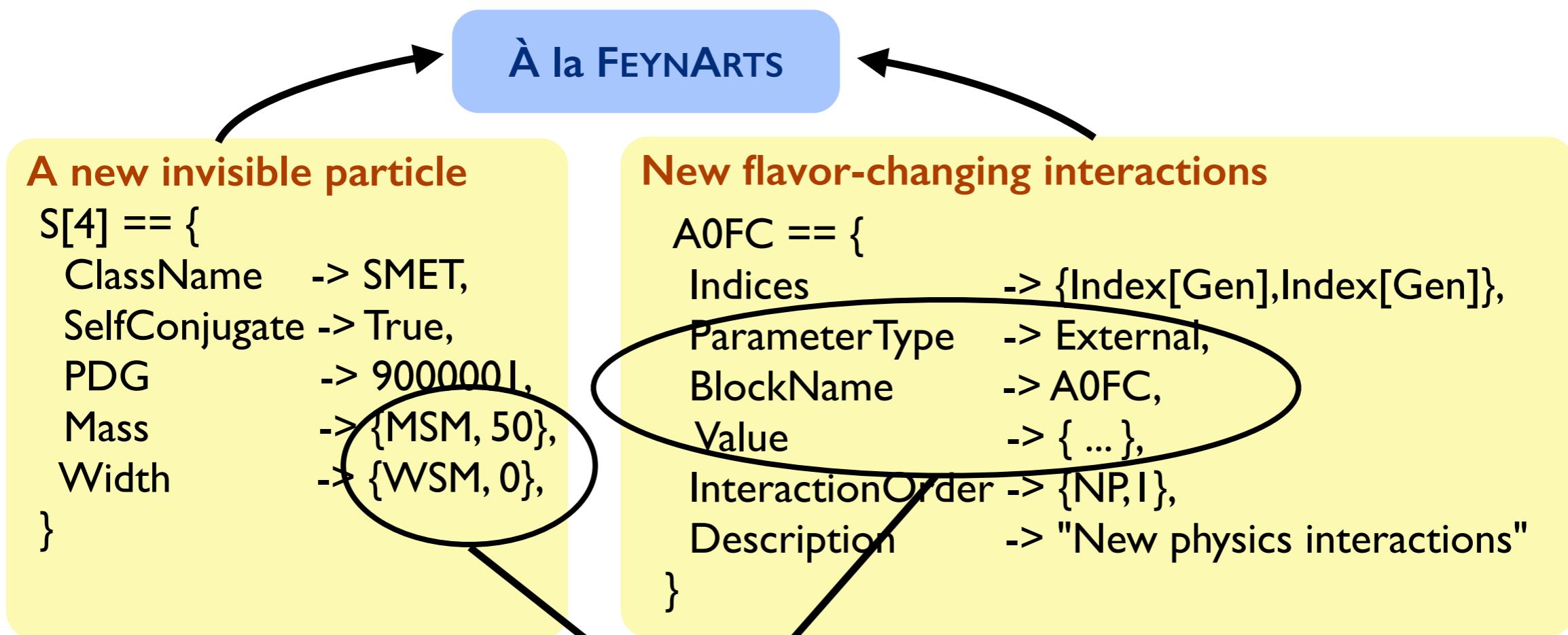
[Christensen, Duhr (CPC '09); Alloul, Christensen, Degrande, Duhr, BenjFuks (arXiv:1310.1921)]



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

Example: monotop model

[Andrea, BenjFuks, Maltoni (PRD '11)]



New input parameters \Rightarrow defines the benchmark (SLHA structure)

Textbook-like
(covariant derivatives,
field strength tensors,
etc., are available)

The Lagrangian: $\mathcal{L} = \varphi_{\text{MET}} \bar{u} a_{\text{FC}}^0 u$
 $\text{Lag} = \text{SMET } \bar{u} q[spl,f1,c1].u q[spl,f2,c1] A0FC[f1,f2];$

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

Features of FEYNRULES 2.0: the UFO (I)

[Degrade, Duhr, BenjFuks, 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)

The new invisible scalar

```
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 UFO [Degrade, Duhr, BenjF, Grellscheid, Mattelaer, Reiter CPC '12].
* UFO = Universal FEYNRULES output (not tied to any I

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

Some of its couplings to quarks (uc and ut)

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

● The UFO [De
* UFO ≡
* FEYNR
* The m

Features of FEYNRULES 2.0: the UFO (2)

[Degrade, Duhr, BenjFuks, Grellscheid, Mattelaer, Reiter (CPC '12)]

◆ The Lagrangian: $\mathcal{L} = \varphi_{\text{MET}} \bar{\mathbf{u}} \mathbf{a}_{\text{FC}}^0 \mathbf{u}$

- ❖ Factorization of the vertices in spin x color space
- ❖ Lorentz/color bases
- ❖ Coupling strengths \leftrightarrow 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- φ_{MET}

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

Coupling strength

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

Lorentz structure

Future developments: towards precision

◆ Ingredients of a NLO model file for **MADGRAPH5_aMC@NLO / MADLOOP**

- ❖ 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

→ **MADGRAPH5_aMC@NLO** for new physics on its way (being validated)

... and beyond: to event analyses

0. Implementation of the model in FEYNRULES and generation of the Monte Carlo model files

I. Event generation with any (LO/NLO) Monte Carlo event generator

- ❖ Both signal and backgrounds
- ❖ If necessary: precision in the normalization: (N)NLO inclusive results
- ❖ Generator choice: beware of restrictions (supported Lorentz and color structures)

2. Parton showering and hadronization

- ❖ Precision in the shapes: multiparton matrix-element merging techniques (at least at leading-order)

3. Fast detector simulation

4. Event analysis (e.g., with MADANALYSIS 5) [Conte, BenjFuks, Serret (CPC '13); Conte, BenjFuks (arXiv:1309.7831)]

- ❖ Parton-level and reconstructed-level analyses

MADANALYSIS 5 in a nutshell

[Conte, BenjFuks, Serret (CPC '13); Conte, BenjFuks (arXiv:1309.7831)]

◆ What is MADANALYSIS 5?

- ❖ A framework for **phenomenological analyses**
- ❖ **Multiple input format:** STDHEP, HEPMC, LHE, LHCO, ROOT
- ❖ **Any level of sophistication:** partonic, hadronic, detector, reconstructed
- ❖ **User friendly and fast**
- ❖ **Flexible**

→ Professional analyses in an easy way
→ No limit on the analysis complexity

◆ Two modules

- ❖ A **PYTHON** command line interface (interactive)
- ❖ A **C++/ROOT** core module, SAMPLEANALYZER

◆ Normal mode

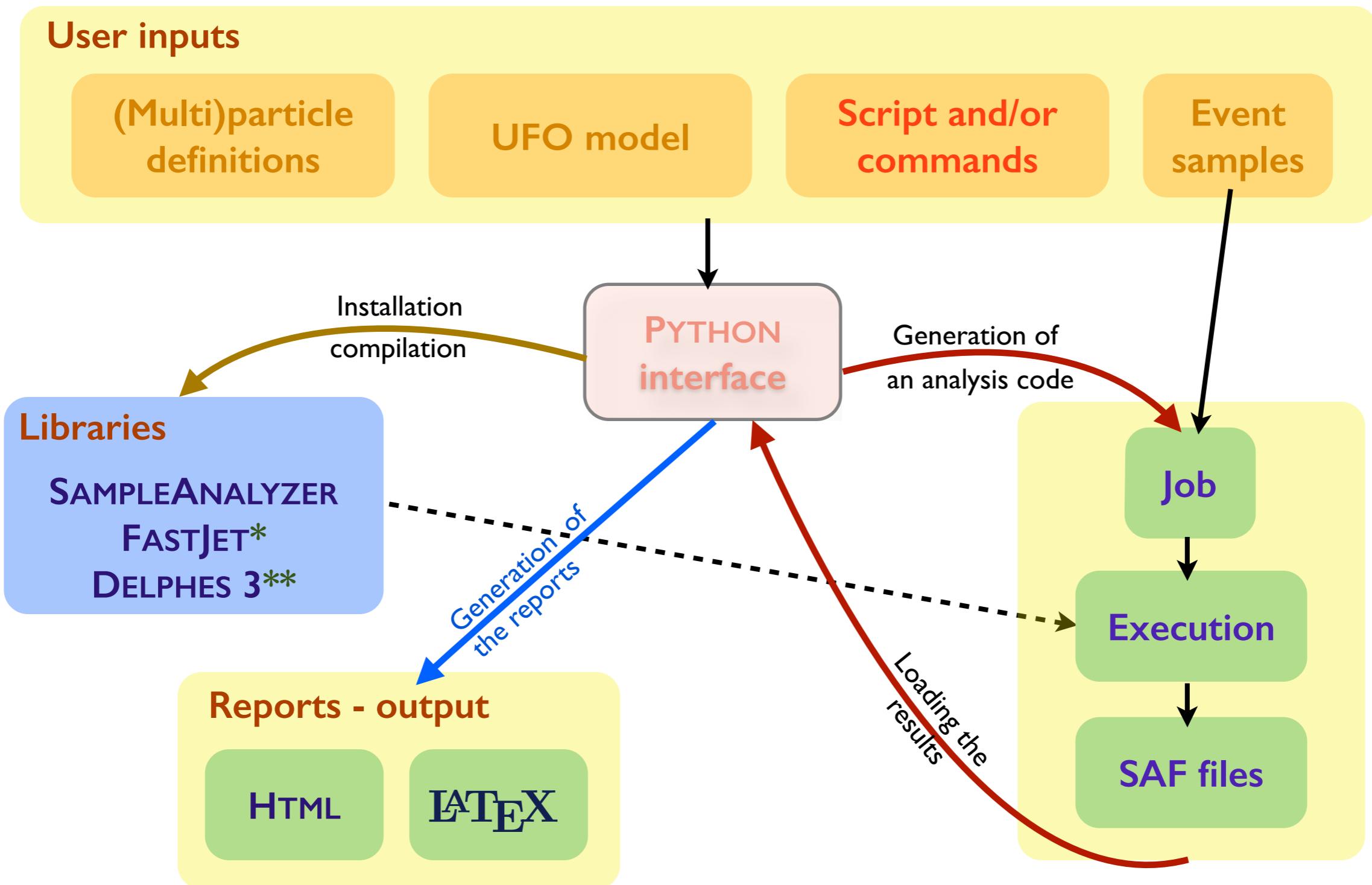
- ❖ Intuitive commands typed in the **PYTHON** interface
- ❖ Analysis performed **behind the scenes** (black box)
- ❖ Human readable output: **HTML** and **LATEX**

◆ Expert mode

- ❖ **C++/ROOT** programming within the SAMPLEANALYZER framework (not covered here)

MADANALYSIS 5: normal running mode

[Conte, BenjFuks, Serret (CPC '13); Conte, BenjFuks (arXiv:1309.7831)]

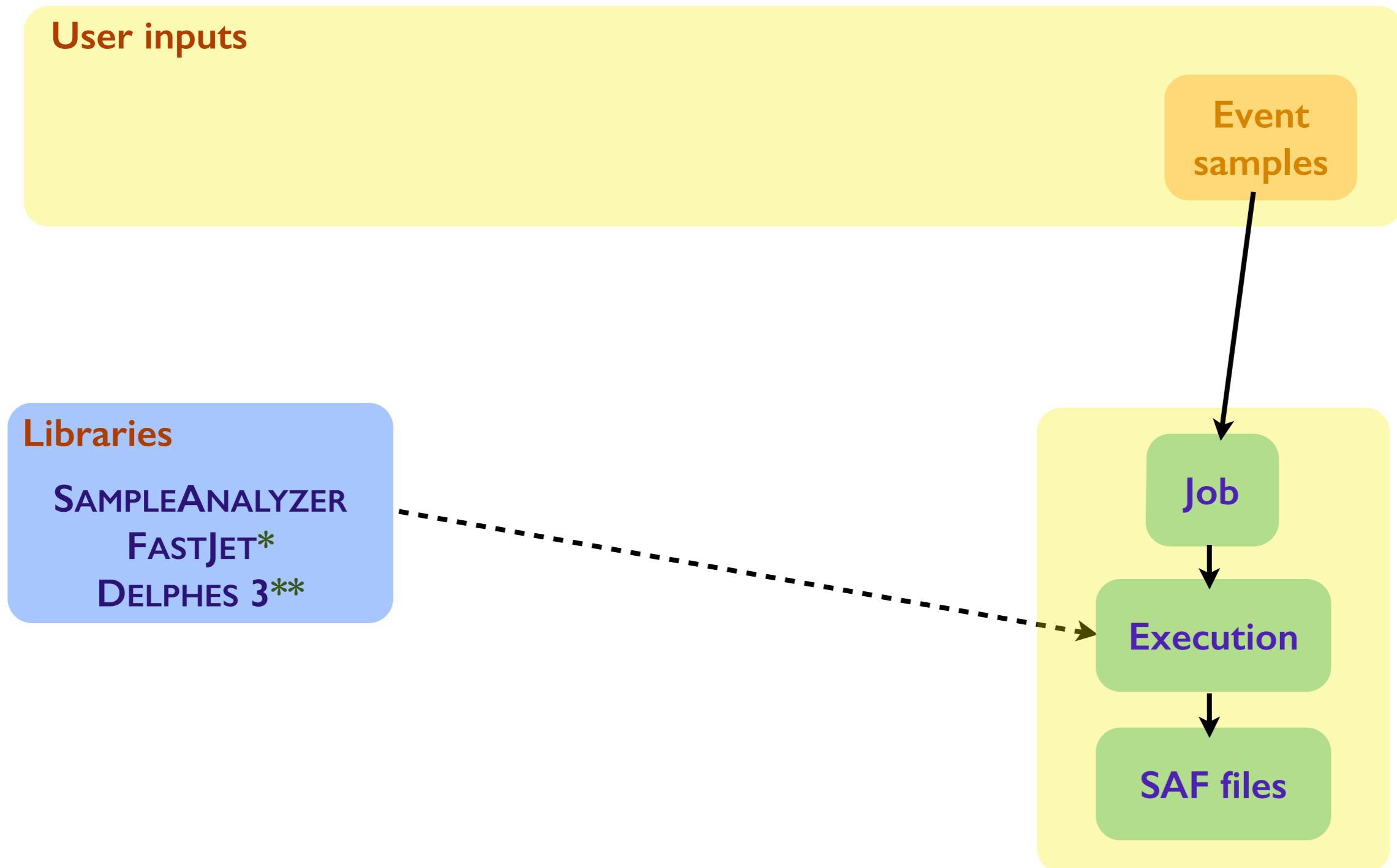


* [Cacciari, Salam (PLB '06)]

** [de Favareau, Delaere, Demin, Giannanco, Lemaitre, Mertens, Selvaggi (arXiv:1307.6346)]

MADANALYSIS 5: expert mode

[Conte, BenjFuks, Serret (CPC '13); Conte, BenjFuks (arXiv:1309.7831)]



* [Cacciari, Salam (PLB '06)]

** [de Favareau, Delaere, Demin, Giannanco, Lemaitre, Mertens, Selvaggi (arXiv:1307.6346)]

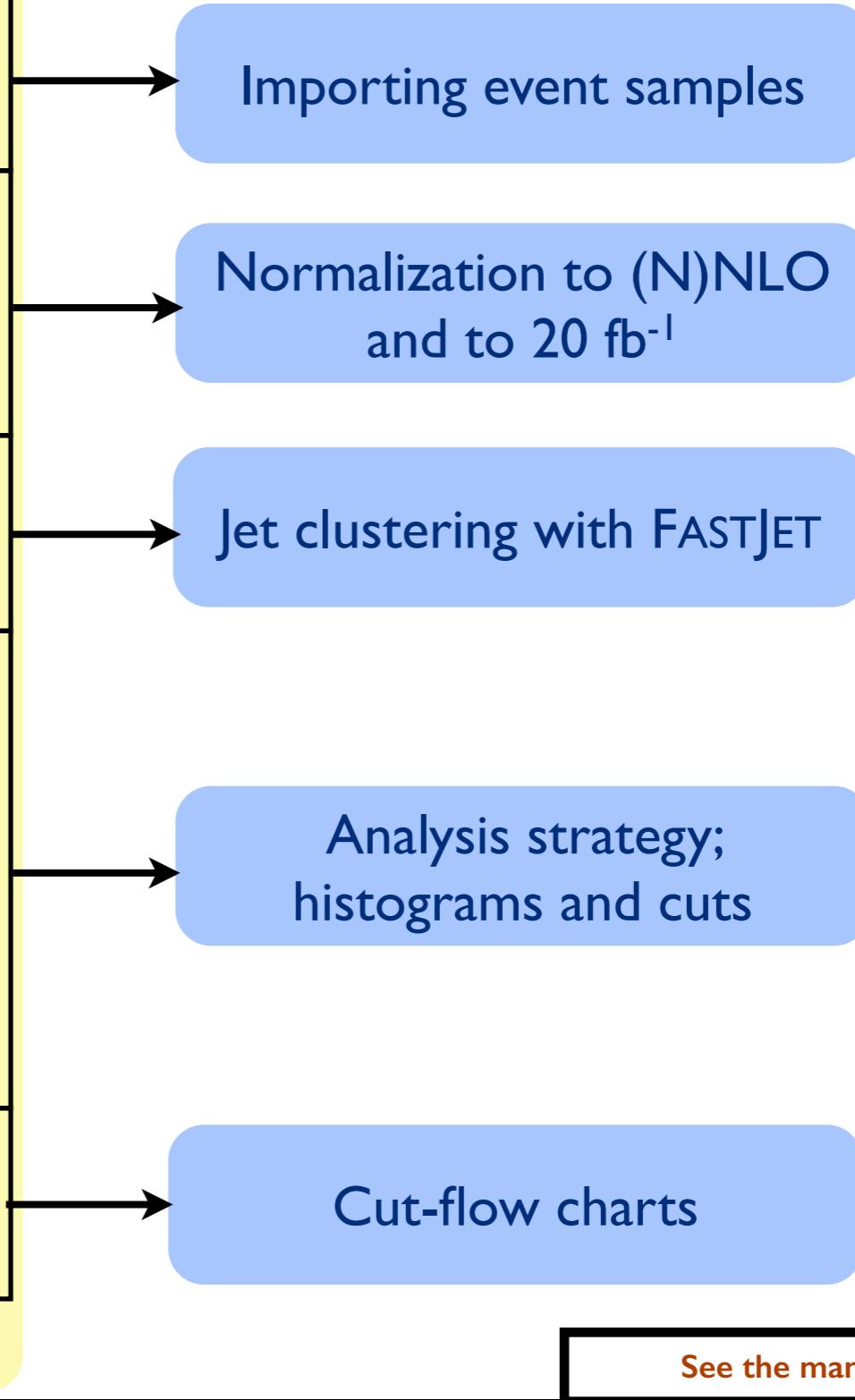
Example: background analysis at the LHC (I)

[Conte, BenjFuks, Serret (CPC '13); Conte, BenjFuks (arXiv:1309.7831)]

```

import ttbar_lep.hep.gz as ttbar
import wjets.hep.gz as wjets
import zjets.hep.gz as zjets
set ttbar.xsection = 139.6
set wjets.xsection = 35678
set zjets.xsection = 10319
set main.lumi = 20
set main.clustering.algorithm = antikt
set main.clustering.ptmin = 5
set main.clustering.radius = 0.4
plot MET 30 0 300 [logy]
plot PT(l[1]) 20 0 200 [logy]
set selection[2].rank = Eordering
plot N(j)
select (j) PT > 20
reject THT < 200
plot M(j[1] j[2])
set wjets.type = background
set zjets.type = background
set main.sbratio = 'S/B'
submit

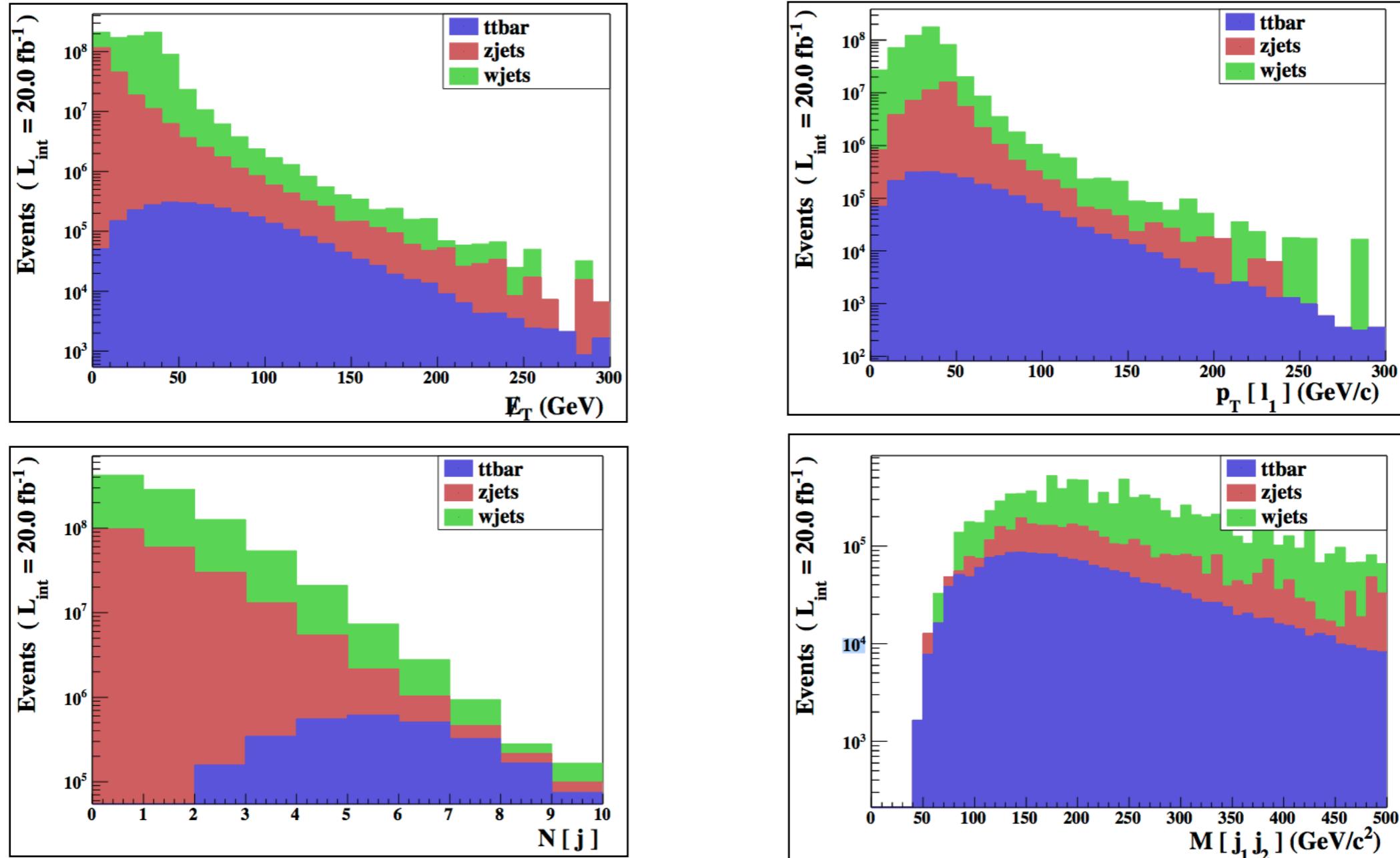
```



See the manual for more details

Example: background analysis (2)

[Conte, BenjFuks, Serret (CPC '13); Conte, BenjFuks (arXiv:1309.7831)]

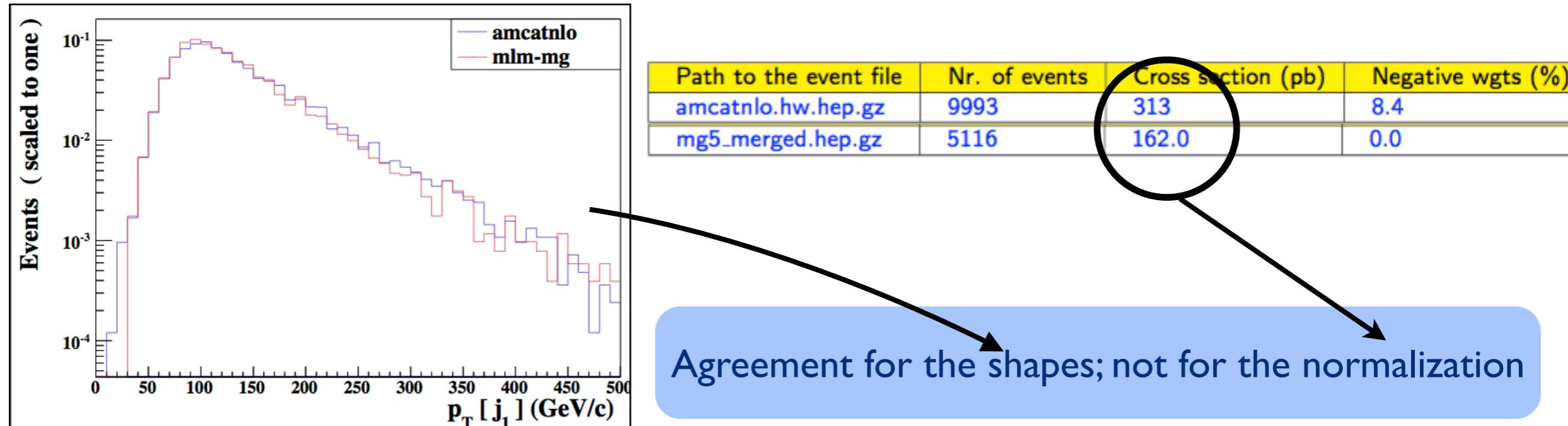


Cuts	Signal (S)	Background (B)	S vs B
initial	2792000	919940000	0.00303
cut 1	2792000	919940000 +/- 0.000173	3.034981e-03 +/- 5.7e-16
cut 2	2792000	919940000 +/- 0.000173	3.034981e-03 +/- 5.7e-16
cut 3	1928561 +/- 772	9583745 +/- 3079	0.201233 +/- 0.000103

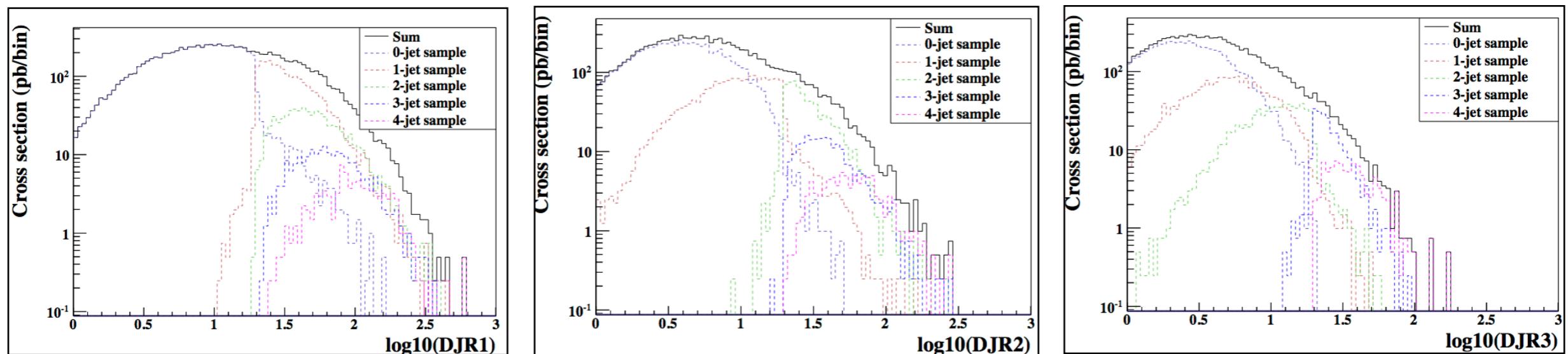
MADANALYSIS 5 and precision

[Conte, BenjFuks, Serret (CPC '13); Conte, BenjFuks (arXiv:1309.7831)]

◆ Handling events with negative weights (as generated by aMC@NLO)



◆ Automatic check of the (leading order) merging procedure



The final words

- ◆ The quest for new physics has started already a while ago
 - ❖ Rely on Monte Carlo event generators for background and signal modeling
 - ❖ Very general BSM structure can be implemented (through, e.g., the UFO)
 - ❖ Satellite tools have been intensively developed (like FEYNRULES, MADANALYSIS 5)
- ◆ FEYNRULES: <http://feynrules.irmp.ucl.ac.be/>
 - ❖ Straightforward implementation of new physics model in the Monte Carlo tools
 - ❖ Has its own computational modules
 - ❖ Will be soon interfaced to NLO tools
- ◆ MADANALYSIS 5: <http://madanalysis.irmp.ucl.ac.be/>
 - ❖ Analysis of event samples generated by Monte Carlo tools
 - ❖ Correct handling of the output of the precision tools

Automation and precision for new physics phenomenology are on their way



We are almost there

