From theory to phenomenology with FeynRules and MadAnalysis 5

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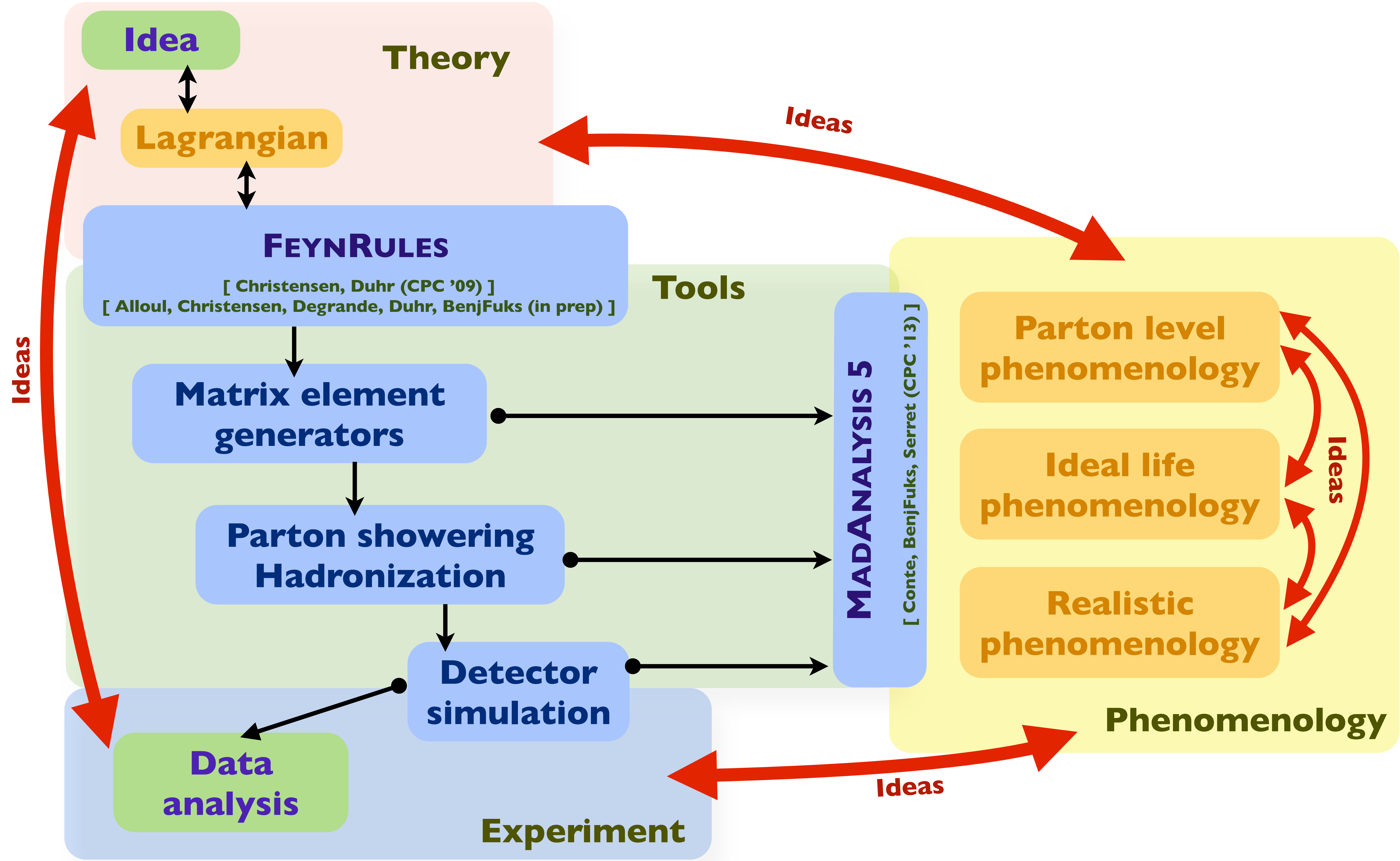
MC4BSM 2013 @ DESY Hamburg

April 18-20, 2013

A framework for LHC analyses: a modern vision

[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
  - 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 1.8 beta):
  - 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

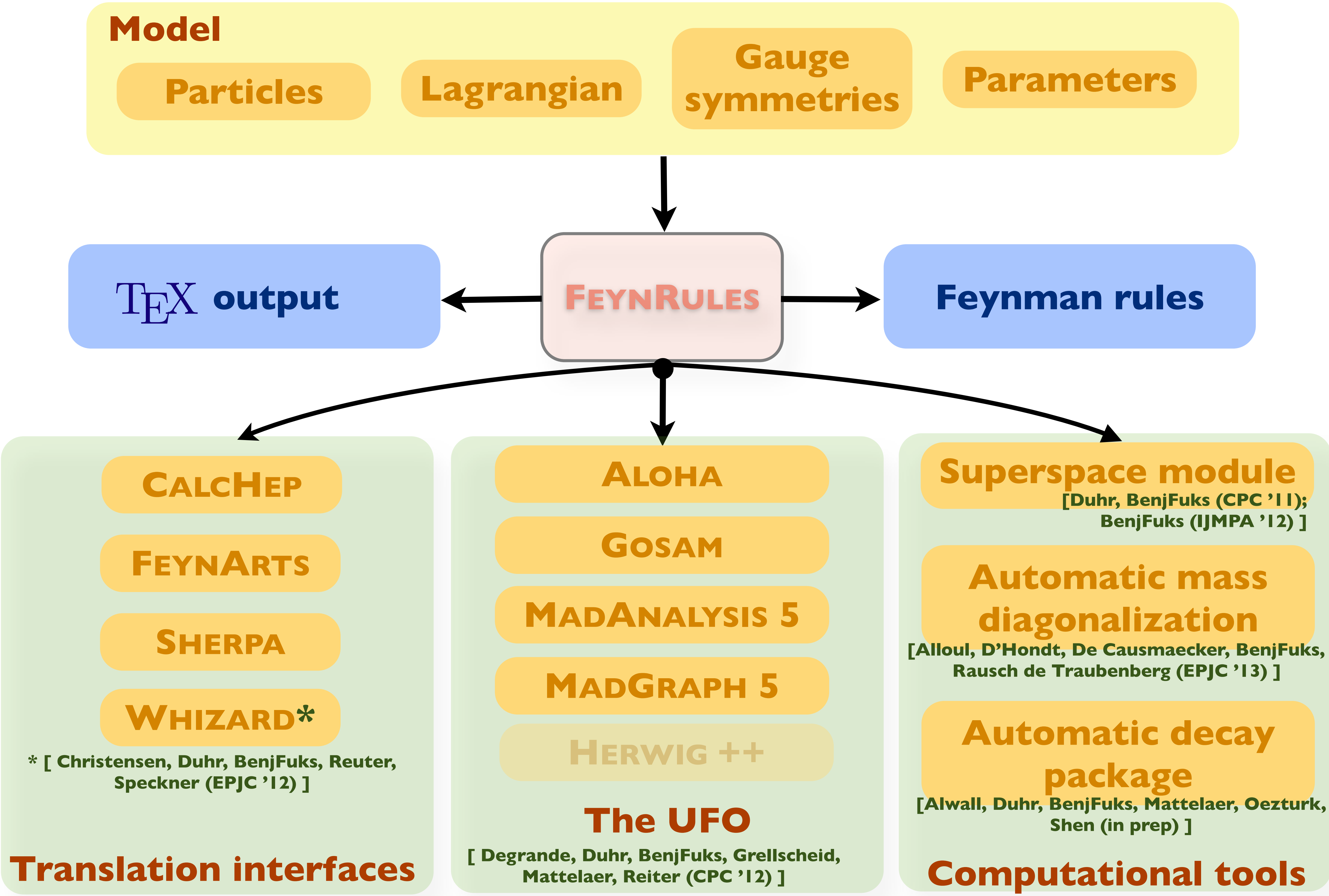
[Christensen, de Aquino, Deutschmann, Duhr, BenjFuks, Garcia-Cely, Mattelaer, Mawatari, Oexl, Taakaesu (in prep)]

- Interfaced to several Monte Carlo event 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)]



Example: monotop production at the LHC (I)

[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)

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

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

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

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

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 comput
        1 vertex obtained.
        (* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
        Vertex 1
        Particle 1 : Dirac , uq
        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]
```

Extension of existing models

New implementations from scratch not always necessary

Check our model database

Getting ready for phenomenology

Features of FeynRules 1.6: 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 ])
```

Back to the monotop example

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

Features of FeynRules 1.6: 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

Features of FeynRules 1.6: supersymmetry

[Duhr, BenjFuks (CPC '11); BenjFuks (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

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

- Supersymmetric renormalization group equations (RGE)
  - Extraction of the RGEs at the two-loop level
  - Export to a numerical module (in development)

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

$$\frac{d\mu}{dt} = \mu\Big[-\frac{3g'^2}{80\pi^2} - \frac{3g_w^2}{16\pi^2} + \frac{3}{16\pi^2}\mathrm{Tr}\big[\mathbf{y^d}^\dagger\mathbf{y^d}\big] + \frac{3}{16\pi^2}\mathrm{Tr}\big[\mathbf{y^u}^\dagger\mathbf{y^u}\big] + \frac{1}{16\pi^2}\mathrm{Tr}\big[\mathbf{y^e}^\dagger\mathbf{y^e}\big]\Big]$$

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

A MSSM Higgs superfield

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

See the manual for more details

New features in FEYNRULES 1.8 (I)

- Automatic mass diagonalization [Alloul, D'Hondt, De Causmaecker, BenjFuks, Rausch de Traubenberg (EPJC '13)]
  - Computation of the model mass matrices from the Lagrangian
  - Numerical diagonalization ➠ spectrum generation

➠ **K. De Causmaecker's talk**

- Automatic decay width computations [Alwall, Duhr, BenjFuks, Mattelaer, Oezturk, Shen (in prep)]
  - 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

```
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*CKM3x3*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*MW**2 - 2*MT**2*MW**2 + MW**4))/(96.*cmath.pi*abs(MT)**3)'})
```

- Multicore is now supported (significant speed increase)

New features in FEYNRULES 1.8 (2)

- Ingredients of a NLO model file for 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

➡ MADLOOP / aMC@NLO for new physics on its way

From FEYNRULES to event analysis

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

1. Event generation with your favorite Monte Carlo generator
   - ✤ Both signal and backgrounds
   - ✤ 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

3. Fast detector simulation

4. Event analysis with MADANALYSIS 5
   - ✤ 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

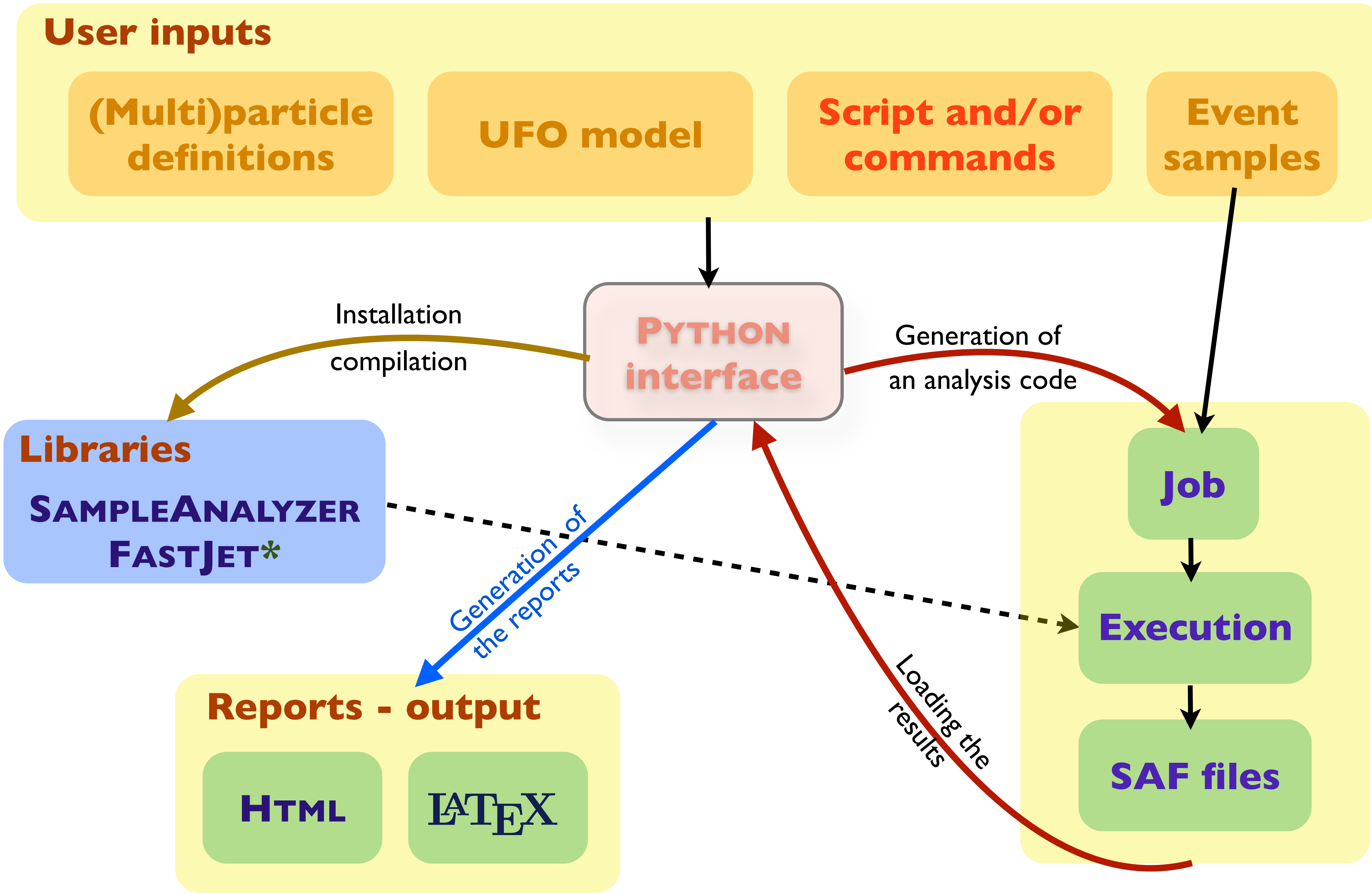
- Two modules
  - A PYTHON command line interface (interactive)
  - A C++/ROOT core module, SAMPLEANALYZER

- 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 (not covered here)

MadAnalysis 5: normal running mode

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



* [Cacciari, Salam (PLB '06)]

Example: background analysis (I)

```
import ttbar_lep.hep.gz as ttbar
import wjets.hep.gz as wjets
import zjets.hep.gz as zjets
```
→ Importing event samples

```
set ttbar.xsection = 139.6
set wjets.xsection = 35678
set zjets.xsection = 10319
set main.lumi = 20
```
→ Normalization to (N)NLO and to 20 fb^{-1}

```
set main.clustering.algorithm = antikt
set main.clustering.ptmin = 5
set main.clustering.radius = 0.4
```
→ Jet clustering with FASTJET

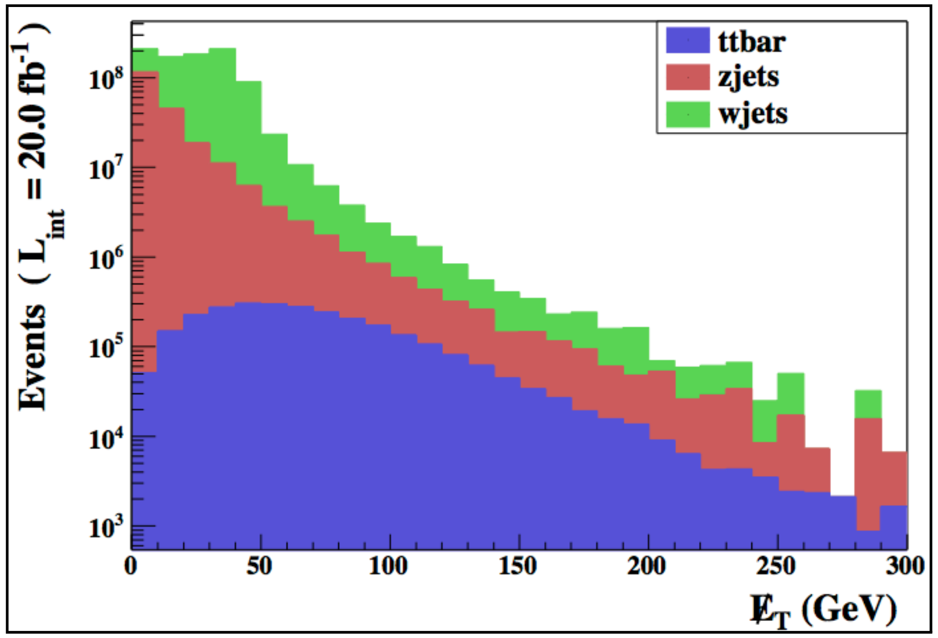
```
plot MET 30 0 300 [logy]
plot PT(l[1]) 20 0 200 [logy]
set selection[2].rank = Eordering
plot N(j)
select (j) PT > 20
reject THT < 200
plot M(j[1] j[2])
```
→ Analysis strategy; histograms and cuts

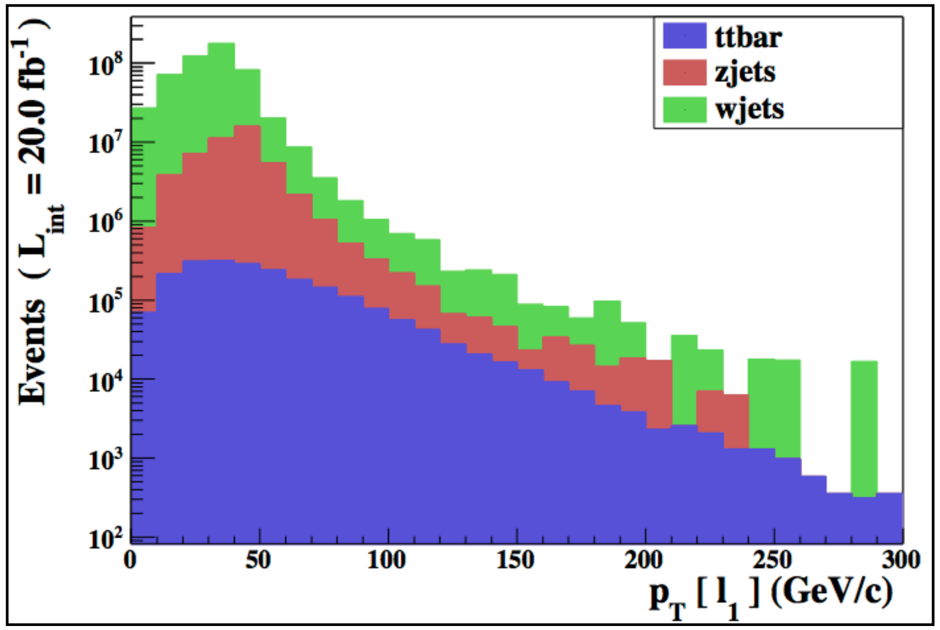
```
set wjets.type = background
set zjets.type = background
set main.sbratio = 'S/B'
```
→ Cut-flow charts

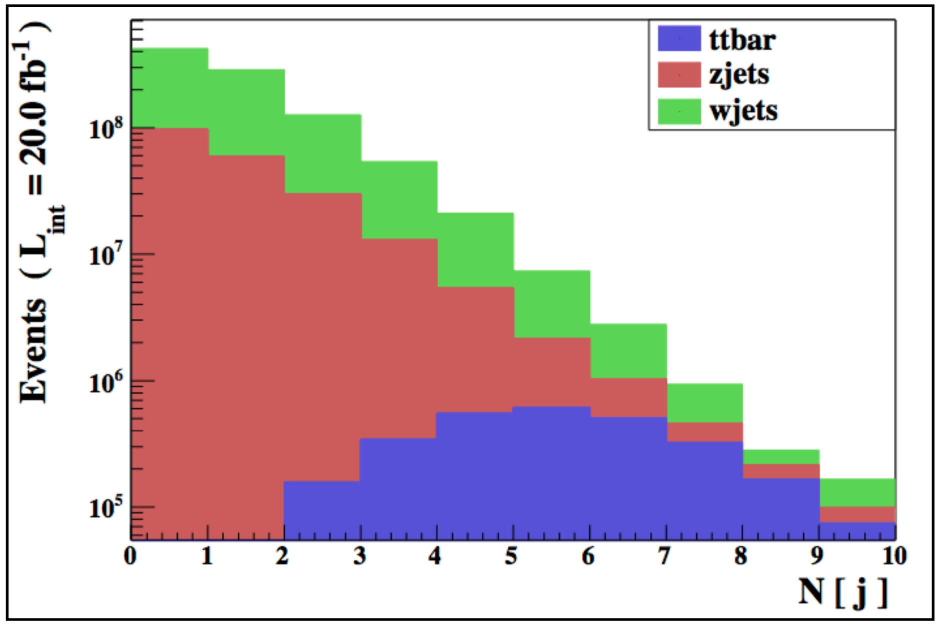
```
submit
```

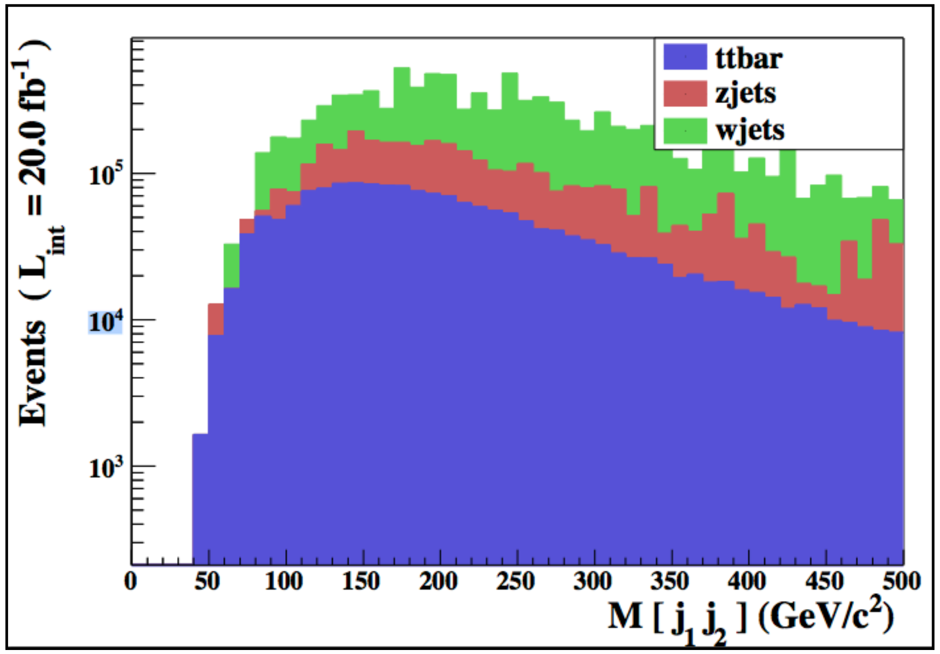
See the manual for more details

Example: background analysis (2)







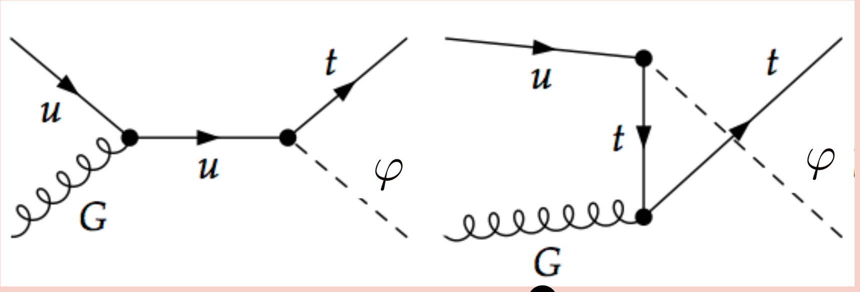


Cuts	Signal (S)	Background (B)	S vs B
initial	2792000	919940000	0.00303
cut 1	2792000	919940000 +/- 0.000173	3.034981e-03 +/- 5.7e-16
cut 2	2792000	919940000 +/- 0.000173	3.034981e-03 +/- 5.7e-16
cut 3	1928561 +/- 772	9583745 +/- 3079	0.201233 +/- 0.000103

From theory to event analysis: monotops

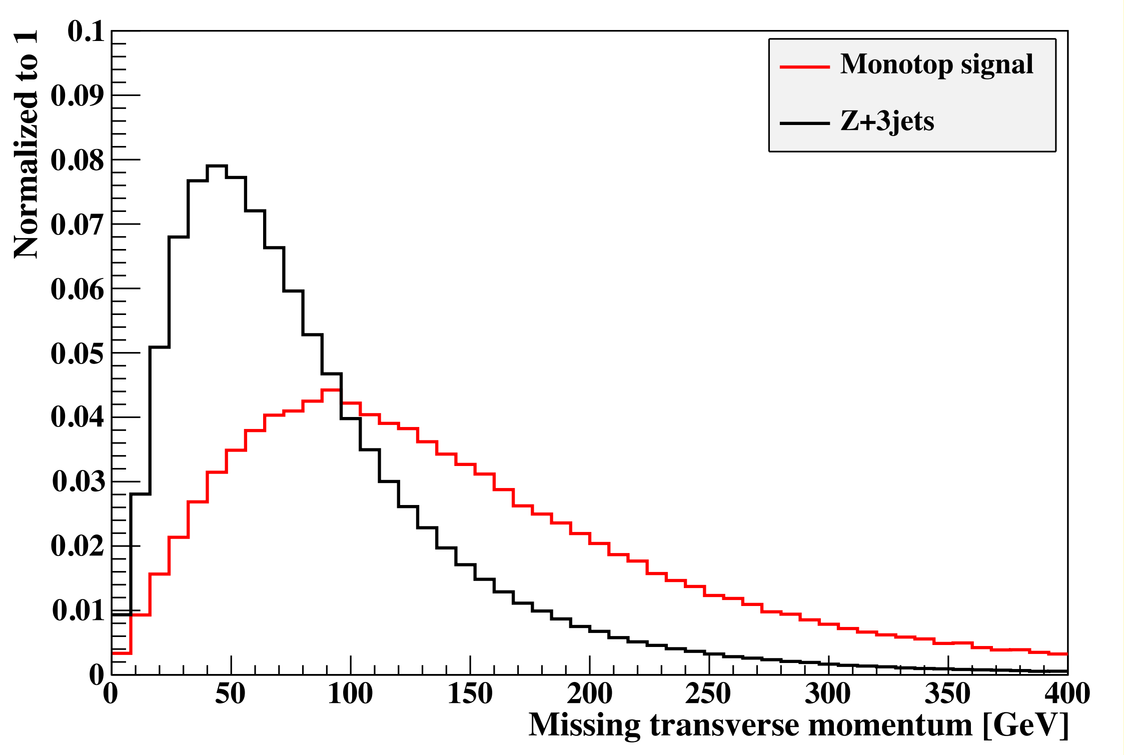
[Andrea, BenjFuks, Maltoni (PRD '11); Andrea, Conte, BenjFuks (in prep)]

Illustrative example: monotops

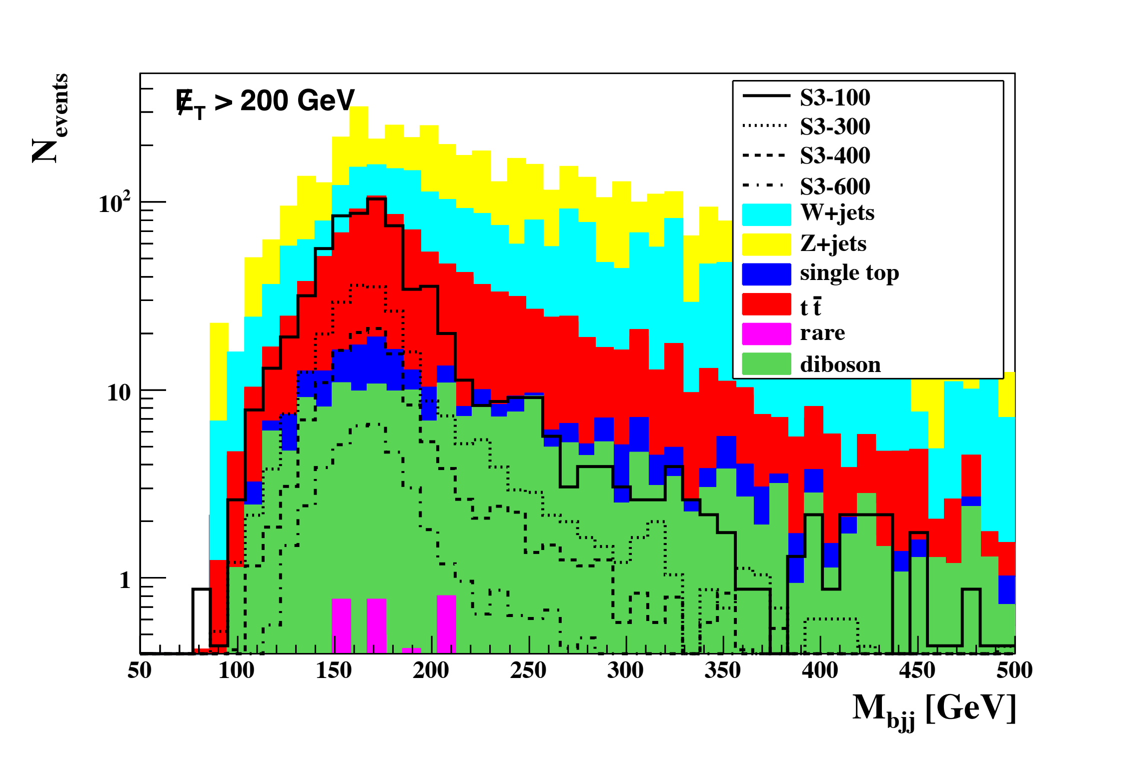


After top reconstruction

Parton level



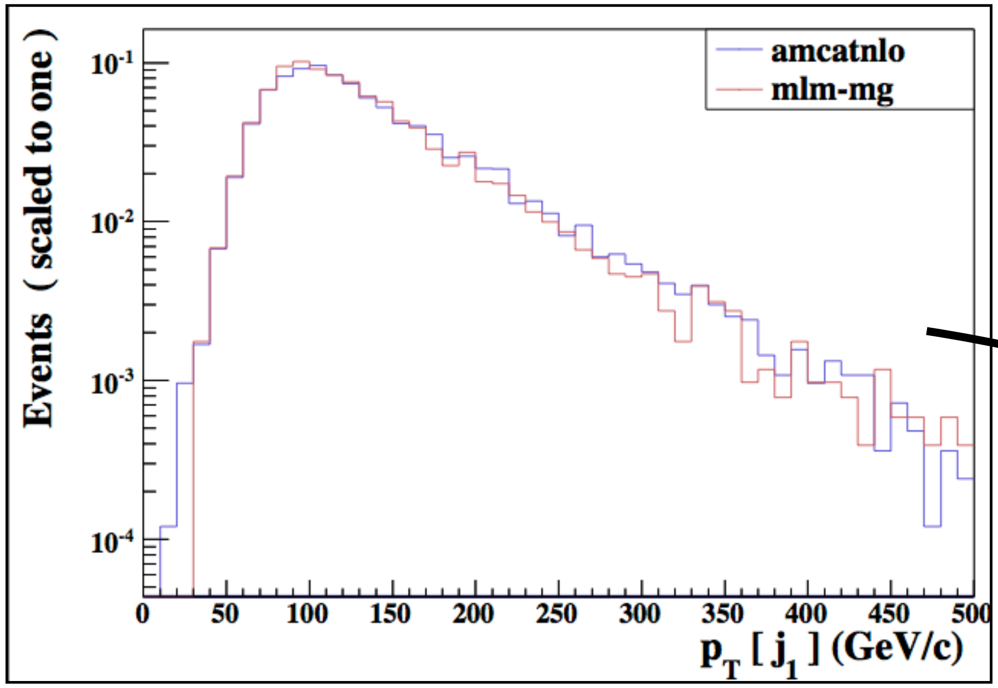
Detector level



MadAnalysis 5 and precision

[Conte, BenjFuks (in prep)]

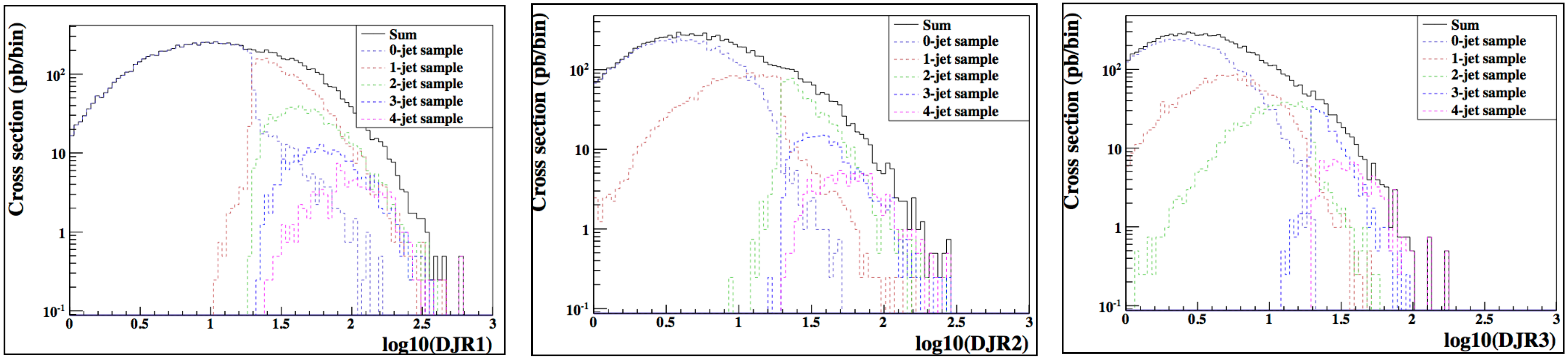
✦ Handling events with negative weights (as generated by aMC@NLO)



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

✦Automatic check of the (leading order) merging procedure



Summary - a last example (I)

[Agram, Andrea, Conte, BenjFuks, Gelé, Lansonneur (to appear on Tuesday)]

✦ Top anomalous couplings to gluons and Z-bosons

$$\mathcal{L} = \sum_{q=u,c} \Big[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q \, G^a_{\mu\nu} + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q \, Z_{\mu\nu} \Big] + \text{h.c.} \ .$$

✤ Few new physics parameters

✦ Implementation in FEYNRULES:

```
Lg :=  gs Sqrt[2] Sig[mu1,mu2,sp1,sp2] (ZctL ProjM[sp2,sp3] + ZctR ProjP[sp2,sp3]) T[aa,cc1,cc2] tbar[sp1,cc1].c[sp3,cc2] FS[G,mu1,mu2,aa] +
       gs Sqrt[2] Sig[mu1,mu2,sp1,sp2] (ZutL ProjM[sp2,sp3] + ZutR ProjP[sp2,sp3]) T[aa,cc1,cc2] tbar[sp1,cc1].u[sp3,cc2] FS[G,mu1,mu2,aa];

LZ := gw/(Sqrt[2] cw) Sig[mu1,mu2,sp1,sp2] (KctL ProjM[sp2,sp3] + KctR ProjP[sp2,sp3]) tbar[sp1,cc1].c[sp3,cc1] FS[Z,mu1,mu2] +
      gw/(Sqrt[2] cw) Sig[mu1,mu2,sp1,sp2] (KutL ProjM[sp2,sp3] + KutR ProjP[sp2,sp3]) tbar[sp1,cc1].u[sp3,cc1] FS[Z,mu1,mu2];
```

✦ Generation of the UFO files

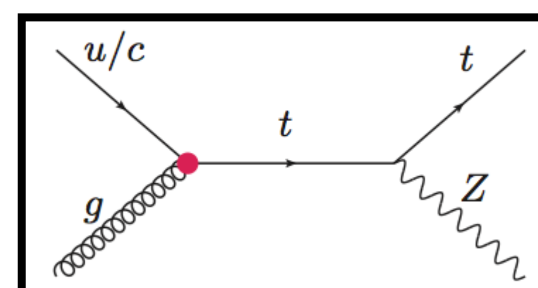
WriteUFO[LSM + Lg + Lz + HC[Lg+Lz]];

✦ Event generation with MADGRAPH 5 (signal and backgrounds; normalization to (N)NLO)

✦ Parton showering and hadronization with PYTHIA and MLM-merging

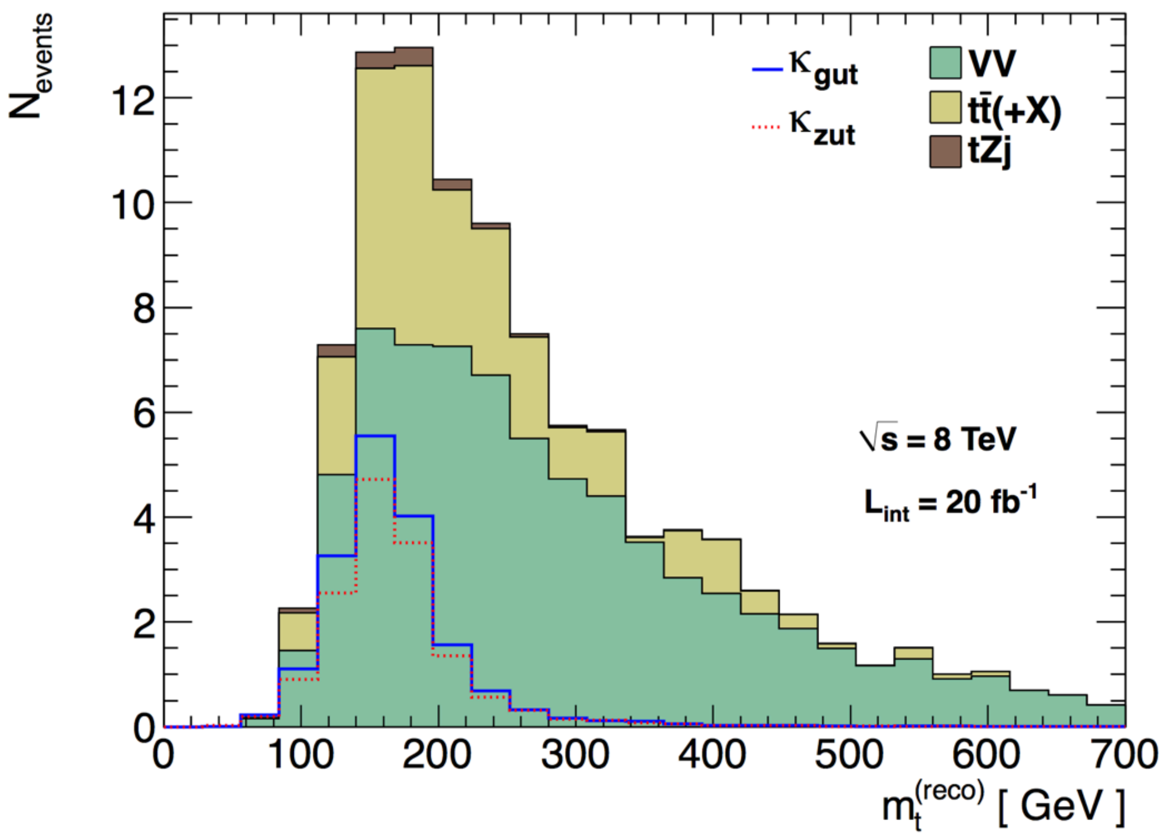
✦ Fast detector simulation with DELPHES (CMS card)

✦ Phenomenological analysis of trileptonic tZ events with MADANALYSIS 5

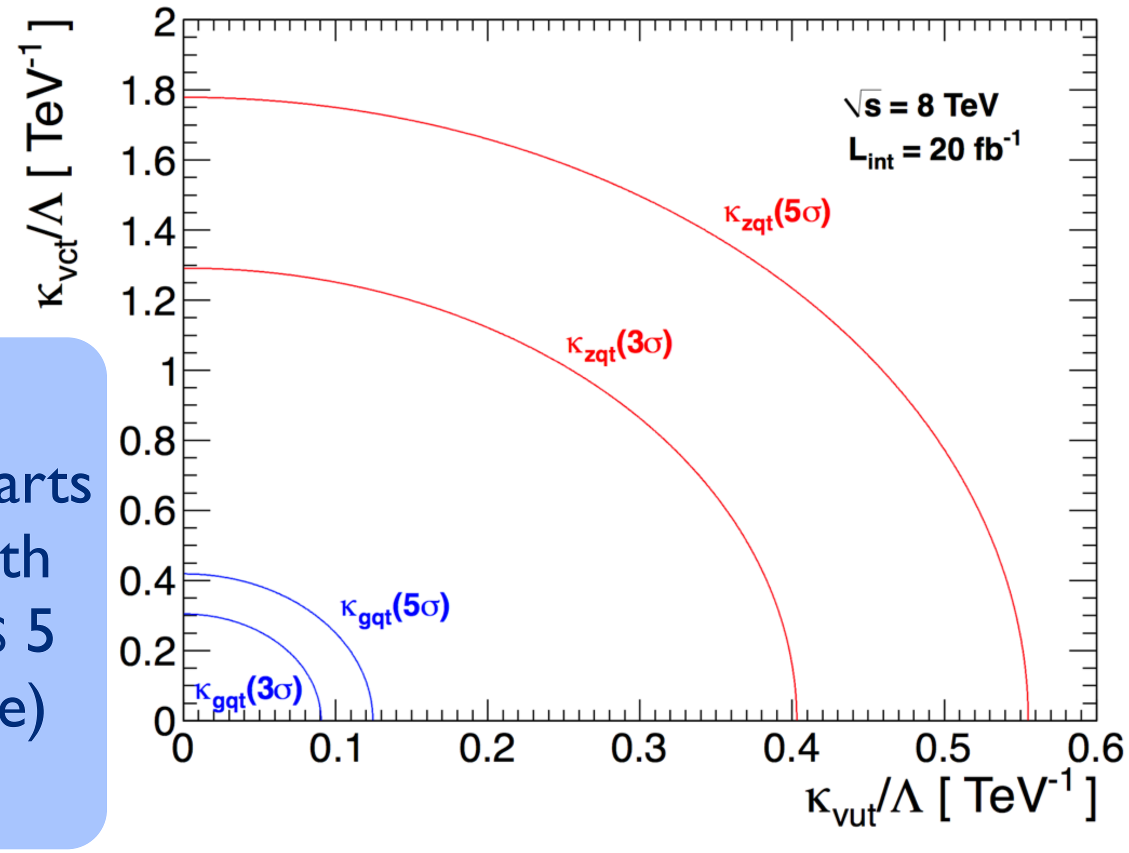


Summary - a last example (2)

[Agram, Andrea, Conte, BenjFuks, Gelé, Lansonneur (to appear on Tuesday)]



Figures and charts generated with MadAnalysis 5 (expert mode)



Selection	$\kappa_{gut} \neq 0$	$\kappa_{zut} \neq 0$	Background
Trilepton topology	41.3±0.3	36.6±0.3	3648.3±143.1
$m_{\ell_1\ell_2} \in [75, 105]$ GeV	38.1±0.3	34.0±0.3	3271.8±136.0
$\not{E}_T \geq 30$ GeV	31.8±0.2	26.9±0.3	1362.9±31.9
$m_T^W \geq 10$ GeV	29.6±0.2	25.4±0.2	1256.9±18.8
At least one jet	25.2±0.2	22.4±0.2	549.0±18.5
One single b-tagged jet	17.4±0.2	14.7±0.2	102.8±2.3
$m_t^{(reco)} \leq 250$ GeV	16.4±0.2	13.8±0.2	55.2±1.9

$$\mathcal{BR}(t \to gu) \leq 0.47\% \ (0.25\%) \ ,$$
$$\mathcal{BR}(t \to gc) \leq \ 5.1\% \ (2.8\%) \ ,$$
$$\mathcal{BR}(t \to Zu) \leq 0.39\% \ (0.20\%) \ ,$$
$$\mathcal{BR}(t \to Zc) \leq \ 3.8\% \ (2.1\%) \ .$$

The 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 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 😄