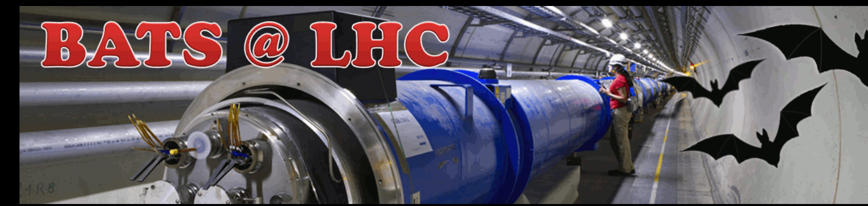

From theory to phenomenology with computer codes

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CERN - IPHC - U. Strasbourg

French IRFU Linear Collider Days @ CEA Saclay

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A new physics story

Assumption

There is some new physics to be discovered

Phase 1

- ✦ *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 ⇔ 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 $\Rightarrow$ nice novelties to search for

★ **Lots of redundancies** (across analyses)
★ **Heavy programming**

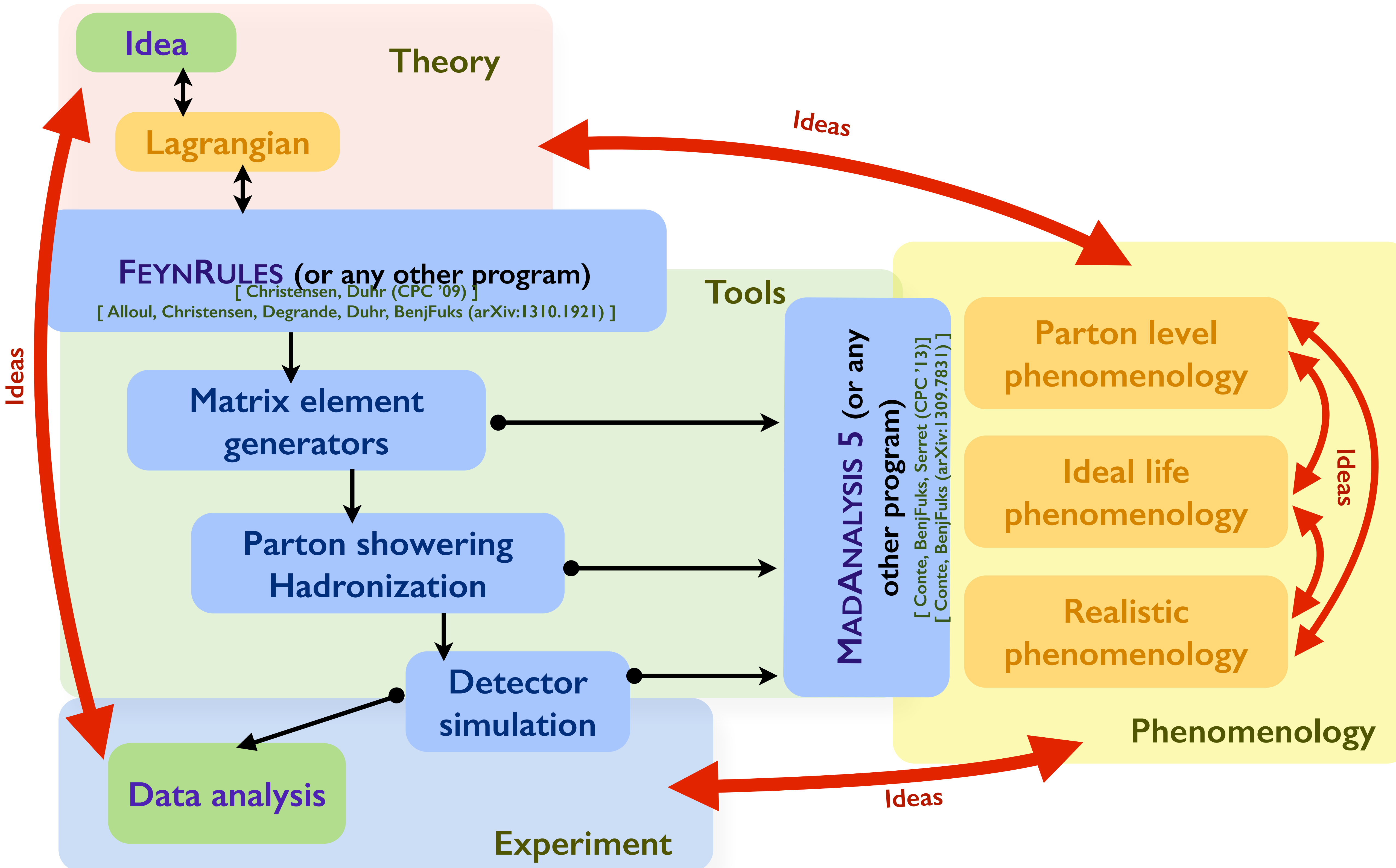
★ **The interesting part**

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

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?

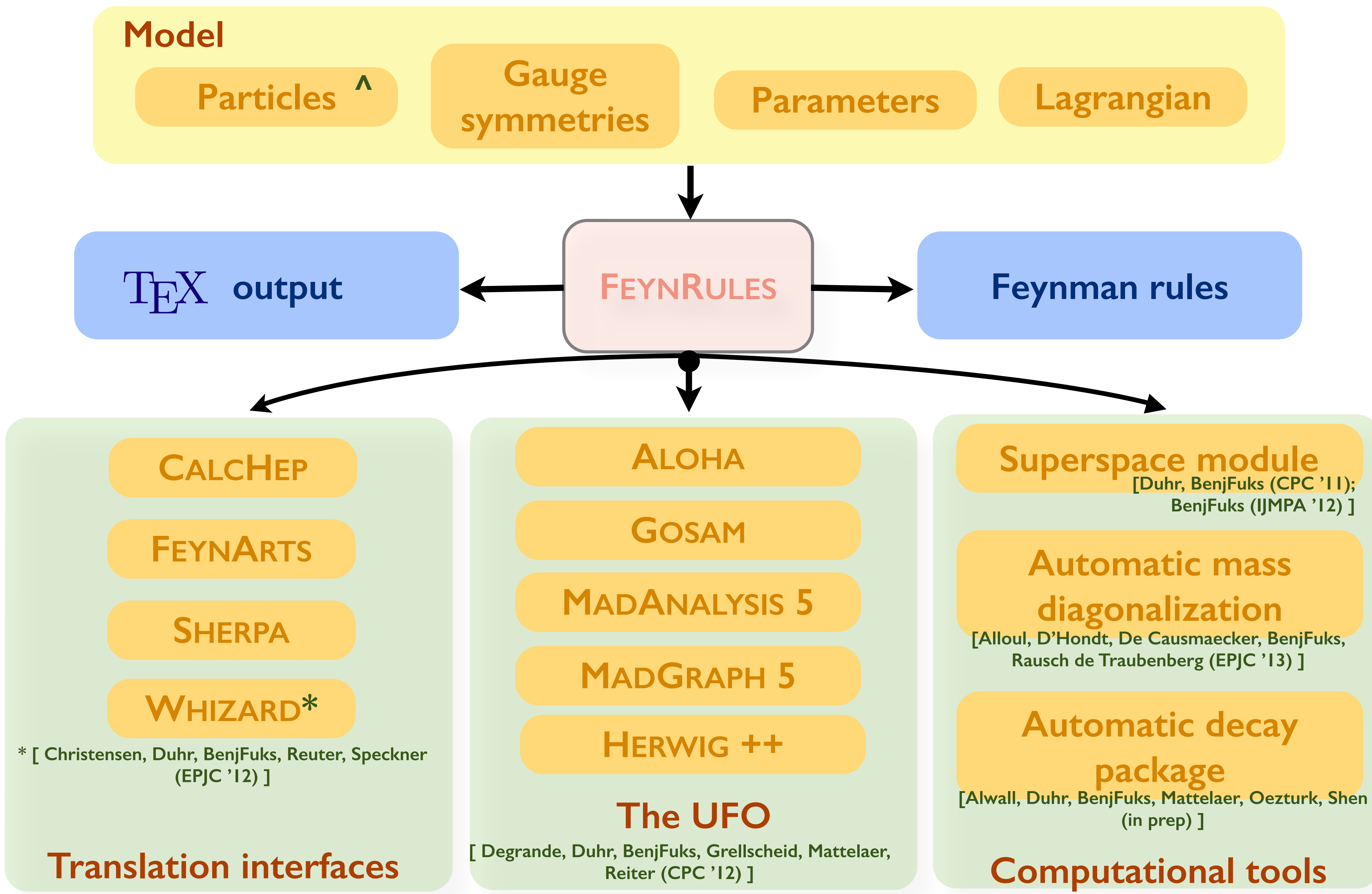
- A framework to develop new physics models
- Automatic export to several Monte Carlo event generators
  - ➡ Facilitate phenomenological investigations of the models
  - ➡ Facilitate the confrontation of the models against data
- Validation of the implementation using several programs

✦ 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)]

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)

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

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

Textbook-like
(covariant derivatives,
field strength tensors,

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

Features of FEYNRULES 2.0: the UFO (I)

[Degrande, 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)
```

Some of its couplings to quarks (uc and ut)

```
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 ])
```

Features of FEYNRULES 2.0: the UFO (2)

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

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

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

1. 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

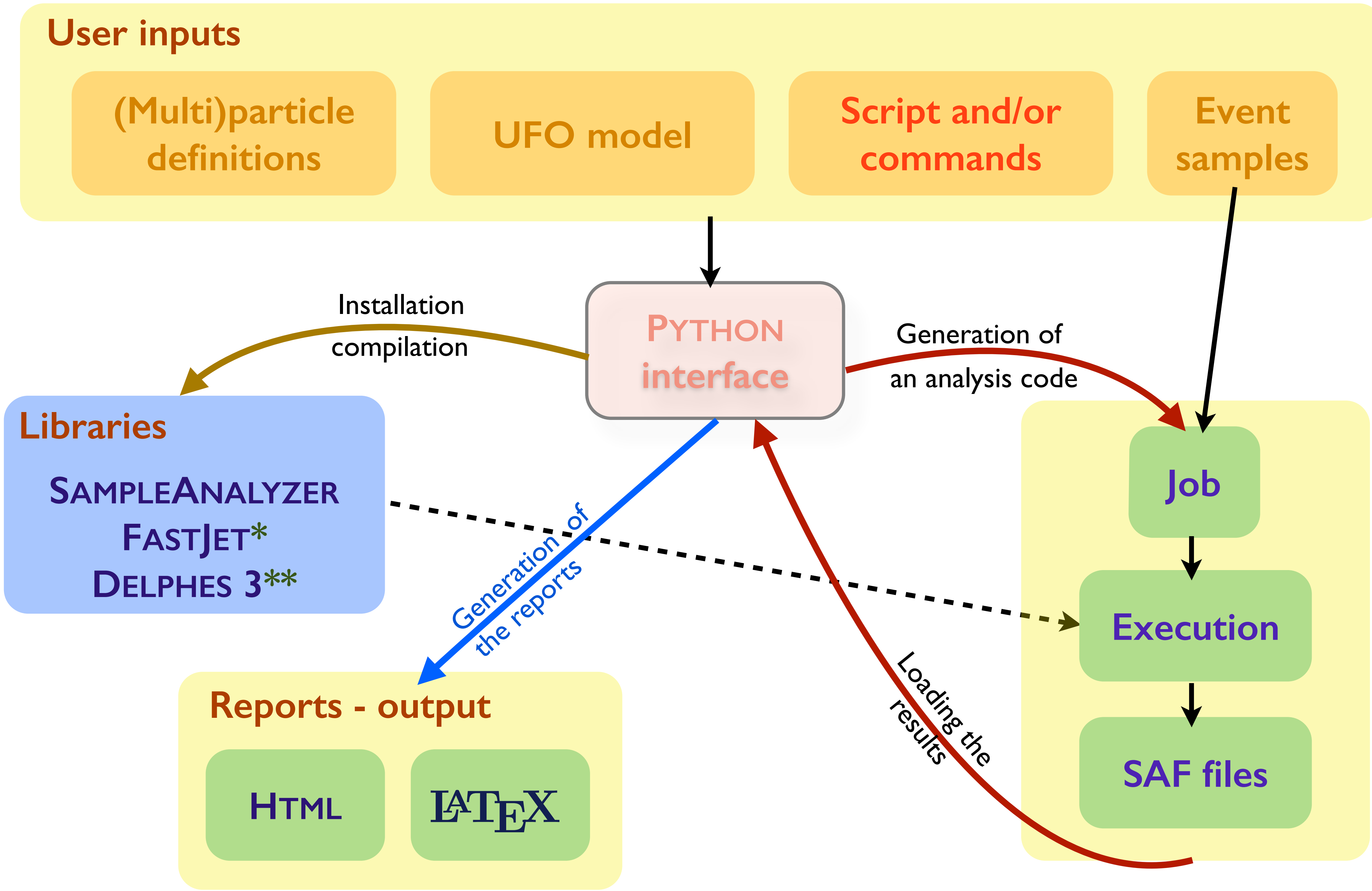
- **Two modules**
  - A Python command line interface (interactive)
  - A C++/Root core module, SampleAnalyzer

- **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

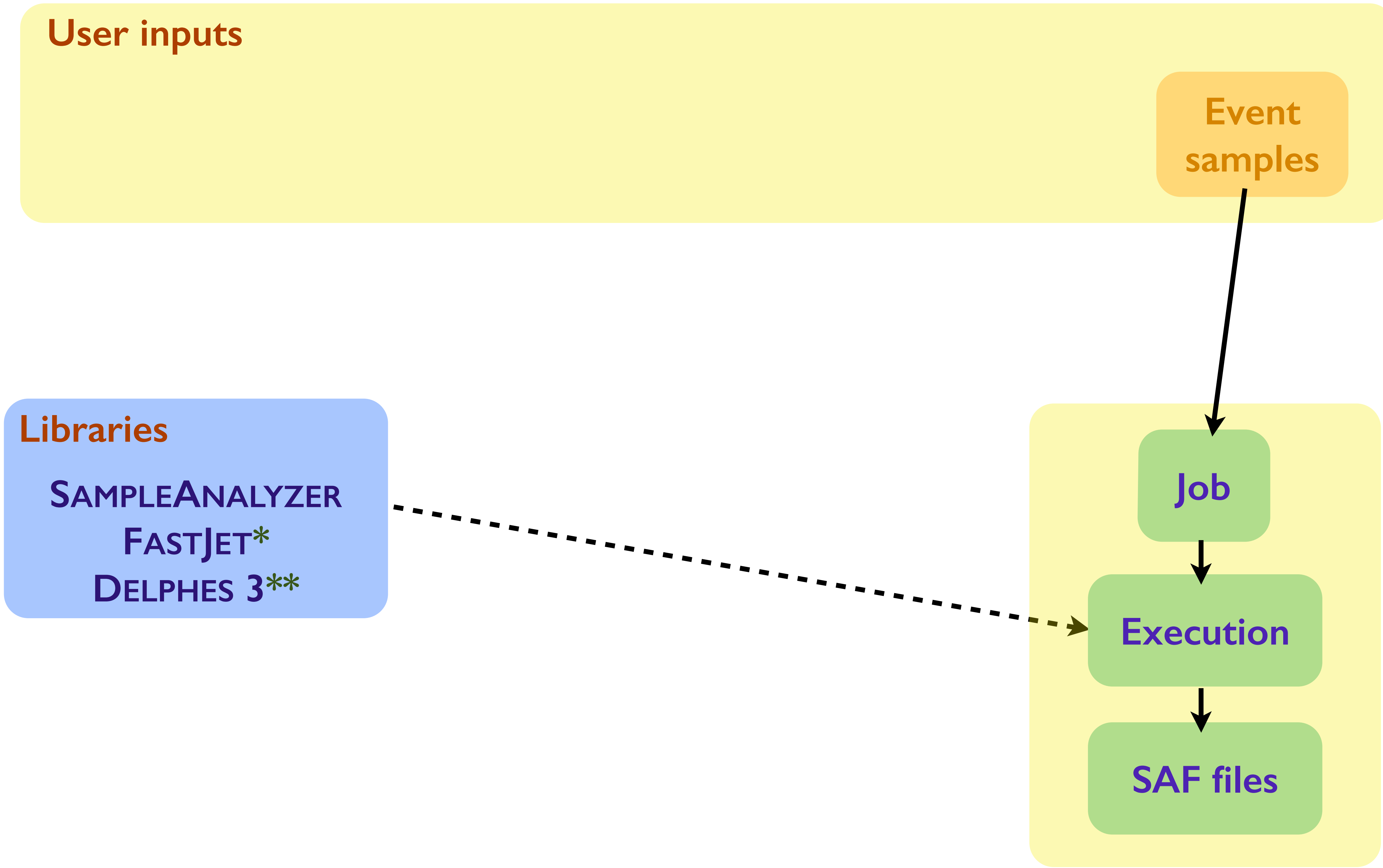
[Conte, BenjFuks, Serret (CPC '13); Conte, BenjFuks (arXiv:1309.7831)]



* [Cacciari, Salam (PLB '06)]
** [de Favareau, Delaere, Demin, Giammanco, 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, Giammanco, Lemaitre, Mertens, Selvaggi (arXiv:1307.6346)]

Example: background analysis (1)

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

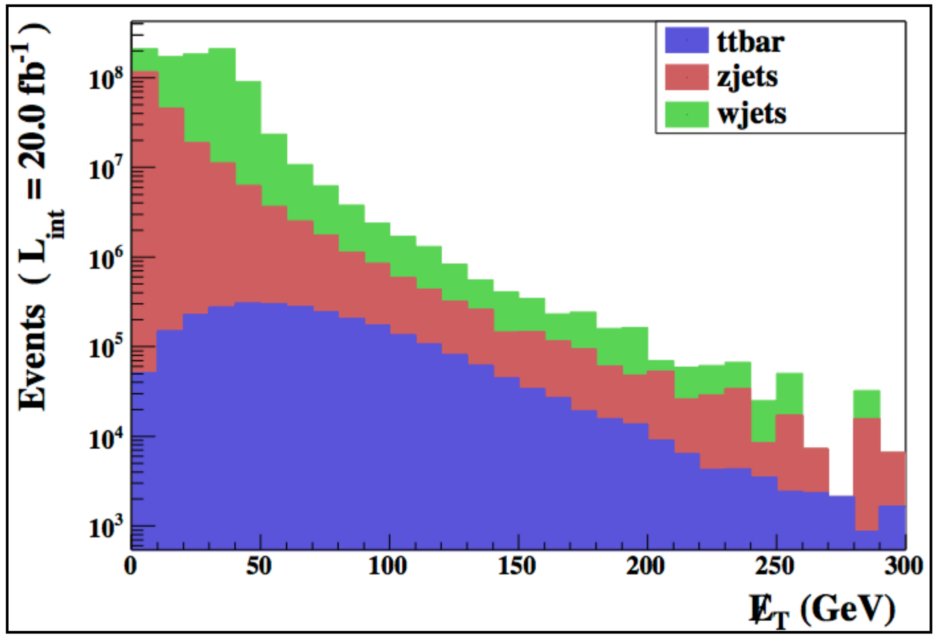
```
import ttbar_lep.hep.gz as ttbar
import wjets.hep.gz as wjets
import zjets.hep.gz as zjets
set ttbar.xsection = 139.6
set wjets.xsection = 35678
set zjets.xsection = 10319
set main.lumi = 20
set main.clustering.algorithm = antikt
set main.clustering.ptmin = 5
set main.clustering.radius = 0.4
plot 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
```

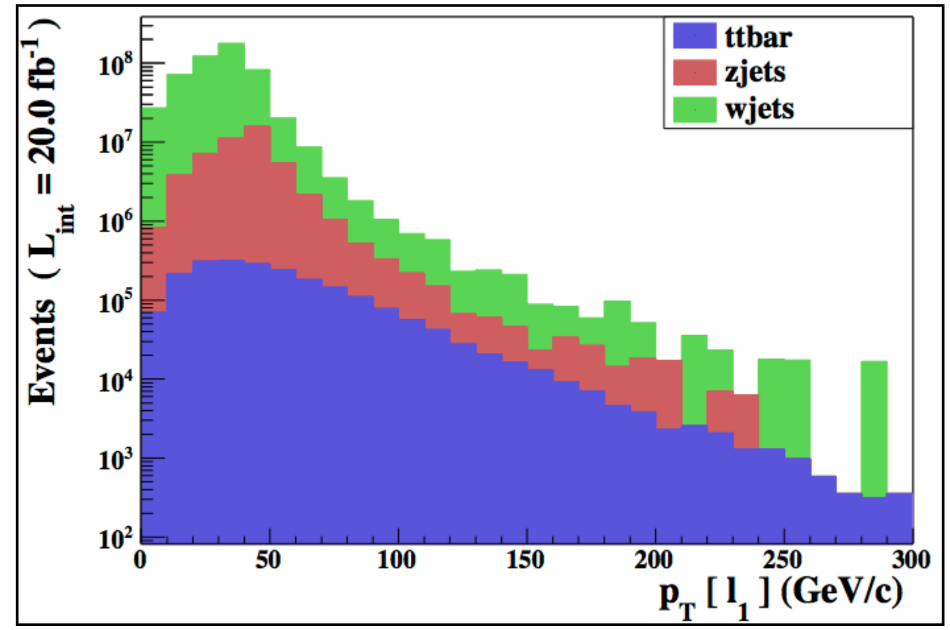
- Importing event samples
- Normalization to (N)NLO and to 20 fb^{-1}
- Jet clustering with FastJet
- Analysis strategy; histograms and cuts
- Cut-flow charts

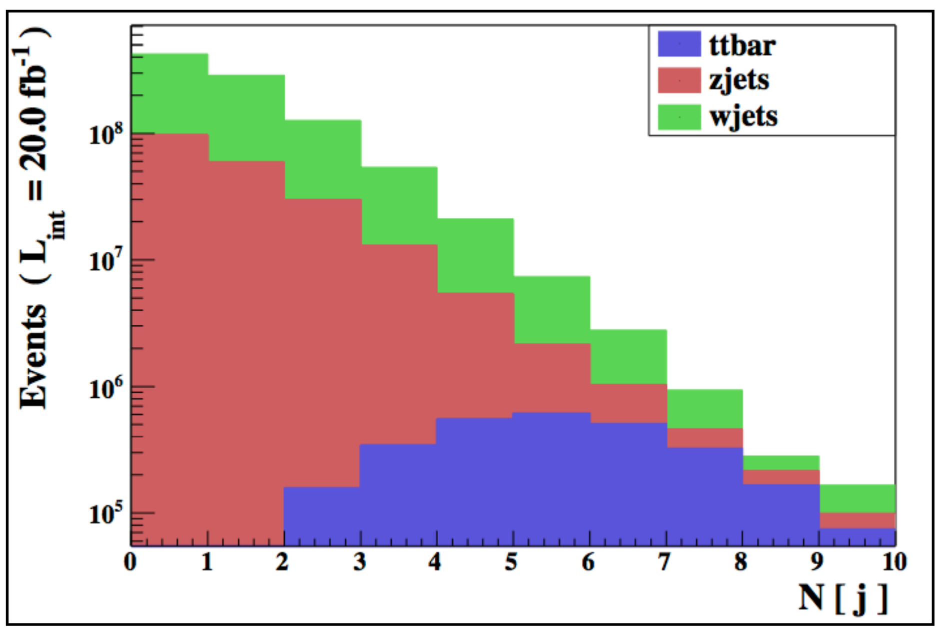
See the manual for more details

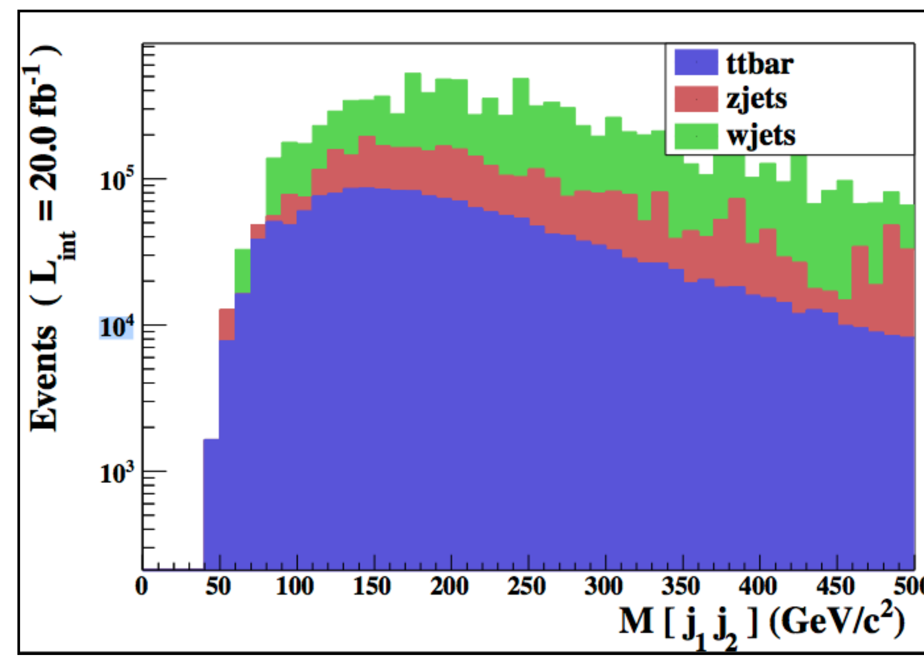
Example: background analysis (2)

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







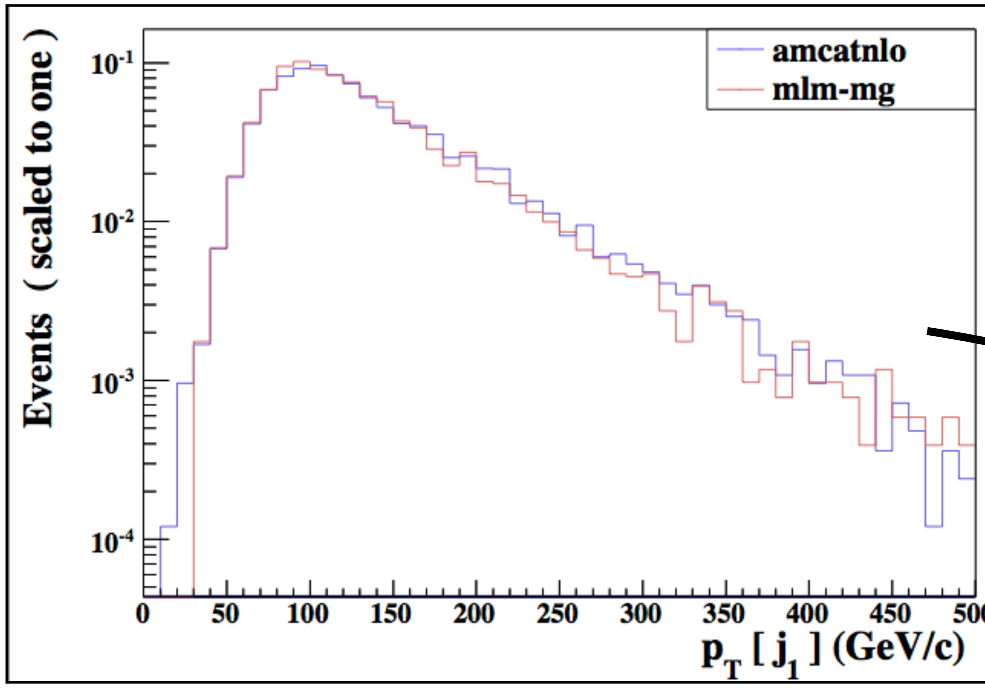


Cuts	Signal (S)	Background (B)	S vs B
initial	2792000	919940000	0.00303
cut 1	2792000	919940000 +/- 0.000173	3.034981e-03 +/- 5.7e-16
cut 2	2792000	919940000 +/- 0.000173	3.034981e-03 +/- 5.7e-16
cut 3	1928561 +/- 772	9583745 +/- 3079	0.201233 +/- 0.000103

MADANALYSIS 5 and precision

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

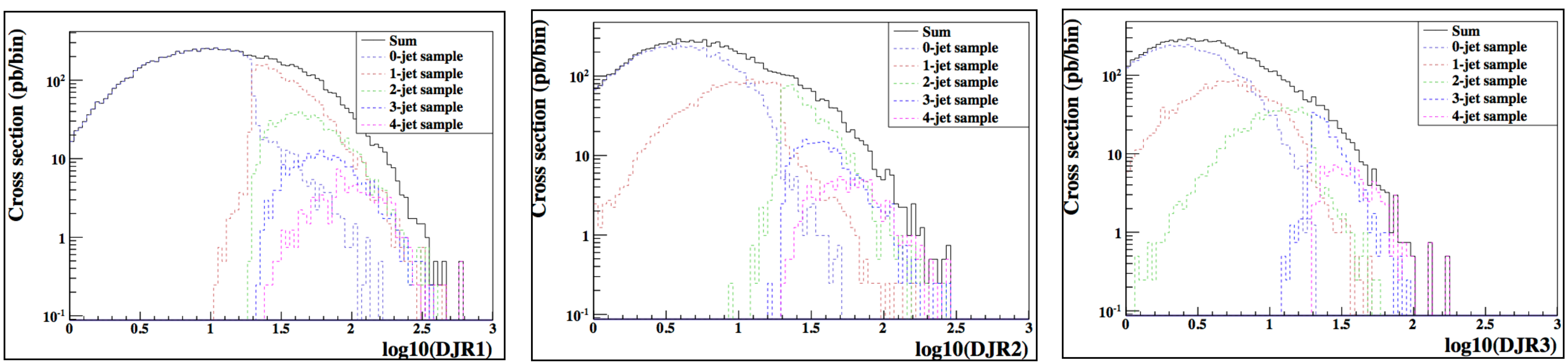
✦ Handling events with negative weights (as generated by aMC@NLO)



Path to the event file	Nr. of events	Cross section (pb)	Negative wgts (%)
amcatnlo.hw.hep.gz	9993	313	8.4
mg5_merged.hep.gz	5116	162.0	0.0

Agreement for the shapes; not for the normalization

✦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