Tools for searches at the LHC

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Outline

1. Introduction
2. Implementing new physics in event generators with FEYNRULES
3. Monte Carlo event simulation and analysis with MADANALYSIS 5
4. Precision and automation
5. Summary

Monte Carlo tools and discoveries at the LHC

- Establishing an excess over the Standard Model backgrounds:
  - Difficult
  - Rely on Monte Carlo event generators (backgrounds, signals)
  - Possible use of data-driven methods (backgrounds)

- Confirmation of the excess:
  - Model building activities
  - Implementation of the new models in the Monte Carlo tools

- Clarification of the new physics:
  - Measurement of the model parameters
  - Use of precision predictions (possibly with Monte Carlo generators)
  - Sophistication of the analyses ⇔ new physics / detector knowledge

➡ Monte Carlo tools play a key role!

A framework for LHC analyses: the older way

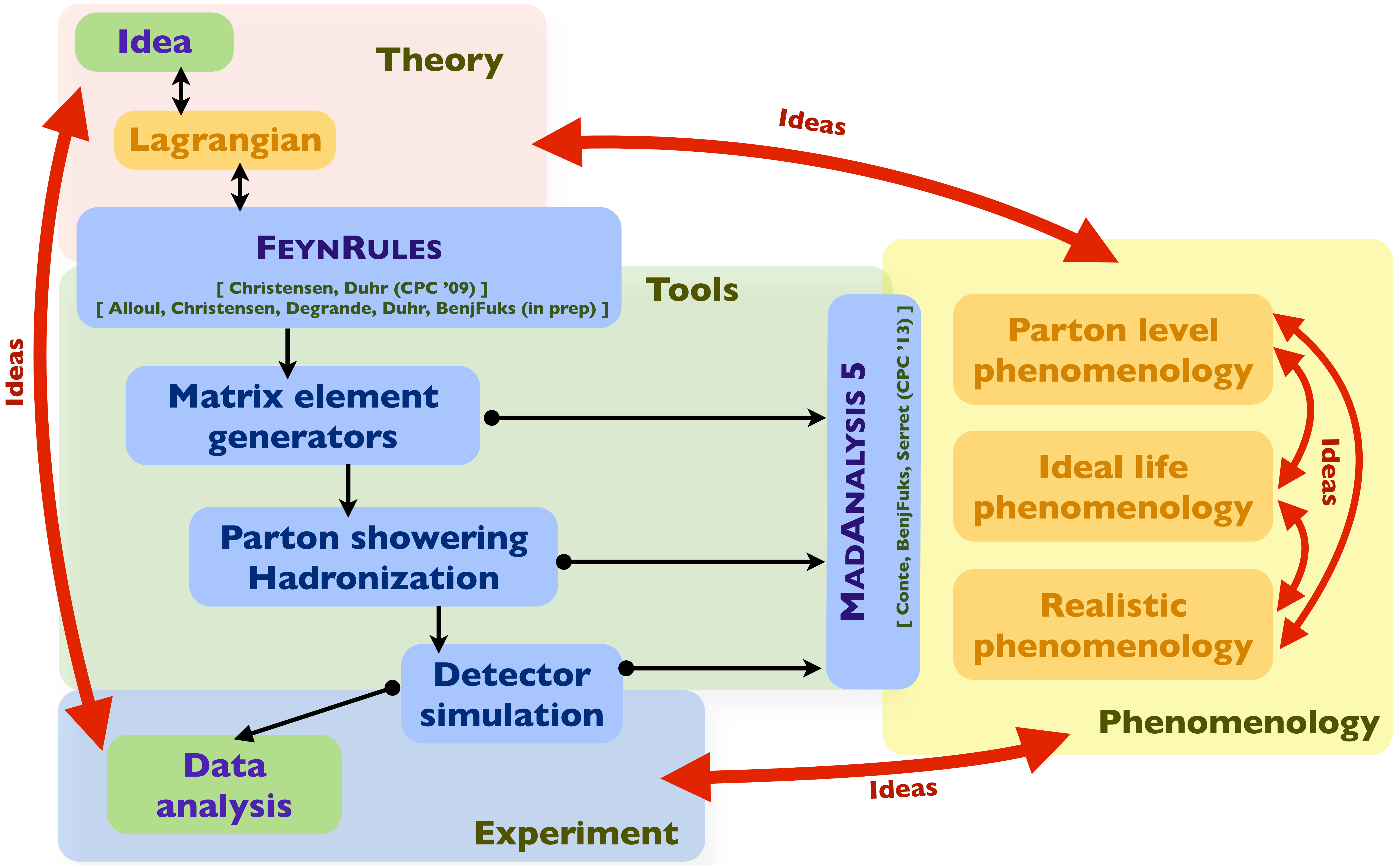
- New physics theories:
  - Lots of very different theories
  - Based on very different ideas
  - Evolve with time
- What is a new physics theory:
  - A set of particles
  - A set of interactions (or Feynman rules) included in a Lagrangian
  - The Lagrangian depends on some parameters
- New physics theory in the context of Monte Carlo tools:
  - Translation in a programming language
  - Error prone, time consuming, tedious, painful, ...
  - Careful validation required
  - Use of the Monte Carlo for phenomenology

➡ Iterate for each model
➡ Iterate for each tool

➡ Redundancy of the work

A framework for LHC analyses: a modern way

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



FEYNRULES in a nutshell

[Christensen, Duhr (CPC '09); Alloul, Christensen, Degrande, Duhr, BenjFuks (in prep)]

- What is FEYNRULES?
  - A framework to develop new physics models
  - Automated 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:
  - 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

- Interfaced to several automated Monte Carlo generators:
  CALCHEP / COMPHEP, FEYNARTS / FORMCALC, SHERPA, WHIZARD / OMEGA

- The Universal FEYNRULES Output (UFO):
  ALOHA & MADGRAPH 5, MADANALYSIS 5, GOSAM

From FeynRules To Monte Carlo tools

[Christensen, Duhr (CPC '09); Alloul, Christensen, Degrande, Duhr, BenjFuks (in prep)]

Model
- Particles
- Lagrangian
- Gauge symmetries
- Parameters

↓

FeynRules

→ TeX output

→ Feynman rules

Translation interfaces
- CalcHep
- FeynArts
- Sherpa
- Whizard*

* [Christensen, Duhr, BenjFuks, Reuter, Speckner (EPJC '12)]

The UFO
- MadGraph 5
- MadAnalysis 5
- Aloha
- GoSam
- Herwig ++

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

Computational tools
- Superspace module [Duhr, BenjFuks (CPC '11); BenjFuks (IJMPA '12)]
- Automated mass diagonalization [Alloul, D'Hondt, De Causmaecker, BenjFuks, Rausch de Traubenberg (EPJC '13)]
- Automated decay package [Alwall, Duhr, BenjFuks, Mattelaer, Oezturk, Shen (in prep)]

Example: monotop production at the LHC (I)

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

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 scenario

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];
```

Example: monotop production at the LHC (2)

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

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] AOFC[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 computation: 1 / 1.
        1 vertex obtained.
        (* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *)
        Vertex 1

        Particle 1 : Dirac , uq̄
        Particle 2 : Dirac , uq
        Particle 3 : Scalar , SMET
        Vertex:
```

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

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

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

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

Getting ready for phenomenology

From FEYNRULES to event analysis

0. Implementation of the model in FEYNRULES and generation of the UFO files

1. Event generation with MADGRAPH 5 **[Alwall, Herquet, Maltoni, Mattelaer, Stelzer (JHEP '11)]**
   - ✤ Both signal and backgrounds
   - ✤ Precision in the normalization: (N)NLO inclusive results
   - ✤ Other generator is possible (beware of restrictions for new physics)
     - ➟ MADGRAPH 5 is agnostic of the Lorentz and color structures of the interactions

2. Parton showering and hadronization with PYTHIA **[Sjostrand, Mrenna, Skands (JHEP '06; CPC '08)]**
   - ✤ Precision in the shapes: MLM-merging technique **[Mangano, Moretti, Piccinini, Treccani (JHEP '07)]**
   - ✤ Other generator is possible

3. Fast detector simulation with DELPHES **[Ovyn, Rouby, Lemaitre (2009)]**
   - ✤ CMS-like and ATLAS-like detectors available

4. Event analysis with MADANALYSIS 5 **[Conte, BenjFuks, Serret (CPC '13)]**
   - ✤ Parton-level and reconstructed-level analyses

MADANALYSIS 5 in a nutshell

[Conte, BenjFuks, Serret (CPC '13)]

- What is MADANALYSIS 5?
  - A framework for phenomenological analyses
  - Multiple input format: STDHEP, HEPMC, LHE
  - 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

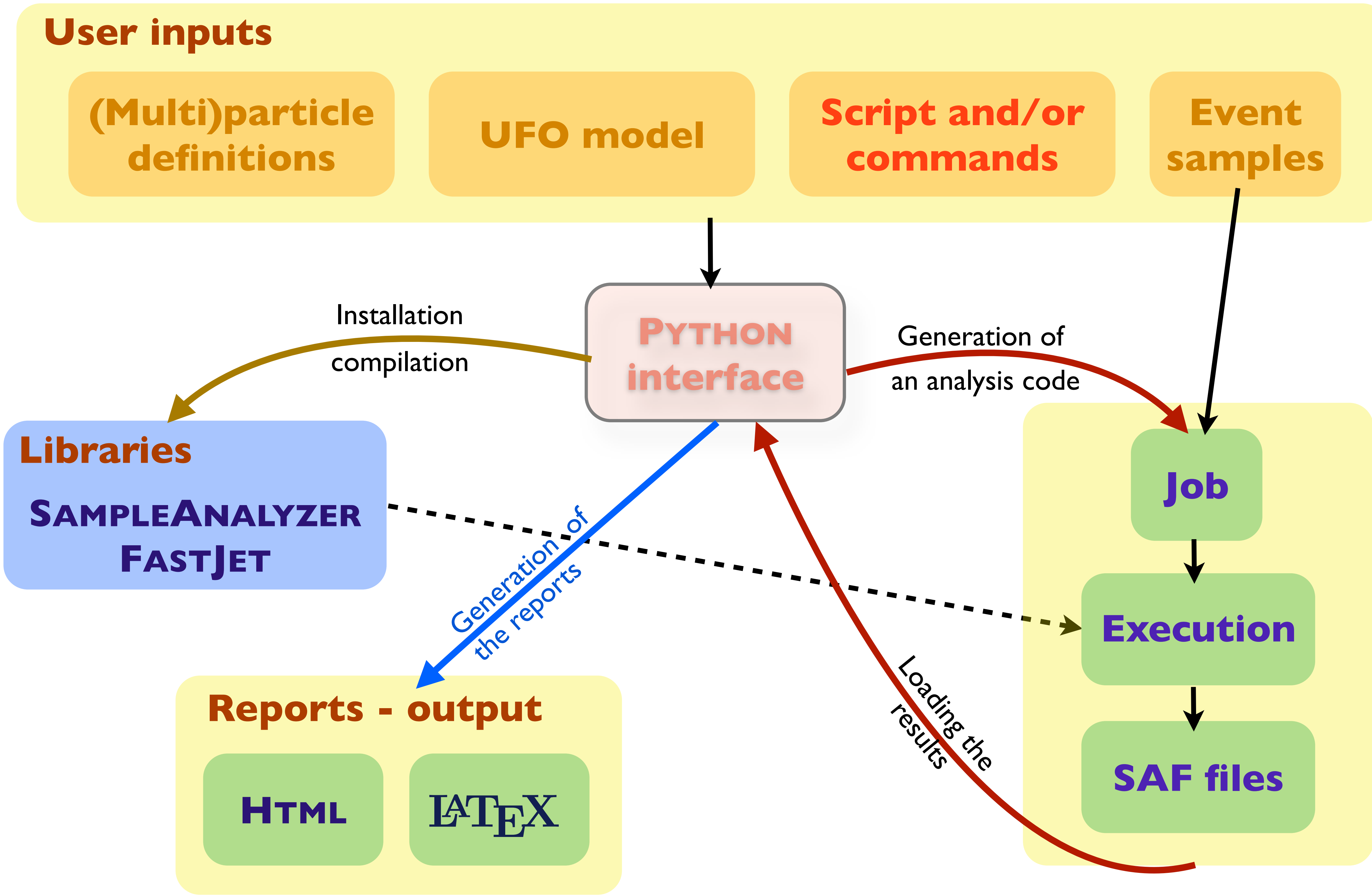
- Two modules
  - A PYTHON command line interface (interactive)
  - A C++/ROOT core module, SAMPLEANALYZER

- 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

MadAnalysis 5: normal running mode

[Conte, BenjFuks, Serret (CPC '13)]



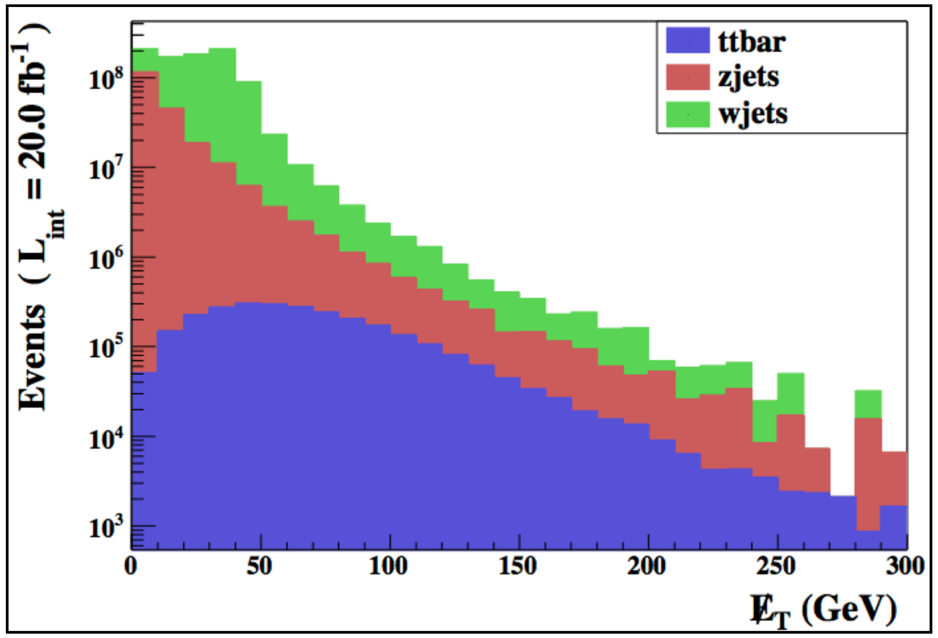
Example: background analysis (I)

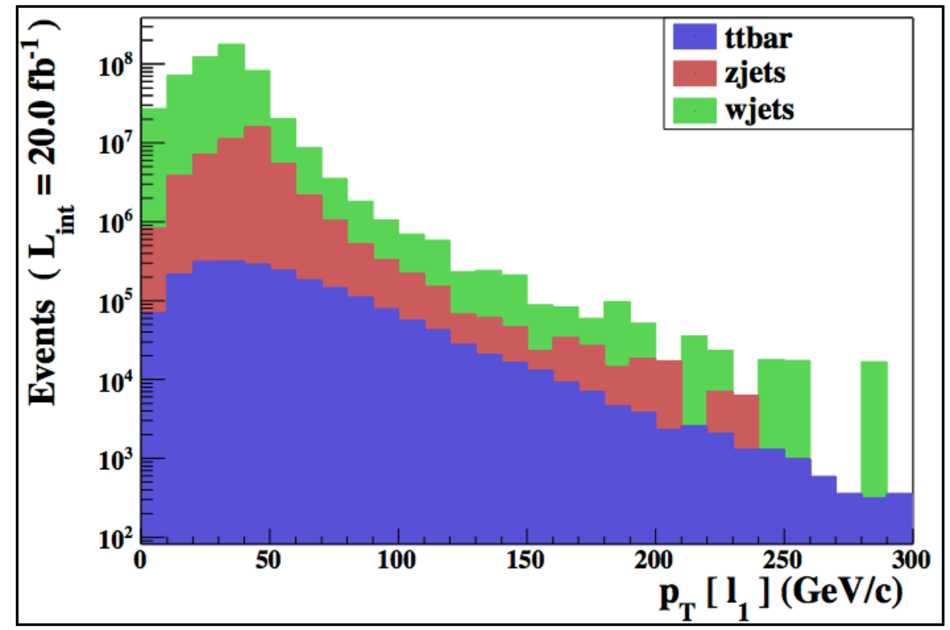
Commands

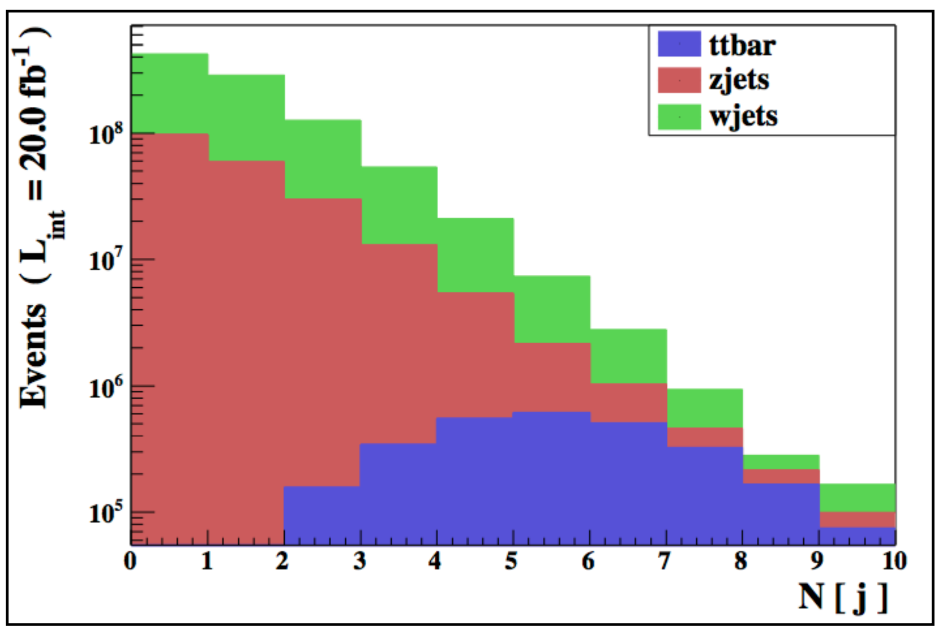
```
import ttbar_lep.lhe.gz as ttbar
import wjets.lhe.gz as wjets
import zjets.lhe.gz as zjets
set ttbar.xsection = 139.6
set wjets.xsection = 35678
set zjets.xsection = 10319
set main.lumi = 20
plot MET 30 0 300 [logy]
define l = l+ l-
plot PT(l[1]) 20 0 200 [logy]
set selection[2].rank = Eordering
define j = j b b~
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
```

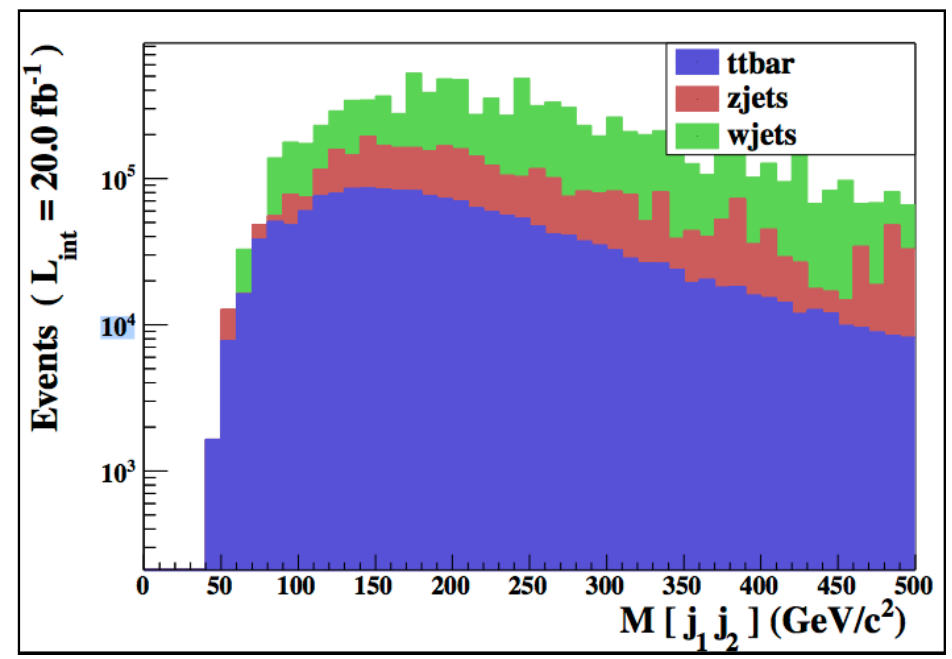
- Importing event samples
- Normalization to (N)NLO and to 20 fb^{-1}
- Analysis strategy; histograms and cuts
- Cut-flow charts

Example: background analysis (2)







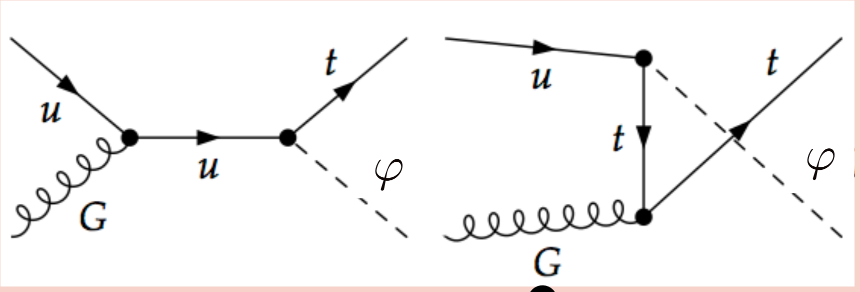


Cuts	Signal (S)	Background (B)	S vs B
initial	2792000	919940000	0.00303
cut 1	2792000	919940000 +/- 0.000173	3.034981e-03 +/- 5.7e-16
cut 2	2792000	919940000 +/- 0.000173	3.034981e-03 +/- 5.7e-16
cut 3	1928561 +/- 772	9583745 +/- 3079	0.201233 +/- 0.000103

From theory to event analysis: monotops

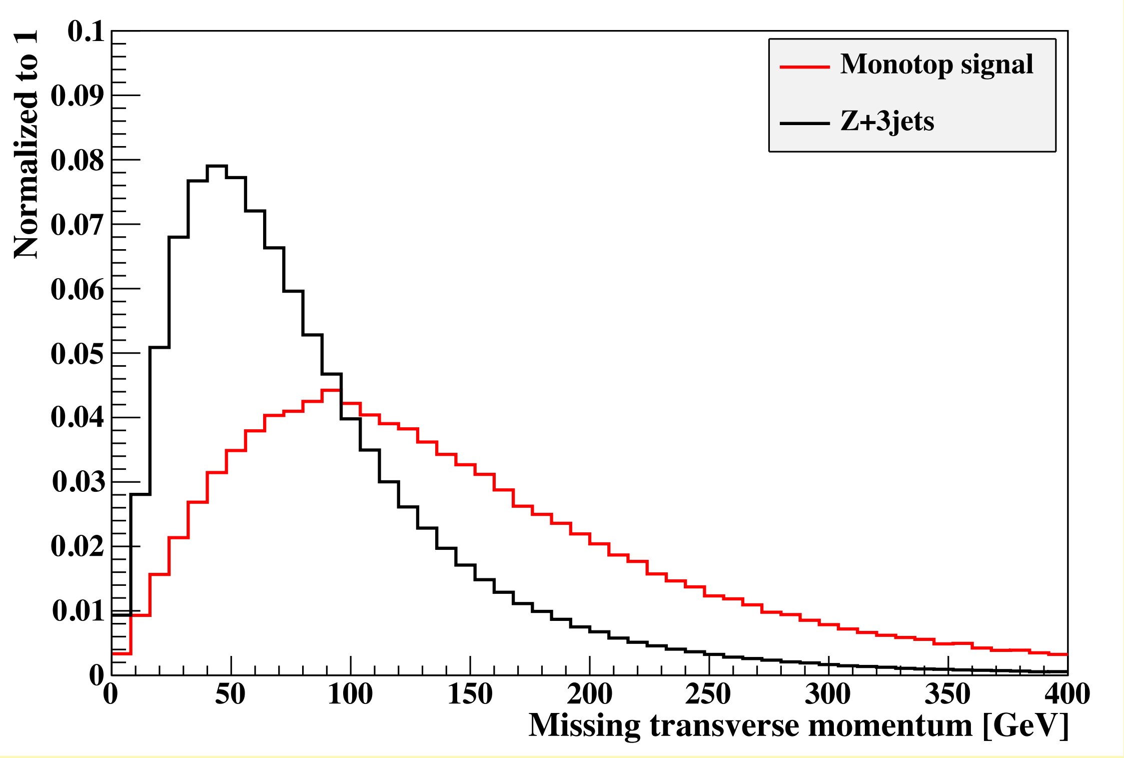
[Andrea, BenjFuks, Maltoni (PRD '11); Andrea, Conte, BenjFuks (in prep)]

Illustrative example: monotops

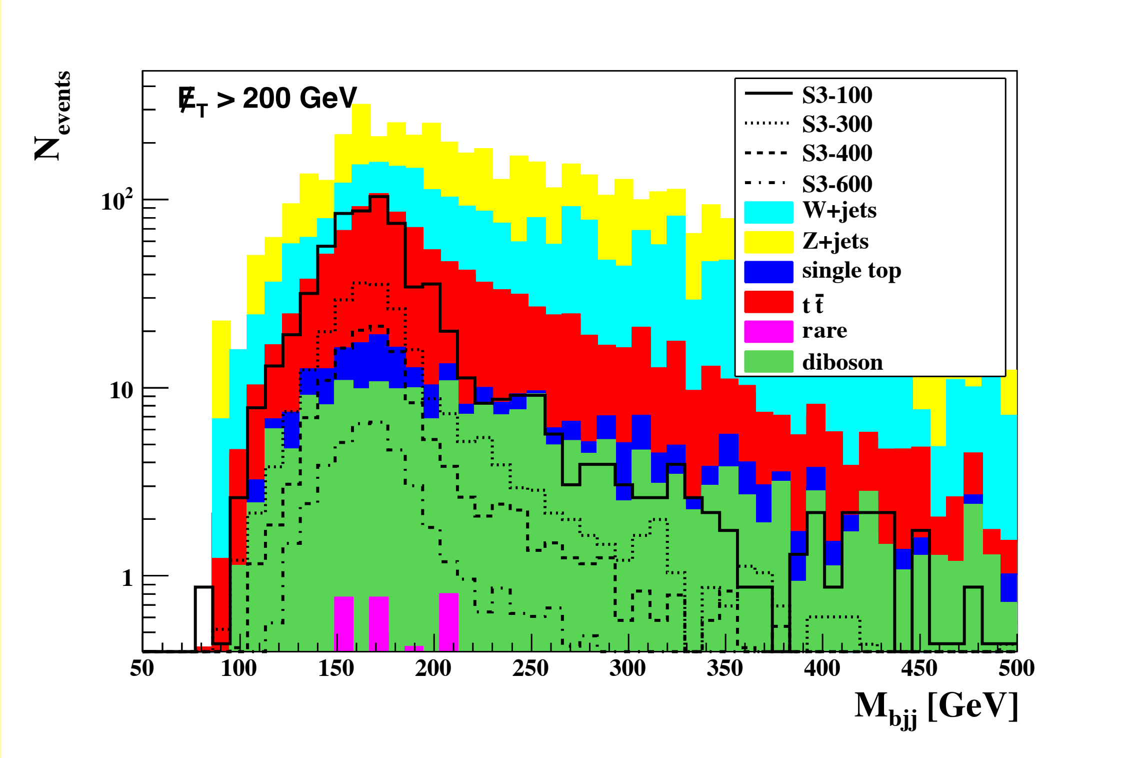


After top reconstruction

Parton level



Detector level



Monte Carlo event generators @ NLO (I)

- Why is NLO necessary? Advantages and disadvantages of Monte Carlo tools @ NLO
  - Reliability of the predictions
  - Theoretical uncertainties (scales, PDFs) under a better control

    ➡ More predictive power

  - Large increase in the process complexity for high-multiplicity final states
  - Double counting issues with real emissions, with virtual contributions

    ➡ Prescriptions are needed

- Classes of Monte Carlo tools @ NLO
  - **MC@NLO**: explicit removal of the double counting
    [Frixione, Webber (JHEP '02); Frixione, Nason, Webber (JHEP '03)]
  - **POWHEG**: parton shower modification + inclusive NLO correction to each event
    [Nason (JHEP '04)]

Monte Carlo event generators @ NLO (2)

✦ **aMC@NLO**: Automation (achieved for the Standard Model)

[Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Pittau, Torrielli, Zaro (in prep)]

- ✤ Reliability of the results (many checks possible)
- ✤ The computer does the hard job (process complexity ↔ CPU)

✦ Multiparton matrix element merging @ NLO (à la MLM, CKKW, ...)

[Lavesson, Lonnblad (JHEP '08); Hamilton, Nason (JHEP '09); Hoeche, Krauss, Schonherr, Siegert (JHEP '11); Giele, Kosower, Skands (PRD '11); Alioli, Hamilton, Re (JHEP '11); Frederix, Frixione (JHEP '12); Gehrmann, Hoeche, Krauss, Schonherr, Siegert (JHEP '13)]

- ✤ New techniques in development
- ✤ Automation in progress (within the aMC@NLO framework)

FeynRules and UFO @ NLO

[Degrande, Duhr, BenjFuks, Hirschi, Mattelaer, Shao (in prep)]

- Ingredients of a NLO model file for aMC@NLO
  - Tree-level vertices
  - UV counterterms
  - R_2 counterterms

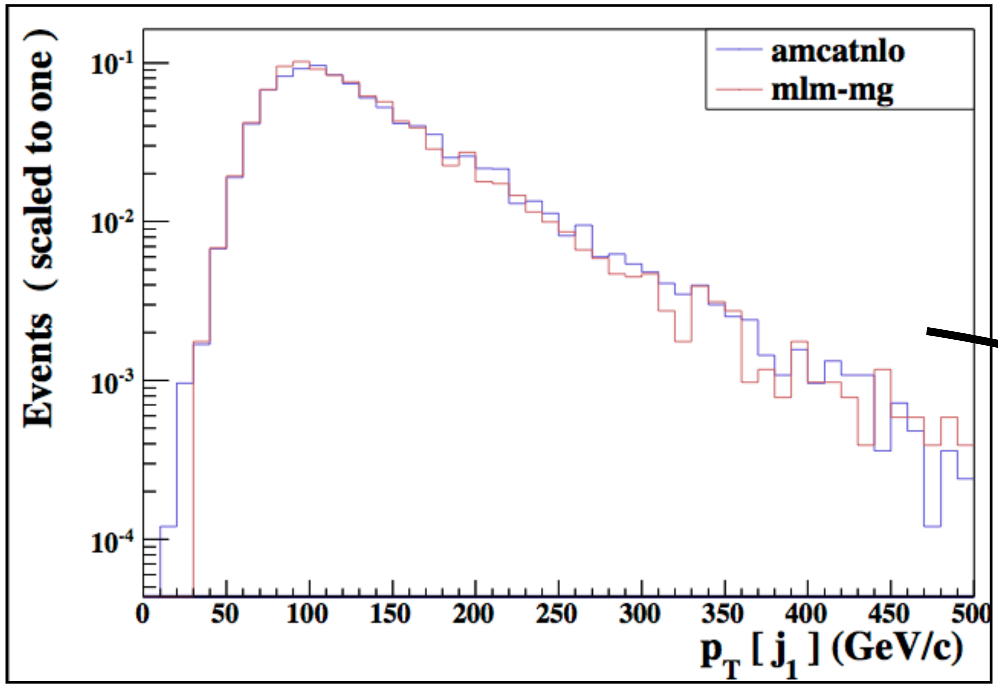
- Technicalities
  - Use of the FeynArts-FormCalc interface of FeynRules
  - Generation of a FeynArts-FormCalc script for NLO vertex generation
  - Script execution → R_2 and UV counterterms
  - Inclusion of the R_2 and UV counterterms in a UFO@NLO model file

➡ aMC@NLO for new physics on its way

MadAnalysis 5 and precision

[Conte, BenjFuks (in prep)]

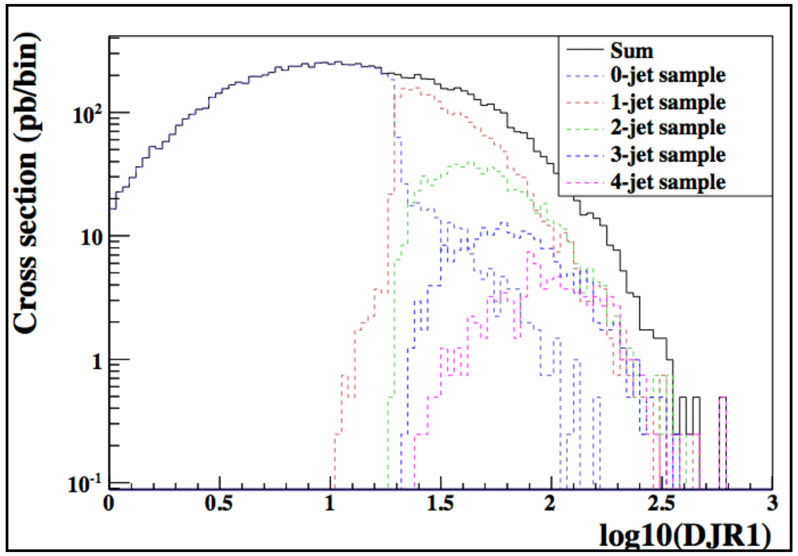
✦ Handling events with negative weights (as generated by aMC@NLO)

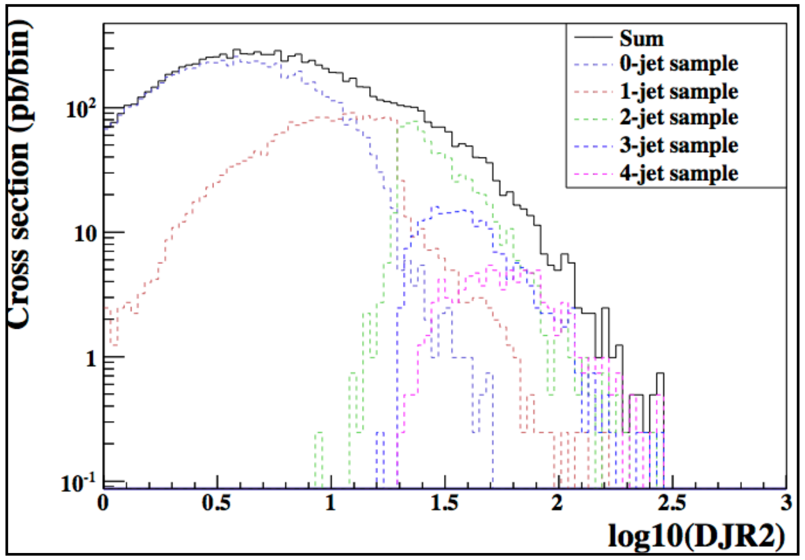


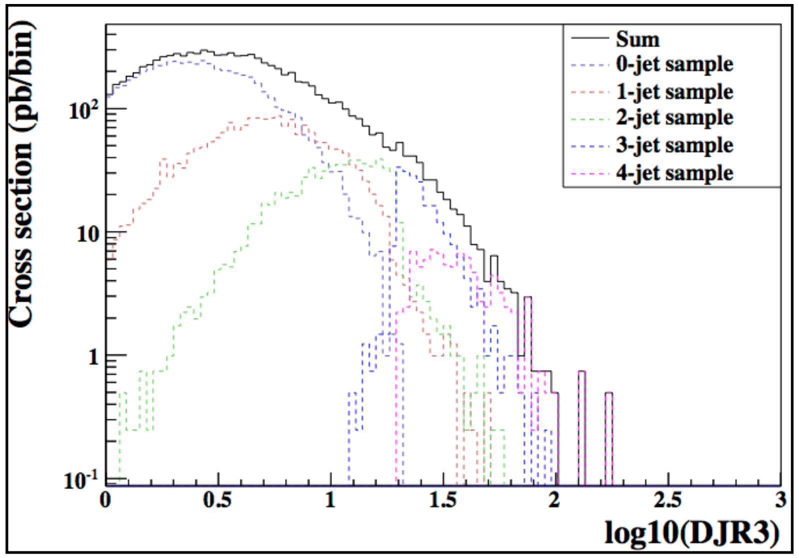
Path to the event file	Nr. of events	Cross section (pb)	Negative wgts (%)
amcatnlo.hw.hep.gz	9993	313	8.4
mg5_merged.hep.gz	5116	162.0	0.0

Agreement for the shapes; not for the normalization

✦ Automated check of the merging procedure







Summary

- The quest for new physics at the LHC has started
  - Rely on Monte Carlo event generators for background and signal modeling
  - Satellite tools have been intensively developed (FEYNRULES, MADANALYSIS 5, ...)

- FEYNRULES:
  - 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:
  - 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 almost there