# Beyond the Standard Model phenomenology with MadAnalysis 5


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# Outline

1. **Introduction & setup for this lecture**
2. Overview of MADANALYSIS 5 and basic concepts
3. Analyzing events with MADANALYSIS 5
4. Summary

# Monte Carlo tools and discoveries at the LHC

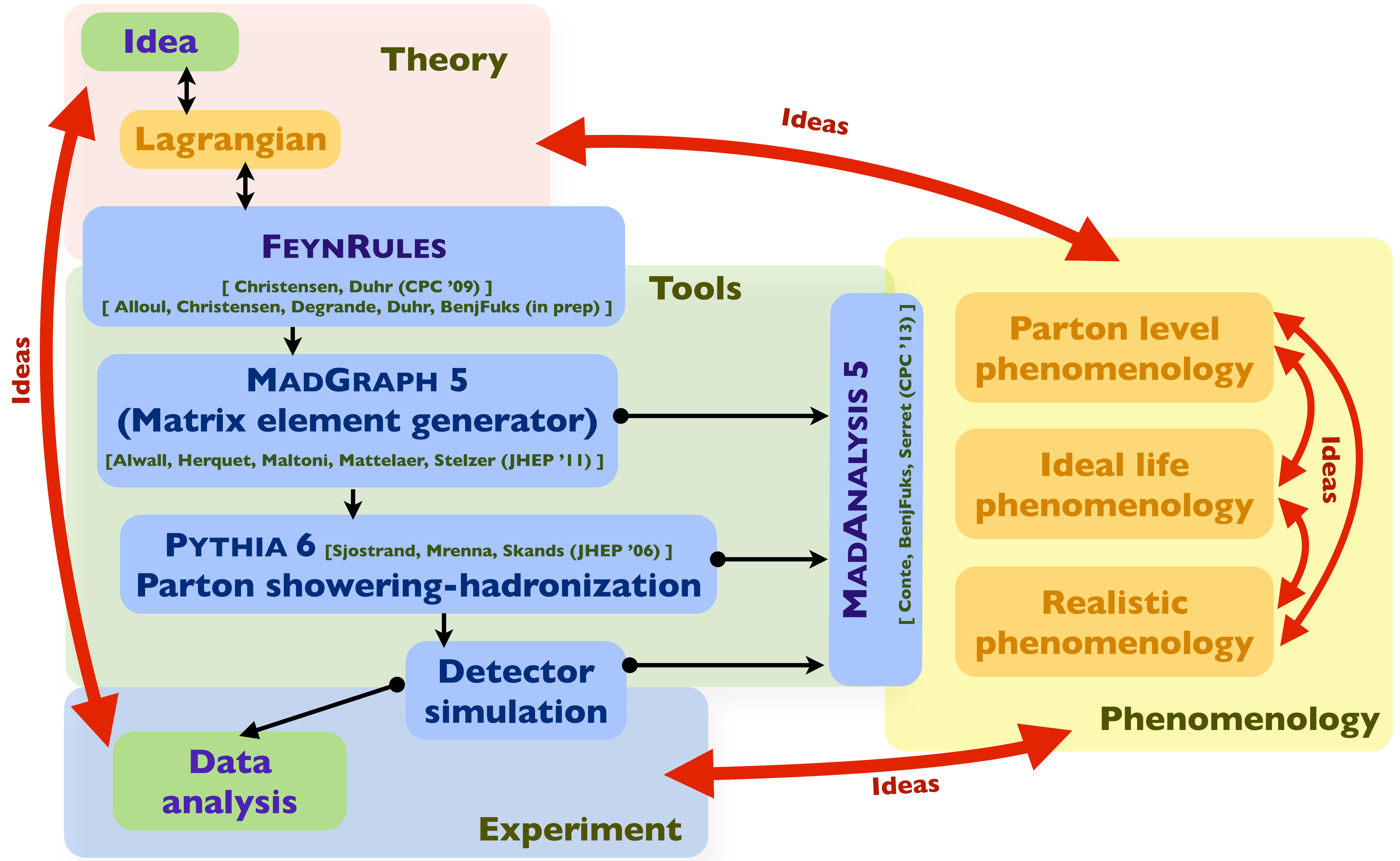
- Establishing an excess over the Standard Model backgrounds:
  - Difficult
  - Rely on Monte Carlo event generators (backgrounds, signals)
  - Possible use of data-driven methods (backgrounds)
- Confirmation of the excess:
  - Model building activities
  - Implementation of new models in the Monte Carlo 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!

➡ **How to easily analyze their output?**

# A framework for LHC analyses: a modern way

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



# The framework for this lecture

1. Implementation of the new physics model in FEYNRULES and generation of the UFO files

2. Event generation with MADGRAPH 5
   - ✤ Signal: dilepton plus jets plus missing energy

$$pp \to U\bar{U} \to (u\Phi_1)(\bar{u}\Phi_2) \to (u\Phi_1)(\bar{u}e^+E^-) \to (u\Phi_1)(\bar{u}e^+e^-\Phi_1)$$

   - ✤ Backgrounds: precision in normalization: (N)NLO inclusive results for the total rates

3. Parton showering and hadronization with PYTHIA 6
   - ✤ Precision in the shapes: MLM-merging technique **[Mangano, Moretti, Piccinini, Treccani (JHEP '07) ]**

4. No detector simulation here
   - ✔ Steps 1 - 4 are not covered in this lecture (see other talks)

5. Event analysis with MADANALYSIS 5
   - ✤ Reconstructed-level analyses (gathering the tons of hadrons after PYTHIA into jets)

# The event samples analyzed in this lecture

- Setup for this tutorial
  - LHC collider at a center-of-mass energy of 8 TeV, 20 $fb^{-1}$
  - No lepton cut (pseudorapidity, transverse momentum, *etc.*)
  - Jet cuts: $p_T$ > 20 GeV, $\Delta R_{jj}$ > 0.4, no pseudorapidity cut

- Standard Model background for a dilepton + missing energy + jets signature
  - top-antitop + jets: two leptonic decays, $t\bar{t} \to (b\ell^+\nu_\ell)(\bar{b}\ell'^-\bar{\nu}_{\ell'})$
  - WW + jets: two leptonic decays, $W^+W^- \to (\ell^+\nu_\ell)(\ell'^-\bar{\nu}_{\ell'})$
  - single top (tW) + jets: two leptonic decays, $tW \to (b\ell^+\nu_\ell)(\ell'^-\bar{\nu}_{\ell'})$
  - ZZ + jets: one leptonic and one invisible decay, $ZZ \to (\nu_\ell\bar{\nu}_\ell)(\ell'^+\ell'^-)$
  - More: instrumental effects such as lepton mis-reconstruction, *etc.*
    
    ⇒ not considered here.

- Cross section for the Standard Model background
  - NNLO: top-antitop pairs (≈ 27 pb)
  - NLO + leading NNLO contributions: single top (≈2.5 pb)
  - NLO: diboson (≈5.8 pb for WW and ≈0.3 pb for ZZ)

- Multiparton matrix element merging: up to two jets

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# MADANALYSIS 5 in a nutshell

- 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

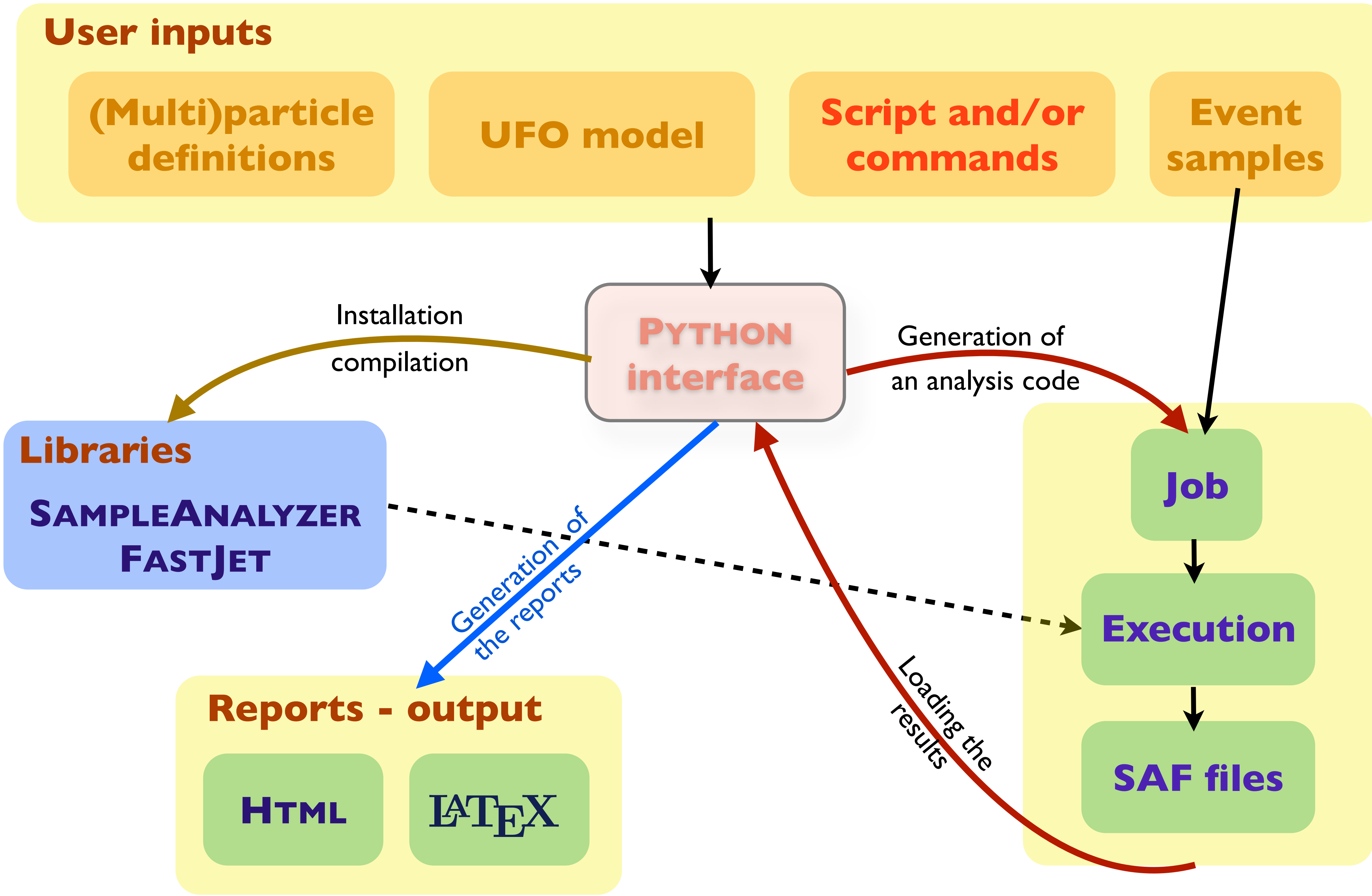
> ➡ Professional analyses in an easy way
> ➡ No limit on the analysis complexity

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

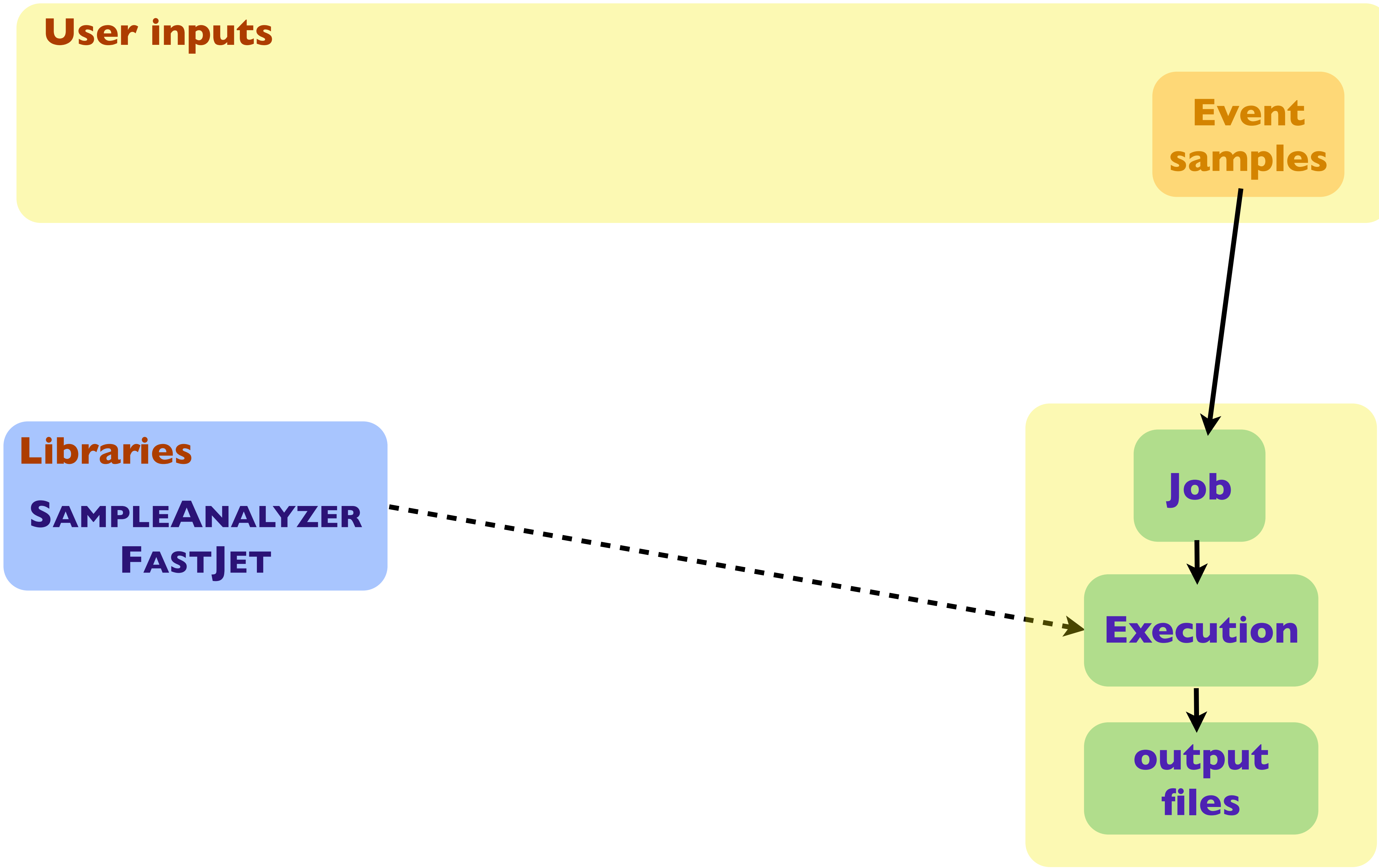
- Normal mode
  - Intuitive commands typed in the PYTHON interface
  - Analysis performed behind the scenes (black box)
  - Human readable output: HTML and LaTeX

- Expert mode (not covered in this lecture)
  - C++/ROOT programming within the SAMPLEANALYZER framework

# MADANALYSIS 5: normal running mode



# MADANALYSIS 5: expert running mode



# Getting started...

- Installing the program
  - Download: https://launchpad.net/madanalysis5
  - Unpacking the tar-ball: tar xvf MadAnalysis5_v1.1.8_patch1.tar.gz
  - This is it: ./bin/ma5

- Requirements (checked when MADANALYSIS 5 is started)
  - PYTHON 2.6 or more recent (but not the 3.X series)
  - The GNU GCC compiler 4.3.0 or more recent
  - ROOT 5.27 or more recent
    - With the PYTHON libraries (./configure --enable-python)
  - The NUMPY PYTHON library

- Optional addons
  - ZLIB headers and libraries (reading compressed event files)
  - LATEX, PDFLATEX, DVIPDF (compiling LaTeX reports)
  - FASTJET 3.3.0 or more recent (necessary for this lecture, to reconstruct jets)
  - DELPHES 3 or more recent (compatibility with the DELPHES output format)
  - In the future: PYTHIA-8, HERWIG-6, HERWIG++

# Getting started: the welcome screen

```
[LeMouth@Benjamins-MacBook-Pro ~/Work/tools/madanalysis/bzr/madanalysis5$] ./bin/ma5

*************************************************************
*                                                           *
*        W E L C O M E  to  M A D A N A L Y S I S  5        *
*                         ______  ______                    *
*                 /'\_/`\/\  __ \/\  ___\                   *
*                /\      \ \ \_\ \ \ \__/                   *
*                \ \ \__\ \ \  __ \ \___``\                 *
*                 \ \ \_/\ \ \ \/\ \/\ \_\ \                *
*                  \ \_\\ \_\ \_\ \_\ \____/                *
*                   \/_/ \/_/\/_/\/_/\/___/                 *
*                                                           *
*   MA5 release : 1.1.8                        2013/08/06   *
*                                                           *
*         Comput. Phys. Commun. 184 (2013) 222-256          *
*                                                           *
*   The MadAnalysis Development Team - Please visit us at   *
*            https://launchpad.net/madanalysis5             *
*                                                           *
*                 Type 'help' for in-line help.             *
*                                                           *
*************************************************************
```

# Getting started: checking the user system

The requirements

```
Checking mandatory packages:
    - python                   [OK]
    - python library: numpy    [OK]
    - g++                      [OK]
    - Root                     [OK]
    - PyRoot libraries         [OK]
Checking optional packages:
    - gfortran                 [OK]
    - zlib library             [OK]
    - delphes library          [DISABLED]
 ** WARNING: Library called 'delphes' not found. Delphes ROOT format will be disabled.
 ** WARNING: To enable this format, please type 'install delphes'.
    - FastJet                  [OK]
    - pdflatex                 [OK]
    - latex                    [OK]
    - dvipdf                   [OK]
    - MCatNLO-utilities        [DISABLED]
 ** WARNING: MCatNLO-utilities not found. Showering aMCatNLO events deactivated.
 ** WARNING: To install the utilities, please type 'install MCatNLO-utilities'.
```

Automated installation sometimes available

The optional packages

# Getting started: SAMPLEANALYZER (the core)

**[ if necessary ]**

Installation of SAMPLEANALYZER

```
Checking the MadAnalysis library:
  => First use of MadAnalysis (or the library is missing).
   Creating a 'Makefile'...
   Compiling the MadAnalysis library...
     => How many cores for the compiling? default = max = 8
     Answer:
     Number of cores used for the compilation = 8
   Linking the MadAnalysis library...
   Checking the MadAnalysis library...
*************************************************************
MadGraph 5 NOT found:
  => Particle labels from input/particles_name_default.txt
  => 86 particles successfully exported.
  => Multiparticle labels from madanalysis/input/multiparticles_default.txt
  => Creation of the label 'invisible' (-> missing energy).
  => Creation of the label 'hadronic' (-> jet energy).
  => 8 multiparticles successfully exported.
```

Looking for MADGRAPH 5, creating default particle labels, *etc.* (see next slides)

Important for variables such as $H_T$, MET, *etc.*

# Basic concepts (I)

## Looking for help...

✤ In-line help from the command-line interface

✤ Auto-completion using the tab key

```
ma5>help

Documented commands (type help <topic>):
========================================
EOF               display_multiparticles  history  plot    reset     shell
define            display_particles       import   quit    resubmit  submit
display           exit                    install  reject  select    swap
display_datasets  help                    open     remove  set

ma5>
```

## Datasets

✤ Events samples are defined through a label.

✤ Supported file formats: LHE, STDHEP, HEPMC, LHCO, ROOT

✤ Several samples can be grouped (e.g., to increase statistics)

✤ Wildcards can be used

```
ma5>import ttbar* as top-antitop
   -> Storing the file 'ttbar.hep.gz' in the dataset 'top-antitop'.
   -> Storing the file 'ttbar2.hep.gz' in the dataset 'top-antitop'.
ma5>import Wjets.lhe.gz as Wboson
   -> Storing the file 'Wjets.lhe.gz' in the dataset 'Wboson'.
ma5>import VV.hep as diboson
   -> Storing the file 'VV.hep' in the dataset 'diboson'.
```

# Basic concepts (2)

## Particles and multiparticles

- Particles are defined through their PDG code.
- One can associate labels with particles (makes our lives easier)
- One can define multiparticles
- Default: SM + MSSM (as in MADGRAPH 5) + invisible + hadronic
- Can be defined from a UFO model

```
ma5>define TheMuon = 13
ma5>define TheAntiMuon = -13
ma5>define AllMuon = TheMuon TheAntiMuon
ma5>display l+
   The multiparticle 'l+' is defined by the PDG-ids -13 -11.
ma5>display e+
   The particle 'e+' is defined by the PDG-id -11.
ma5>display invisible
   The multiparticle 'invisible' is defined by the PDG-ids -16 -14 -12 12 14 16 1000022.
ma5>remove TheMuon
ma5>display TheMuon
 ** ERROR: no object called 'TheMuon' found.
```

# Basic concepts (3)

## Histograms - the command *plot*

- ✤ Typing plot implies the creation of an histogram (check the *display* command once created)
- ✤ Global observables: related to the full event (MET, $H_T$, *etc.)*
- ✤ Properties of a particle species (the $p_T$ of the jets, *etc*.)
- ✤ Particle ordering can be used
- ✤ Particles can be combined
- ✤ Log scales can be employed
- ✤ Different ways to normalize the histogram
- ✤ Virtual particle properties can be studied

```
ma5>plot MET [
ETAordering    PTordering    PZordering    allstate      interstate    normalize2one
ETordering     PXordering    Pordering     finalstate    logX          stack
Eordering      PYordering    ]             initialstate  logY          superimpose
ma5>plot MET [ logY ]
ma5>plot N(mu)
ma5>plot PT( mu[1] )
ma5>plot ETA(t) [ interstate ]
ma5>plot M(t t~)
ma5>plot dPHI( mu[1] mu[2] ) [logX logY]
```

# Basic concepts (3)

## Selection cuts - the commands *reject/select*

- ✤ Events can be selected/rejected whether a condition is satisfied or not
- ✤ Particles can be selected/rejected from the analysis whether a condition is satisfied or not

```
ma5>reject MHT < 200
ma5>select N(j) > 3
ma5>reject (j) PT < 20
ma5>reject (j) DELTAR(mu) < 0.4
```

## Executing the analysis - the command *submit*

- ✤ Create a C++ code with the analysis
- ✤ Create all the histograms
- ✤ Apply all the cuts
- ✤ Generate the reports

```
ma5>submit
   Creating folder 'ANALYSIS_0'...
   Copying 'SampleAnalyzer' source files...
   Inserting your selection into 'SampleAnalyzer'...
   Writing the list of datasets...
   Writing the command line history...
   Creating Makefiles...
   Compiling 'SampleAnalyzer'...
   Linking 'SampleAnalyzer'...
   Running 'SampleAnalyzer' over dataset 'top-antitop'...
    ***************************************************
    * SampleAnalyzer for MadAnalysis 5 - Welcome.
    * Initializing all components
     - version: 1.1.8 (2013/08/06)
     - general: everything is default.
     - extracting the list of event samples...
      - analyzer 'MadAnalysis5job'
```

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# Recall: event samples

- Setup for this tutorial
  - LHC collider at a center-of-mass energy of 8 TeV, 20 $fb^{-1}$

- New physics signal
  - $pp \to U\bar{U} \to (u\Phi_1)(\bar{u}\Phi_2) \to (u\Phi_1)(\bar{u}e^+E^-) \to (u\Phi_1)(\bar{u}e^+e^-\Phi_1)$
  - Two lepton + jets + missing energy

- Standard Model background for a dilepton + missing energy + jets signature
  - top-antitop + jets: two leptonic decays, $t\bar{t} \to (b\ell^+\nu_\ell)(\bar{b}\ell'^-\bar{\nu}_{\ell'})$
  - WW + jets: two leptonic decays, $W^+W^- \to (\ell^+\nu_\ell)(\ell'^-\bar{\nu}_{\ell'})$
  - single top (tW) + jets: two leptonic decays, $tW \to (b\ell^+\nu_\ell)(\ell'^-\bar{\nu}_{\ell'})$
  - ZZ + jets: one leptonic and one invisible decay, $ZZ \to (\nu_\ell\bar{\nu}_\ell)(\ell'^+\ell'^-)$

- Cross section for the Standard Model background
  - NNLO: top-antitop pairs (≈ 27 pb)
  - NLO + leading NNLO contributions: single top (≈2.5 pb)
  - NLO: diboson (≈5.8 pb for WW and ≈0.3 pb for ZZ)
  - LO: signal (MadGraph result: ≈0.02 pb)

# Jet clustering (I)

- The output of PYTHIA is non-practical for an analysis
  - It contains tons of hadrons
  - We employ jets rather than each individual hadron
  - Jets have to be reconstructed
  - The event file is non-readable with human eyes (STDHEP)
  - The event file size is very large
- Jet reconstruction with FASTJET
  - Large selection of jet algorithms ($k_T$, anti-$k_T$, *etc.*)
  - FASTJET can be used within MADANALYSIS 5
  - If FASTJET is installed on the system, ready-to-be-used by MADANALYSIS 5; otherwise:

```
ma5>install fastjet
```

- Jet reconstruction with MADANALYSIS 5 and FASTJET
  - The output can be saved to a LHE or a LHCO file (*set main.outputfile* = ...)
  - Human-readable, smaller file size
  - Can be reemployed later
  - The total rate is set to zero (not present in the STDHEP file); set manually later

# Jet clustering (2)

✦ Jet reconstruction with MADANALYSIS 5 (and FASTJET) for the five considered samples

✤ The four background (top-antitop, WW, single top and ZZ) and the signal samples

✤ MADANALYSIS 5 must be run in the reconstructed mode: ./bin/ma5 -R

```
ma5>set main.clustering.algorithm =
antikt      cambridge    cdfjetclu    cdfmidpoint   genkt        gridjet      kt          none      siscone
ma5>set main.clustering.algorithm = antikt
ma5>set main.clus
main.clustering.algorithm               main.clustering.bjet_id.misid_cjet   main.clustering.radius
main.clustering.bjet_id.efficiency      main.clustering.bjet_id.misid_ljet   main.clustering.tau_id.efficiency
main.clustering.bjet_id.exclusive       main.clustering.exclusive_id         main.clustering.tau_id.misid_ljet
main.clustering.bjet_id.matching_dr     main.clustering.ptmin
ma5>set main.clustering.radius = 0.5
ma5>set main.clustering.bjet_id.efficiency = .6
ma5>set main.clustering.bjet_id.misid_cjet = .1
ma5>set main.clustering.bjet_id.misid_ljet = .01
ma5>import ttbar.hep.gz
   -> Storing the file 'ttbar.hep.gz' in the dataset 'defaultset'.
ma5>submit
```

Many clustering algorithms available

Many options (clustering parameters, b-tagging, tau-tagging, *etc.*)

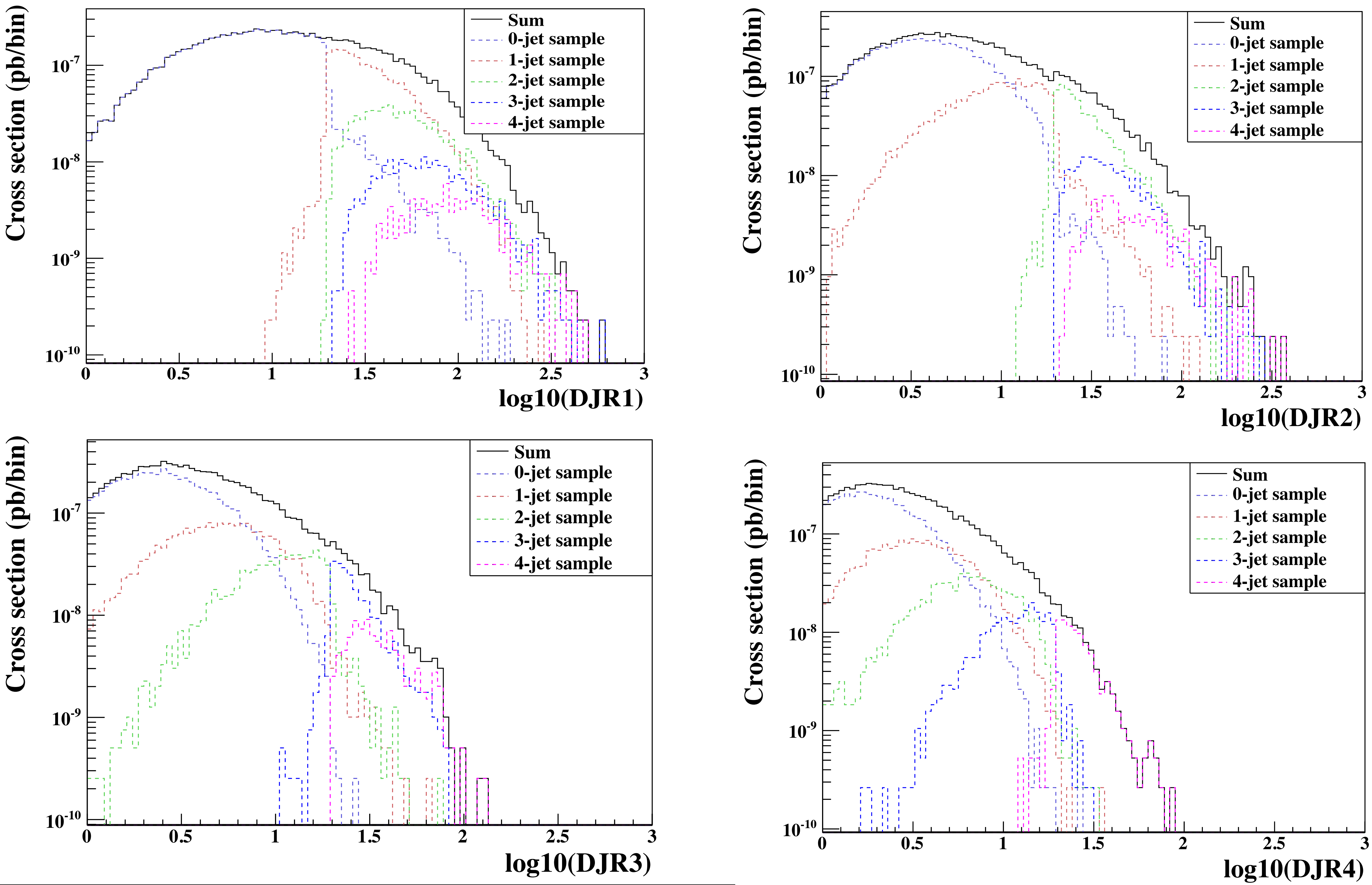
# Checking the merging procedure (I)

- ✦ Example with a Z plus jets sample
  - ✤ Parton-level: Z+ 0,1,2,3,4 jets
  - ✤ Parton-showering is then applied
  - ✤ MLM merging: removal of the double counting consistently
  - ✤ Check of that procedure: the differential jet rate (DJR) distributions
    - ➢ the scale for which one event goes from a N to a N+1 jet configuration
    - ➢ Extremely sensible to the merging procedure
    - ➢ Gives strong check of the choices for the parameters of the merging technique

- ✦ With MADANALYSIS 5
  - ✤ MADANALYSIS 5 must be run in hadron mode: ./bin/ma5 -H
  - ✤ The maximum value for N can be entered (default: 4)

```
ma5>set main.merging.check = true
ma5>set main.merging.njets = 4
ma5>import zjets.hep.gz
   -> Storing the file 'zjets.hep.gz' in the dataset 'defaultset'.
ma5>submit
```

# Checking the merging procedure (2)



# Importing and defining the samples

- Importing the reconstructed LHE samples, setting their properties
  - We define the type (signal or background) of each dataset
  - We assign the cross section associated with each dataset (necessary for a correct normalization)

```
ma5>import samples/signal.lhe as signal
   -> Storing the file 'signal.lhe' in the dataset 'signal'.
ma5>import samples/t_tw.lhe.gz as singletop
   -> Storing the file 't_tw.lhe.gz' in the dataset 'singletop'.
ma5>import samples/ttb2.lhe.gz as ttbar
   -> Storing the file 'ttb2.lhe.gz' in the dataset 'ttbar'.
ma5>import samples/ww2l2v.lhe.gz as ww
   -> Storing the file 'ww2l2v.lhe.gz' in the dataset 'ww'.
ma5>import samples/zz2l2v.lhe.gz as zz
   -> Storing the file 'zz2l2v.lhe.gz' in the dataset 'zz'.
ma5>set ttbar.xsection = 27
ma5>set ww.xsection = 5.8
ma5>set zz.xsection = 0.3
ma5>set singletop.xsection = 2.5
ma5>set signal.xsection = 0.021
ma5>set ww.type = background
ma5>set zz.type = background
ma5>set singletop.type = background
ma5>set ttbar.type = background
```

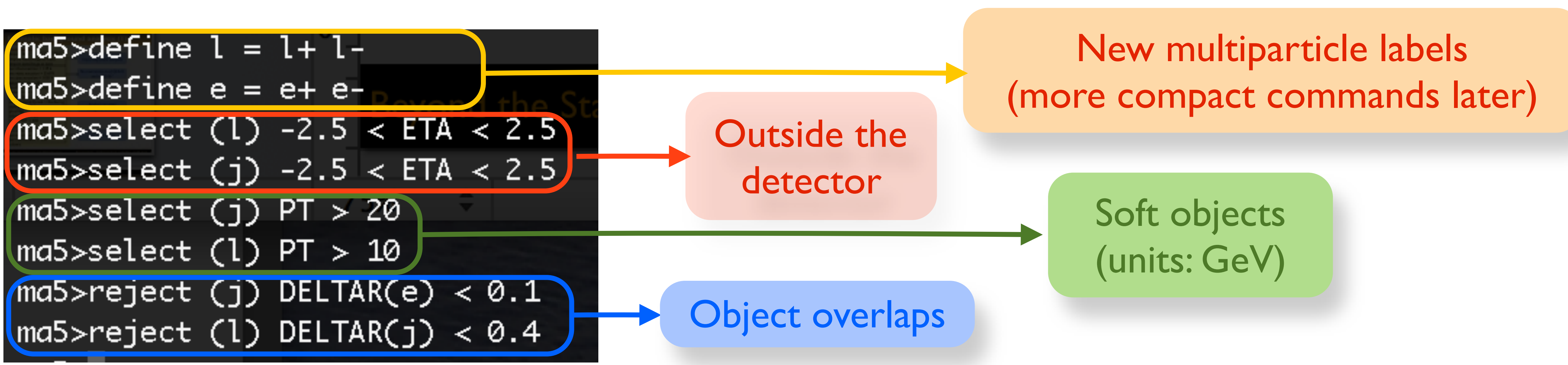
Importing the samples

Cross sections in pb

Signal and background definitions

# Getting closer to the detector...

- We have not simulated any detector response
  - Include reasonable selections getting us close to the experiment
  - Soft objects are not detected
    - Remove from each event any soft jet, lepton, *etc*.
  - Objects lying outside the detector are not detected
    - Remove from each event any jet, lepton, *etc*, whose pseudorapidity is too large.
  - Remove objet overlaps
    - Any electron too close to a jet is removed
    - Any jet too close to a charged lepton is the removed (we are interested in isolated leptons)



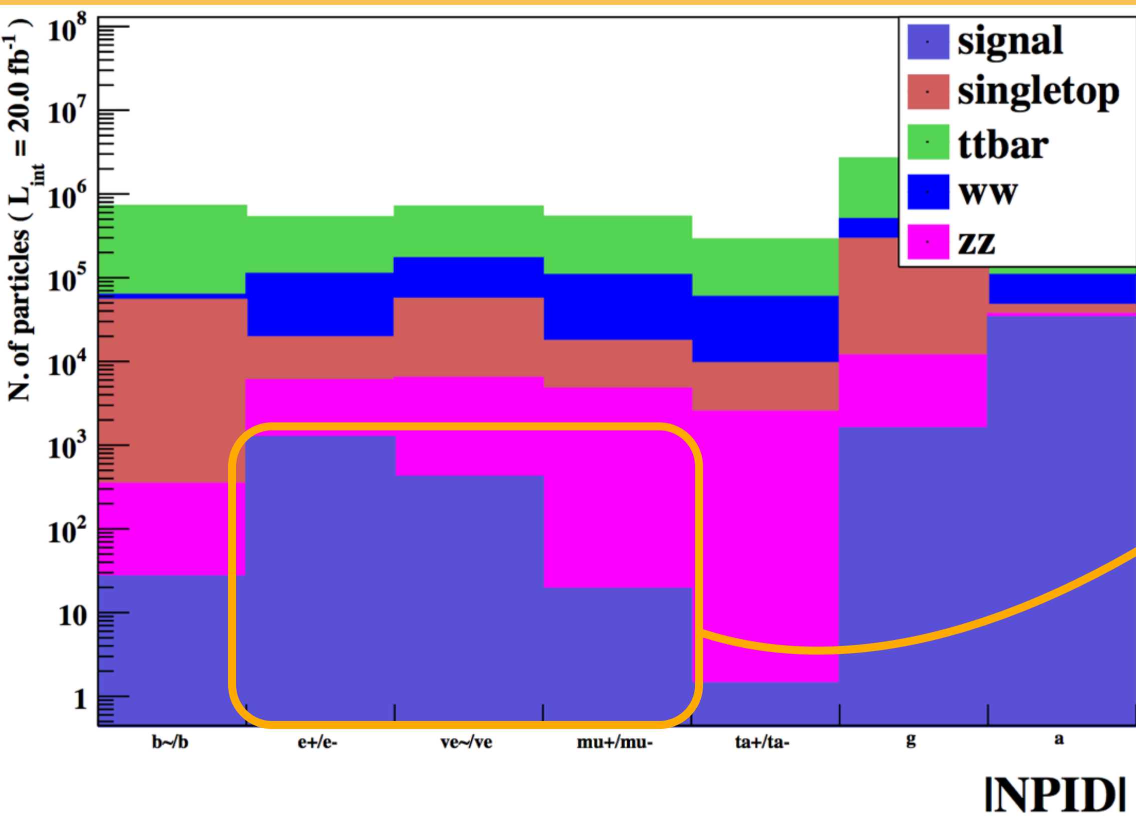
# Investigating some global event properties (I)

- Some observables are related to the full event (called global)
  - Missing and visible energy (*MET, TET*)
  - Missing and visible hadronic energy (*MHT, THT*)
  - The partonic center-of-mass energy (*SQRTS*)
  - The $\alpha_T$ variable (*ALPHAT*): depends on the missing energy, $H_T$ and jet configuration
  - The particle content of the event (*NPID, NAPID, N*)
- General setup for the histograms
  - The luminosity in $fb^{-1}$ (*set main.lumi* = ...)
  - How to superimpose the curves on a single histogram (*set main.stacking_method* = ...)

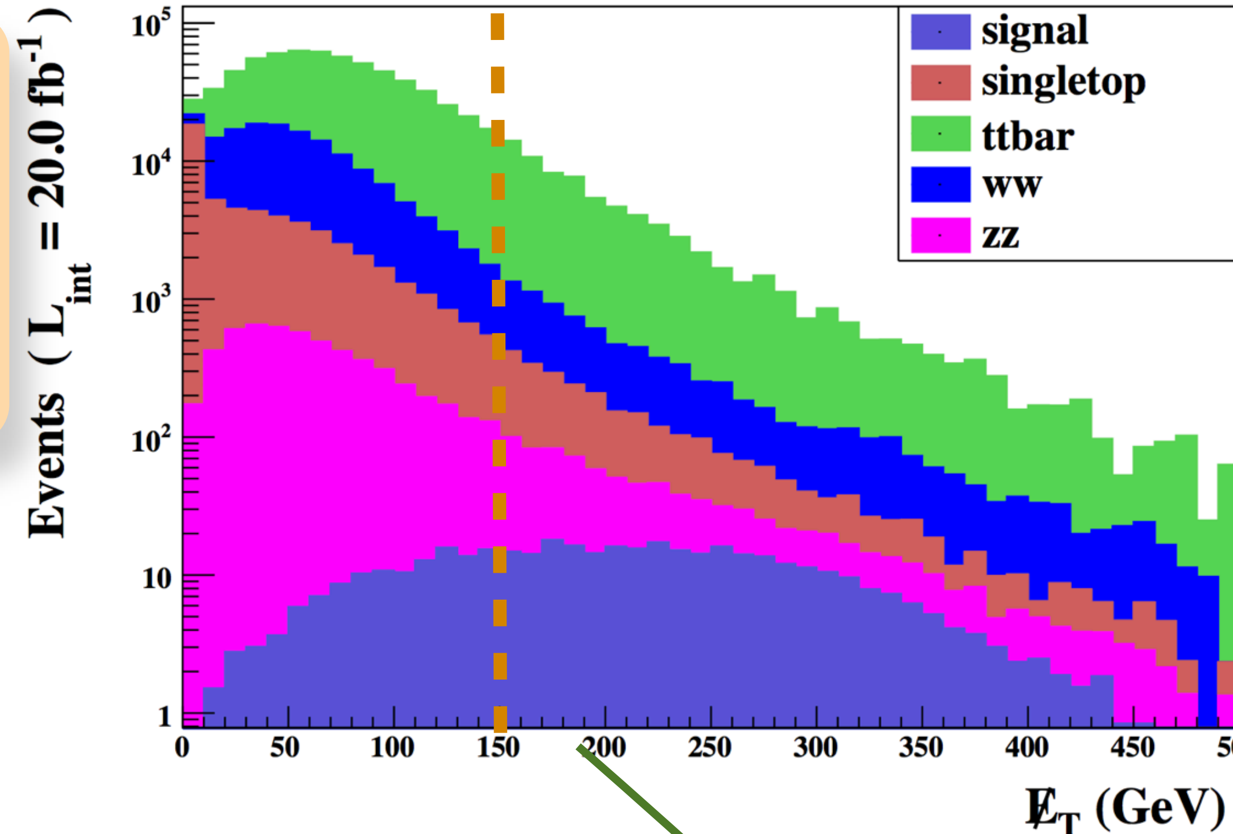
```
ma5>set main.stacking_method = stack
ma5>set main.lumi = 20
ma5>plot NAPID [logY]
ma5>plot MET 50 0 500 [logY]
ma5>plot THT 50 0 500 [logY]
```

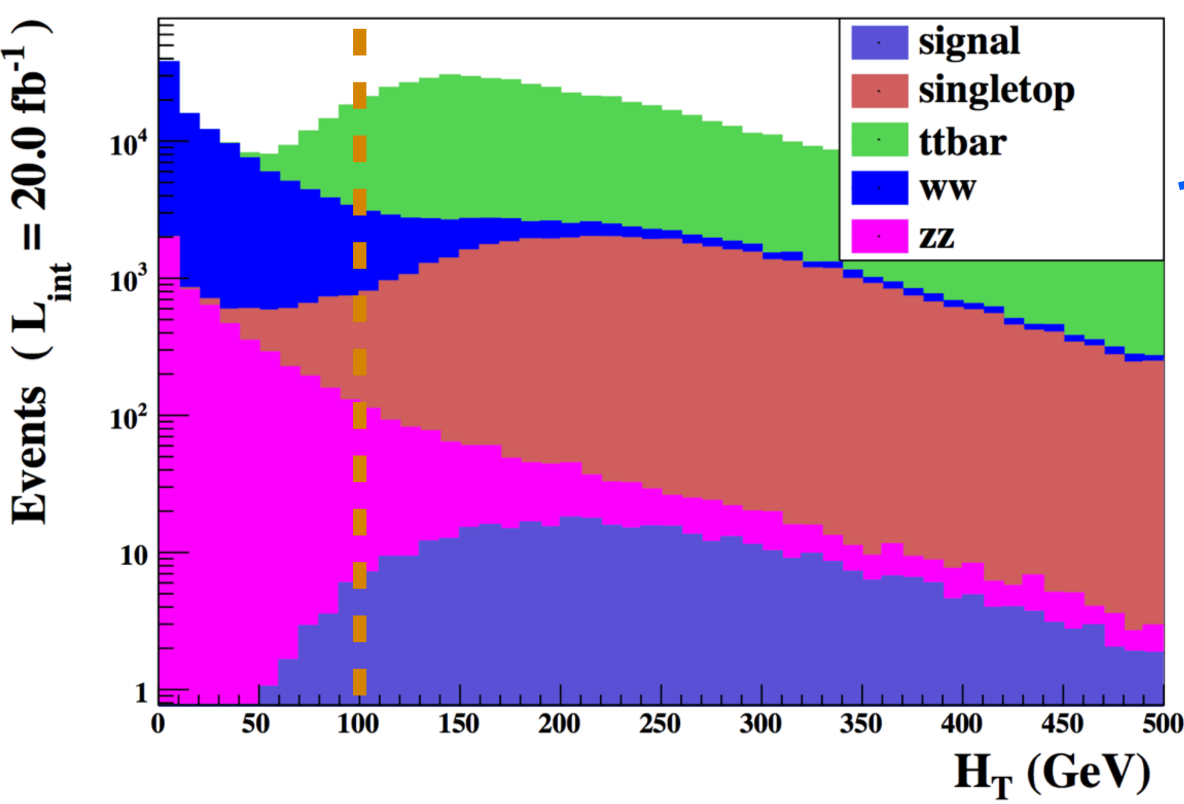
- Executing the analysis and browsing the results
  - The command *submit* (the progress can be followed on the screen)
  - The command *open* (open a webpage with the report containing all results)

# Investigating some global event properties (2)




More electrons than muons in the signal




VV: jets generated by parton showering, then softer

Different shapes for signal and background

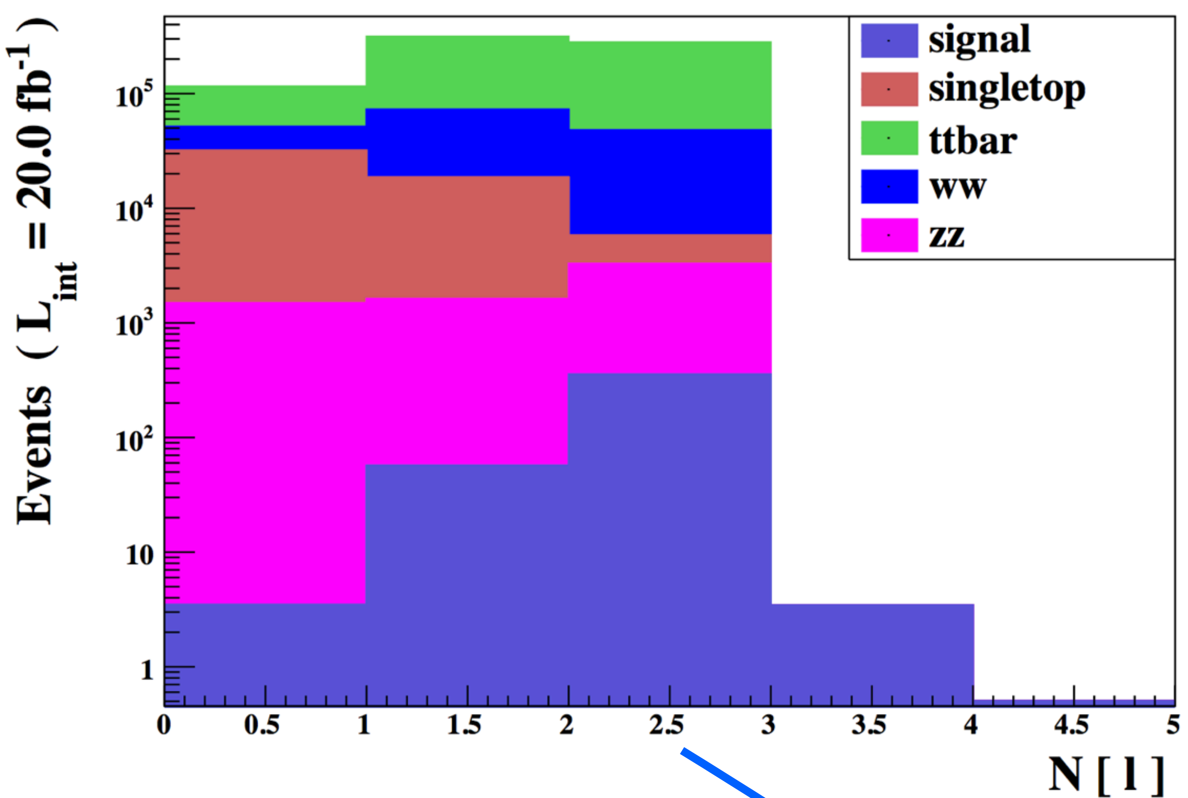
This suggest selection cuts to improve the signal vs background ratio (see in two slides)

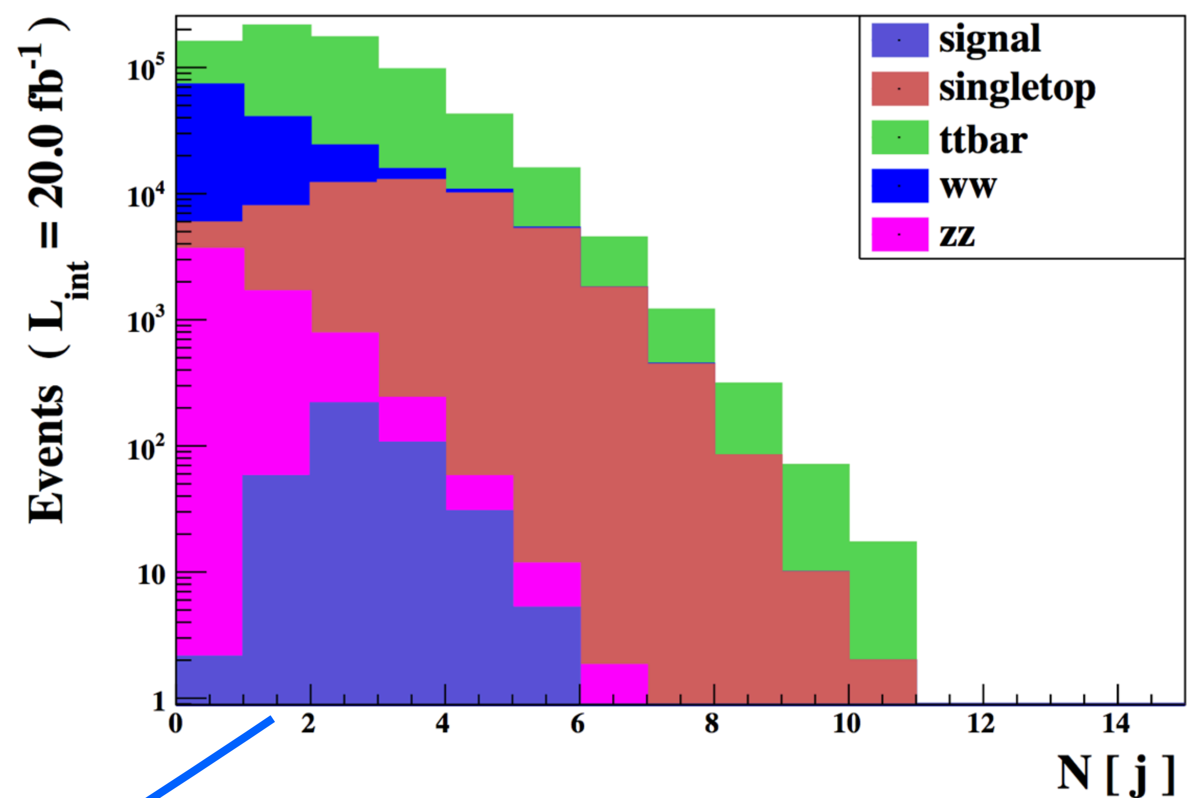
- ➢ on the missing energy (e.g.,150 GeV);
- ➢ on the $H_T$ (e.g., *100 GeV*)

# Investigating some global event properties (3)

- Let us study the number of jets and leptons
  - We have defined our backgrounds by assuming a dilepton + missing energy + jets topology
  - Can we add a selection on the number of jets to increase the sensitivity?

```
ma5>plot N(l) 5 0 5 [logY]
ma5>plot N(j) 15 0 15 [logY]
ma5>submit
```




Most of the signal events have two leptons and two jets

This suggests selection cuts to improve the signal vs background ratio
- exactly two leptons;
- two or three jets.

# Selection cuts

- ✦ Disclaimer: the cuts should be optimized
  - ✤ This is not the scope of this lecture
  - ✤ This consists of a complete physics project
  - ✤ Instead: we take rough cuts here based on the previous findings

- ✦ Four selections:
  - ✤ The missing energy must be greater than 150 GeV
  - ✤ The $H_T$ must be greater than 100 GeV
  - ✤ We want exactly two charged leptons
  - ✤ We want two or three light jets

```
ma5>reject MET < 150
ma5>select THT > 100
ma5>reject N(l) != 2
ma5>select 2 <= N(j) <= 3
```

- ✦ MADANALYSIS 5 provide the efficiencies for each sample and for each cut

**Cut: reject MET < 150.0**

| Dataset | Events kept: K | Rejected events: R | Efficiency: K / (K + R) | Cumul. efficiency: K / Initial |
|---|---|---|---|---|
| signal | 297.78 +/- 9.31 | 122.22 +/- 9.31 | 0.7090 +/- 0.0222 | 0.7090 +/- 0.0222 |
| singletop | 1801.5 +/- 41.7 | 48198.5 +/- 41.7 | 0.036030 +/- 0.000833 | 0.036030 +/- 0.000833 |
| ttbar | 67347 +/- 242 | 472652 +/- 242 | 0.12472 +/- 0.00045 | 0.12472 +/- 0.00045 |
| ww | 5804.9 +/- 74.3 | 110195.1 +/- 74.3 | 0.05004 +/- 0.00064 | 0.05004 +/- 0.00064 |
| zz | 598.5 +/- 23.2 | 5401.5 +/- 23.2 | 0.09974 +/- 0.00387 | 0.09974 +/- 0.00387 |

How to choose a cut?
- ✤ The signal efficiency must be large
- ✤ The background efficiencies must be small

# The signal over background ratio (I)

- Are those cuts sufficient?
  - Let us investigate the evolution of the signal over background ratio
  - We can indicate to MADANALYSIS 5 how to calculate it
    - In our example: $\frac{S}{\sqrt{S+B}}$

      S = number of signal events;
      B = number of background events

  - This number comes with an error
    - In our example: $\frac{\sqrt{(S+2B)^2(\Delta S)^2 + S^2(\Delta B)^2}}{(S+B)^{3/2}}$

      ΔS = error on the number of signal events;
      ΔB = error on the number of background events

- The user can enter any formula (using *S*, *B*, *ES*, *EB*)

```
ma5>set main.SBratio = "S/sqrt(S+B)"
Checking the formula ...
Formula corresponding to the uncertainty calculation has been found and set to the variable main.SBerror :
  1./pow(S+B,3./2.)*sqrt((S+2*B)**2*ES**2+S**2*EB**2)
ma5>
```

# The signal over background ratio (2)

**Cut-flow chart**

- How to compare signal (S) and background (B): S/sqrt ( S+B ) .
- Associated uncertainty: 1./pow(S+B,3./2.)*sqrt((S+2*B)**2*ES**2+S**2*EB**2).

| Cuts | Signal (S) | Background (B) | S vs B |
|---|---|---|---|
| Initial (no cut) | 420 | 712000 | 0.498 |
| Cut 1 | 4.20e+02 +/- 2.38e-07 | 712000 | 4.98e-01 +/- 5.65e-10 |
| Cut 2 | 4.20e+02 +/- 2.38e-07 | 712000 | 4.98e-01 +/- 5.65e-10 |
| Cut 3 | 4.20e+02 +/- 2.38e-07 | 712000 | 4.98e-01 +/- 5.65e-10 |
| Cut 4 | 4.20e+02 +/- 2.38e-07 | 712000 | 4.98e-01 +/- 5.65e-10 |
| Cut 5 | 4.20e+02 +/- 2.38e-07 | 712000 | 4.98e-01 +/- 5.65e-10 |
| Cut 6 | 4.20e+02 +/- 2.38e-07 | 712000 | 4.98e-01 +/- 5.65e-10 |
| Cut 7 | 297.78 +/- 9.31 | 75552 +/- 258 | 1.0812 +/- 0.0676 |
| Cut 8 | 288.16 +/- 9.51 | 69996 +/- 249 | 1.0869 +/- 0.0717 |
| Cut 9 | 240.2 +/- 10.1 | 32182 +/- 174 | 1.334 +/- 0.112 |
| Cut 10 | 187.7 +/- 10.2 | 15172 +/- 121 | 1.514 +/- 0.164 |

Not relevant (cuts on objects)

Our cuts improve the sensitivity, but not enough

We need to investigate other variables

# Investigating particle properties (I)

- Many kinematical properties of a given particle can be studied
  - *BETA,E, ET, ETA, GAMMA, M, MT, P, PHI, PT, PX, PY, PZ, R,THETA,Y*
  - Each of these functions take a single argument (a particle)
- The particles are ordered
  - Use squared brackets to select the right one
  - Several ordering variables are available (*PT, E, PX, etc.*)

```
ma5>plot PT(l[1]) 50 0 500 [logY]
ma5>plot MT(j[1]) 50 0 500 [logY]
```

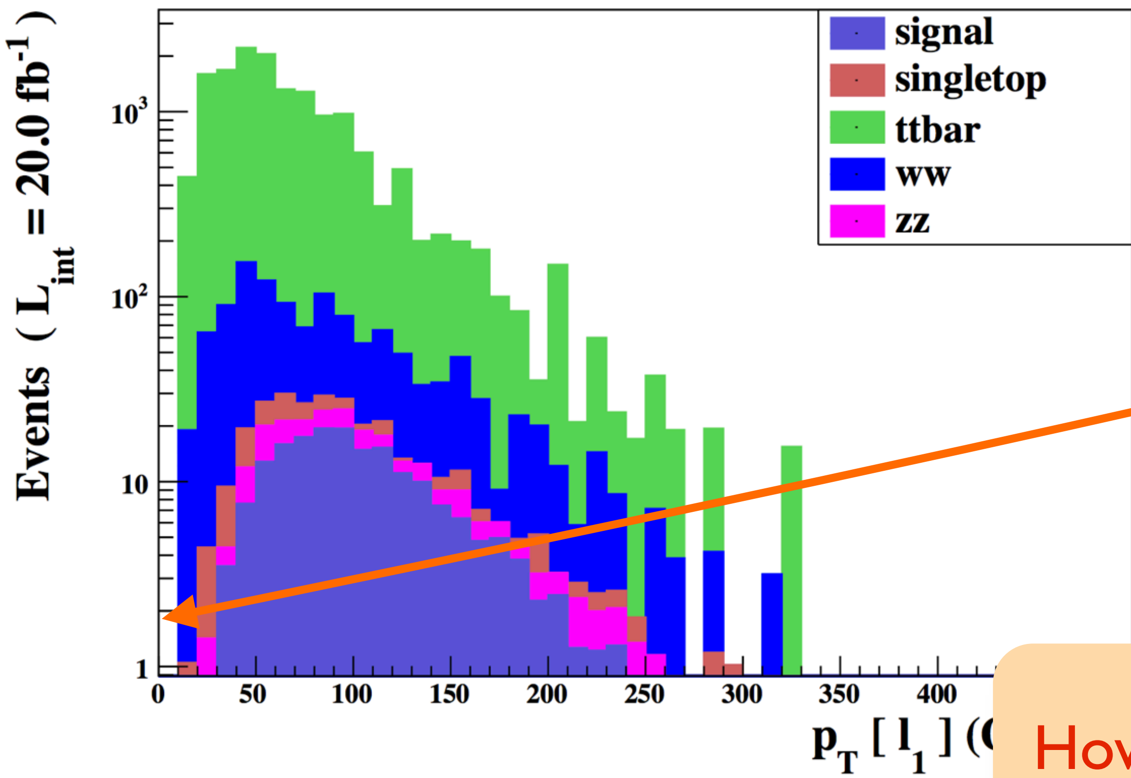
- Combining particles
  - Replace the argument by several particles
  - Their four-momenta are summed and the relevant observable is then computed
  - Vectorial and scalar sums/differences as well as ratios are available (*s, v, ds, dv, r* prefixes)

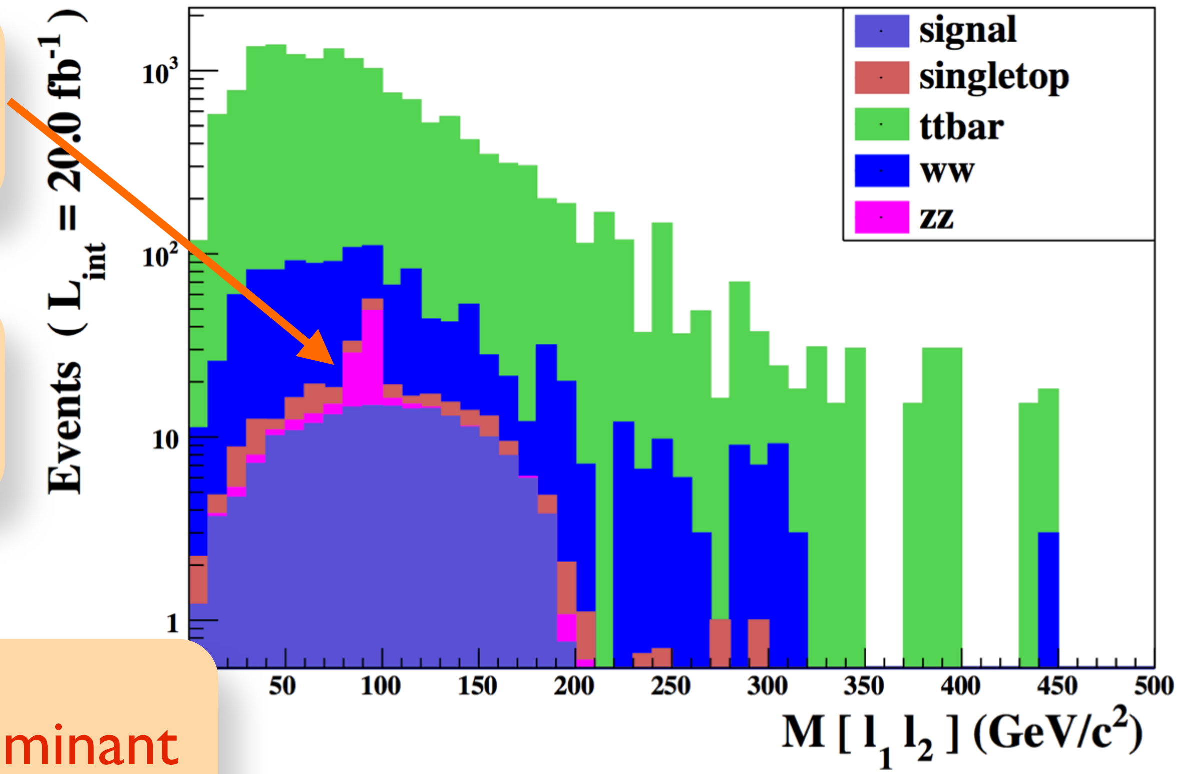
```
ma5>plot M(l[1] l[2]) 50 0 500 [logY]
ma5>plot dPHI(l[1] l[2]) 15 0 6.28 [logY]
```

- Two special functions
  - *DELTAR*: take two arguments
  - *MT_MET*: compute the transverse mass obtained when combining one particle with the missing momentum

```
ma5>plot DELTAR(l[1],l[2]) 15 0[redacted]5 [logY]
ma5>plot MT_MET(l[1]) 50 0 500 [logY]
ma5>plot MT_MET(j[2]) 50 0 500 [logY]
```

# Investigating particle properties (2)



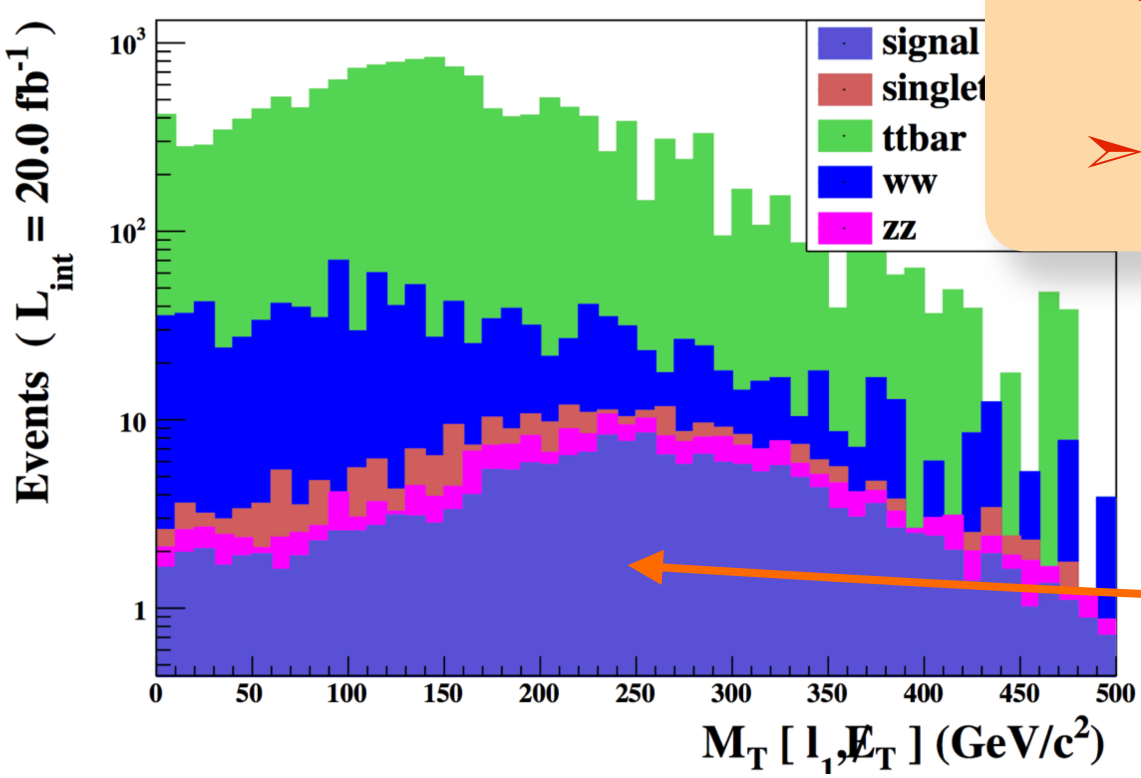



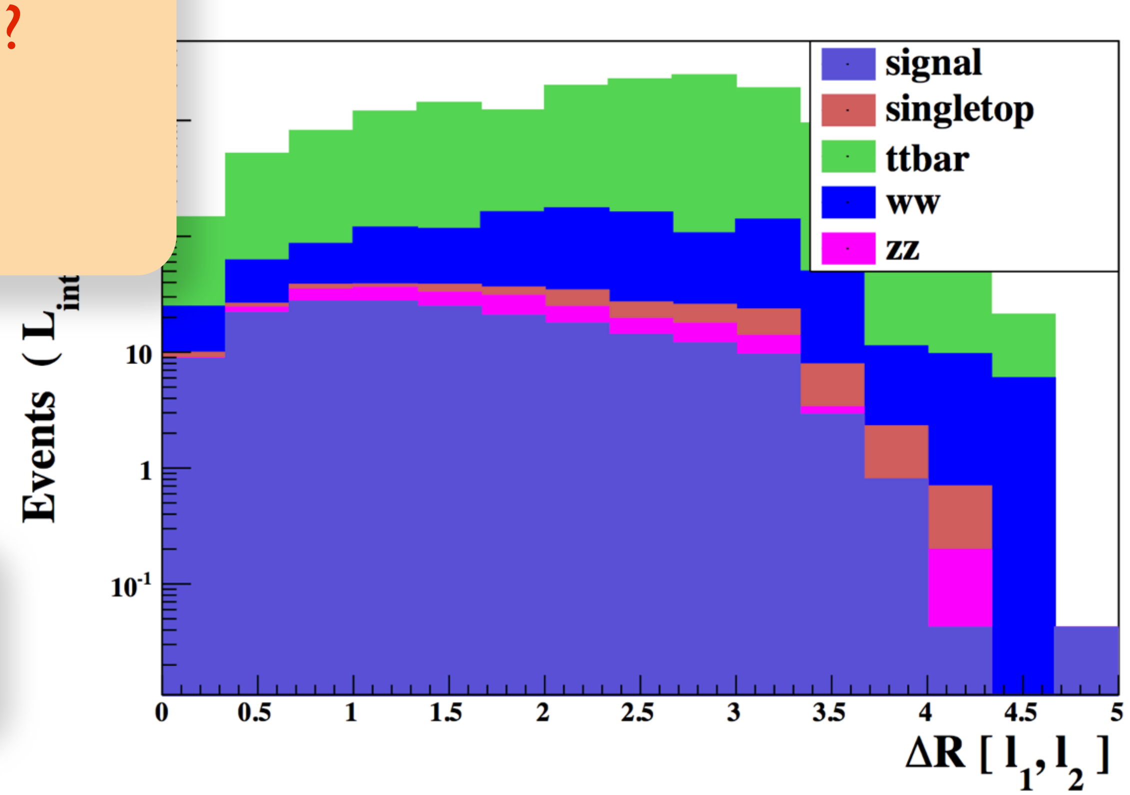

Bonus: the Z-peak

The first bin is empty

How to kill the dominant top background?

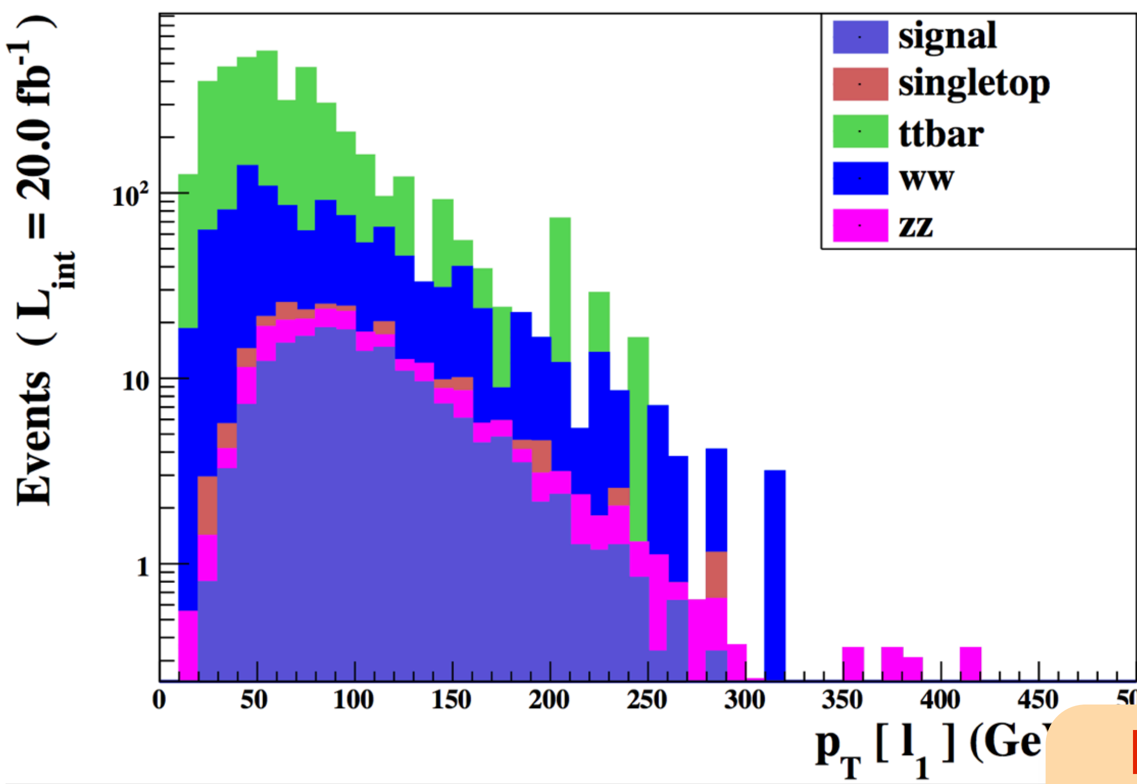
➢ a b-veto

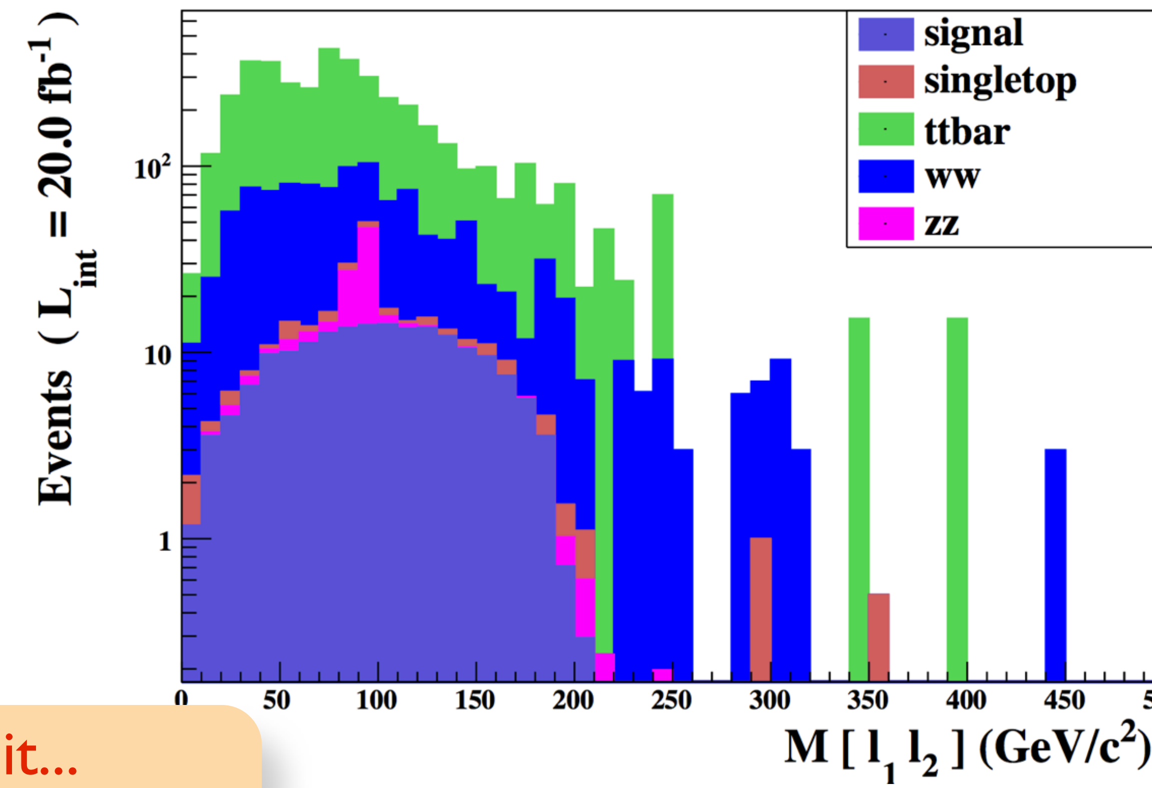


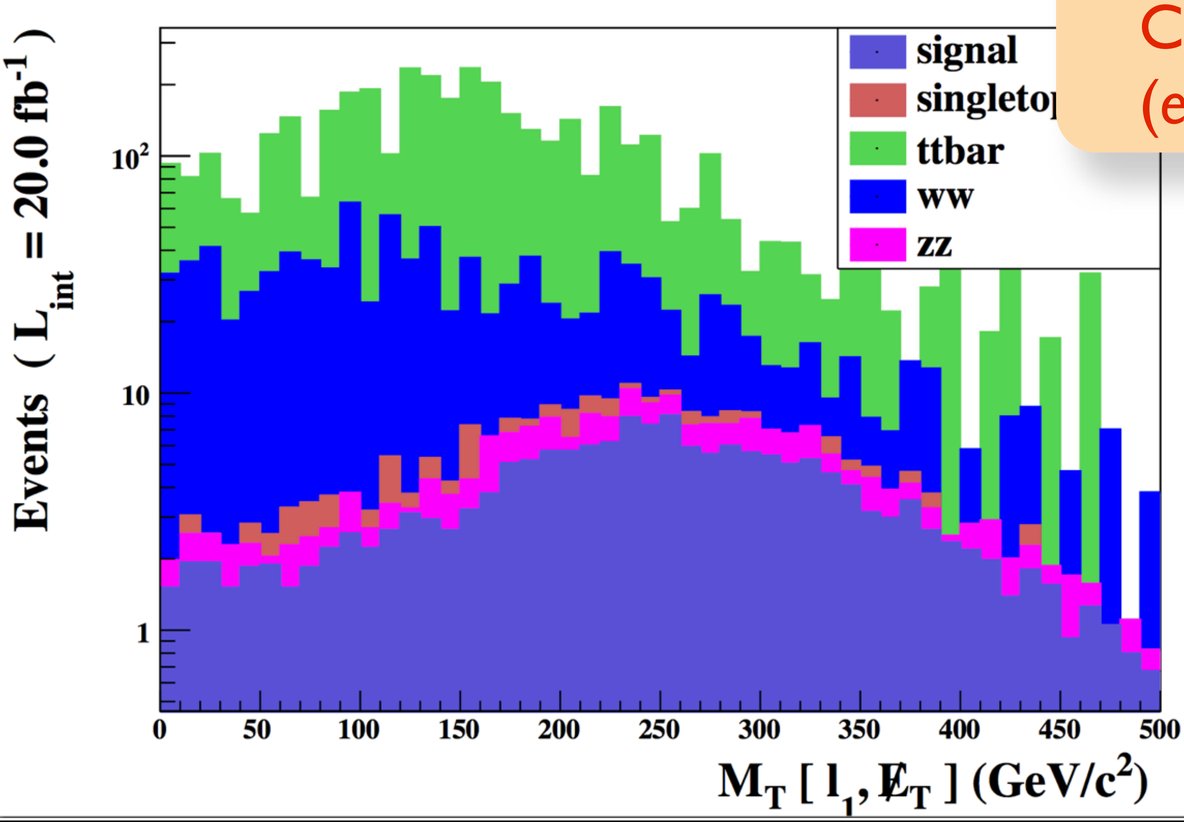

Idea for a cut?

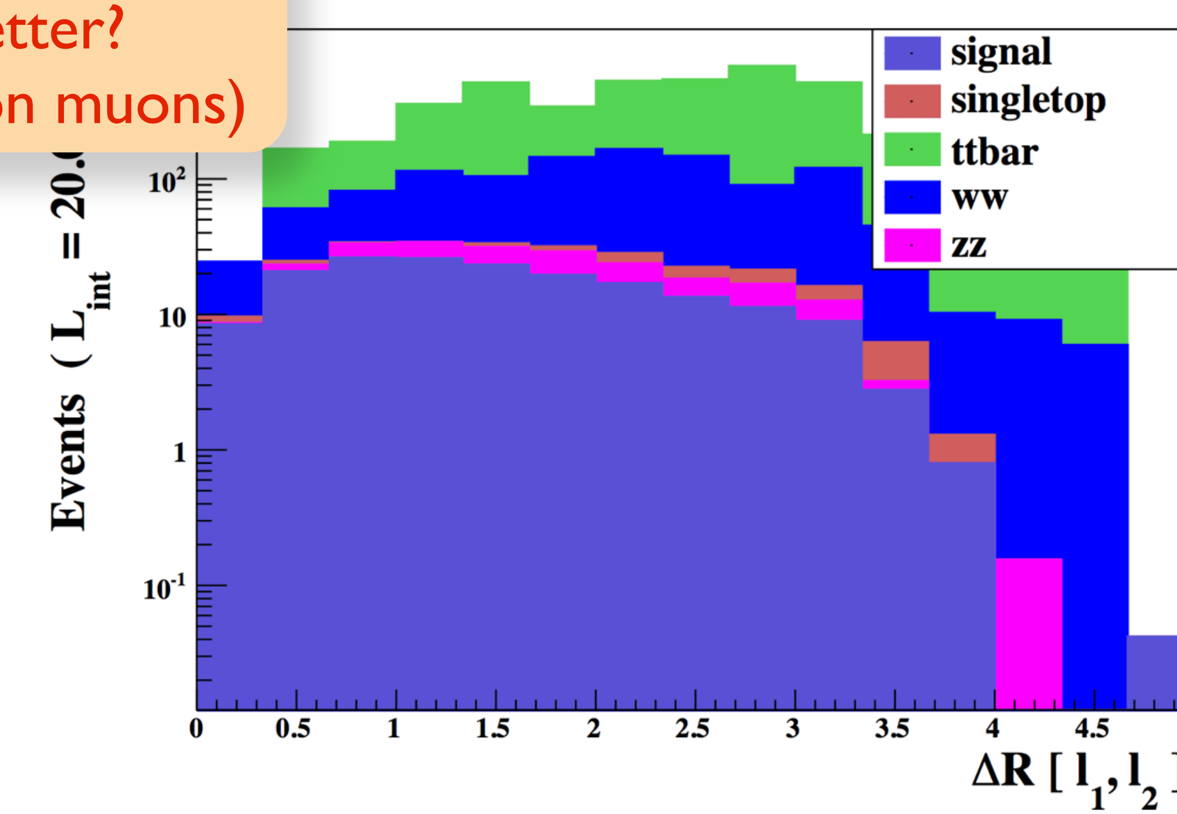
# Investigating particle properties (3)




It improves a bit...
Can we do better?
(e.g., cutting on muons)



# Outline

1. Introduction & setup for this lecture
2. Overview of MADANALYSIS 5 and basic concepts
3. Analyzing events with MADANALYSIS 5
4. **Summary**

# Summary

✦ The quest for new physics at the LHC has started

✤ Relies on Monte Carlo event generators (such as MADGRAPH 5) for background and signal modeling (and also on data for the background)

✤ Satellite tools have been intensively developed (FEYNRULES, MADANALYSIS 5, ...)

✦ MADANALYSIS 5:

✤ A unique framework for collider phenomenology (parton-, hadron-, reco-levels)

✤ User-friendly by means of its PYTHON interface

✤ Flexible thanks to its C++ kernel

✤ Allows to perform professional phenomenological analyses in an easy way

Please try the code, you will love it! :)
https://launchpad.net/madanalysis5