Introduction to the Combine Tool

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Overview of Combine

- Combine is a RooStats based command line tool which executes different statistical methods (compute limits/significance, make fits, etc.)
- Internally, there are two main components
  - ➔ text2workspace: a python module which converts a textual datacard into a RooStats model ("workspace")
    - Datacards can also be used to load user created workspaces
  - ➔ C++ code which is responsible for the statistical methods
- Highly customizable: anything which is possible in RooStats is possible in the Combine package
- Supported by a HIG PAG Subgroup: Hcomb

[Much more information on the Combine Tool Twiki]

The commands in the blue boxes on each slide provide a hands on commands which can be run to follow along. You may also use the SWAN notebook combine_intro/python_CombineIntro.ipynb

```
cd HiggsAnalysis/CombinedLimit/combine_tutorials_2016/combine_intro/
./get_ws.sh
```

Datacard: Simple Counting Experiment

```
# Simple counting experiment, with one signal and one background process
# Extremely simplified version of the 35/pb H->WW analysis for mH = 200 GeV,
# for 4th generation exclusion (EWK-10-009, arxiv:1102.5429v1)
imax 1  number of channels
jmax 1  number of backgrounds
kmax 2  number of nuisance parameters (sources of systematical uncertainties)
------------
# we have just one channel, in which we observe 0 events
bin         1
observation 0
------------
# now we list the expected events for signal and all backgrounds in that bin
# the second 'process' line must have a positive number for backgrounds, and 0 for signal
# then we list the independent sources of uncertainties, and give their effect (syst. error)
# on each process and bin
bin             1      1
process       ggh4G  Bckg
process         0      1
rate          4.76   1.47
------------
deltaS  lnN   1.20     -    20% uncertainty on signal
deltaB  lnN     -    1.50   50% uncertainty on background
```

- The “datacard” is a textual input which combine converts into a RooStats model (“workspace”)

```
cat simple-counting-experiment.txt
```

Datacard: Simple Counting Experiment

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observation 0
------------
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# then we list the independent sources of uncertainties, and give their effect (syst. error)
# on each process and bin
bin             1      1
process       ggh4G  Bckg
process         0      1
rate          4.76   1.47
------------
deltaS  lnN    1.20    -    20% uncertainty on signal
deltaB  lnN      -   1.50   50% uncertainty on background
```

- First block specifies the number of channels, backgrounds, nuisances
- Can also use “*” and combine can determine on the fly, but specifying explicitly can help spot mistakes

```
cat simple-counting-experiment.txt
```

Datacard: Simple Counting Experiment

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# for 4th generation exclusion (EWK-10-009, arxiv:1102.5429v1)
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jmax 1  number of backgrounds
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------------
# we have just one channel, in which we observe 0 events
bin         1
observation 0
------------
# now we list the expected events for signal and all backgrounds in that bin
# the second 'process' line must have a positive number for backgrounds, and 0 for signal
# then we list the independent sources of uncertainties, and give their effect (syst. error)
# on each process and bin
bin             1      1
process       ggh4G  Bckg
process         0      1
rate          4.76   1.47
------------
deltaS  lnN   1.20     -    20% uncertainty on signal
deltaB  lnN     -    1.50   50% uncertainty on background
```

- Second block labels the channel (here “1”, can be any string)
- Specifies the number of of observed events

```
cat simple-counting-experiment.txt
```

Datacard: Simple Counting Experiment

```
# Simple counting experiment, with one signal and one background process
# Extremely simplified version of the 35/pb H->WW analysis for mH = 200 GeV,
# for 4th generation exclusion (EWK-10-009, arxiv:1102.5429v1)
imax 1  number of channels
jmax 1  number of backgrounds
kmax 2  number of nuisance parameters (sources of systematical uncertainties)
------------
# we have just one channel, in which we observe 0 events
bin         1
observation 0
------------
# now we list the expected events for signal and all backgrounds in that bin
# the second 'process' line must have a positive number for backgrounds, and 0 for signal
# then we list the independent sources of uncertainties, and give their effect (syst. error)
# on each process and bin
bin              1      1
process        ggh4G  Bckg
process          0      1
rate           4.76   1.47
------------
deltaS  lnN    1.20     -    20% uncertainty on signal
deltaB  lnN      -    1.50   50% uncertainty on background
```

- Third block specifies the number of expected events (“rate”) for each process
- Two process lines: one gives a label to each process, and the second a number which if ≤0 denotes signal and if >0 denotes background
  - ➔ Signal processes will be given a free floating normalization parameter

`cat simple-counting-experiment.txt`

Datacard: Simple Counting Experiment

```
# Simple counting experiment, with one signal and one background process
# Extremely simplified version of the 35/pb H->WW analysis for mH = 200 GeV,
# for 4th generation exclusion (EWK-10-009, arxiv:1102.5429v1)
imax 1  number of channels
jmax 1  number of backgrounds
kmax 2  number of nuisance parameters (sources of systematical uncertainties)
------------
# we have just one channel, in which we observe 0 events
bin         1
observation 0
------------
# now we list the expected events for signal and all backgrounds in that bin
# the second 'process' line must have a positive number for backgrounds, and 0 for signal
# then we list the independent sources of uncertainties, and give their effect (syst. error)
# on each process and bin
bin             1      1
process       ggh4G  Bckg
process         0      1
rate          4.76   1.47
------------
deltaS  lnN    1.20    -    20% uncertainty on signal
deltaB  lnN      -   1.50   50% uncertainty on background
```

- Final block specifies the nuisance parameters affecting the processes
- A label and prior distribution (e.g. Log-normal, Gamma, Uniform) are given
- Nuisances with different names are uncorrelated (and a single nuisance is correlated across all processes which it affects)

```
cat simple-counting-experiment.txt
```

From Datacard to RooWorkspace

- The text2workspace.py script converts the textual datacard into a RooWorkspace, defining the Likelihood function used for the statistical methods
- The RooWorkspace contains variables, pdf's, functions, datasets, etc.
- One can inspect the workspace to see how the likelihood has been constructed

```
RooWorkspace(w) w contents

variables
---------
(deltaB,deltaB_In,deltaS,deltaS_In,n_obs_binbin1,r)

p.d.f.s
-------
SimpleGaussianConstraint::deltaB_Pdf[ x=deltaB mean=deltaB_In sigma=1 ] = 1
SimpleGaussianConstraint::deltaS_Pdf[ x=deltaS mean=deltaS_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.229925
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.00196945
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.229925
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.00196945
RooProdPdf::nuisancePdf[ deltaS_Pdf * deltaB_Pdf ] = 1
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.00196945
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.229925

functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggh4G + n_exp_binbin1_proc_Bckg ] = 6.23
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_Bckg ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_Bckg[ thetaList=(deltaB) asymmThetaList=() otherFactorList=() ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggh4G[ thetaList=(deltaS) asymmThetaList=() otherFactorList=(r) ] = 4.76

datasets
--------
RooDataSet::data_obs(n_obs_binbin1)

named sets
----------
ModelConfig_GlobalObservables:(deltaS_In,deltaB_In)
ModelConfig_NuisParams:(deltaS,deltaB)
ModelConfig_Observables:(n_obs_binbin1)
ModelConfig_POI:(r)
ModelConfig_bonly_GlobalObservables:(deltaS_In,deltaB_In)
ModelConfig_bonly_NuisParams:(deltaS,deltaB)
ModelConfig_bonly_Observables:(n_obs_binbin1)
ModelConfig_bonly_POI:(r)
POI:(r)
globalObservables:(deltaS_In,deltaB_In)
nuisances:(deltaS,deltaB)
observables:(n_obs_binbin1)

generic objects
---------------
RooStats::ModelConfig::ModelConfig
RooStats::ModelConfig::ModelConfig_bonly
RooArgSet::discreteParams
```

```
text2workspace.py simple-counting-experiment.txt
root -l simple-counting-experiment.root
root [1] RooWorkspace* w = (RooWorkspace*)_file0->Get("w")
root [2] w->Print()
```

Likelihood From the RooWorkspace

- Lets start from the pdf called model_s in the workspace, which is the full likelihood including the signal, and expand as much as we can:
  - For brevity, I won't always copy the full name of every object

```
L = model_s

L = modelObs_s * nuisancePdf

L = pdf_binbin1 * deltaS_Pdf * deltaB_Pdf

L = Poisson[x=n_obs mean=n_exp]
    * Gauss[x=deltaS mean=deltaS_In sigma=1] * Gauss[x=deltaB mean=deltaB_In sigma=1]

L = Poisson[x=n_obs mean=(n_exp_ggh4G + n_exp_Bckg)]
    * Gauss[x=deltaS mean=0 sigma=1] * Gauss[x=deltaB mean=0 sigma=1]

L = Poisson[x=n_obs mean=( n_nom_ggh4G*f(deltaB)*r + n_nom_Bckg*f(deltaS))]
       * Gauss[x=deltaS mean=0 sigma=1] * Gauss[x=deltaB mean=0 sigma=1]
```

- Which is the single bin example of a generic likelihood function:

$$L(r,\vec{\theta}) = \prod_i \frac{[r\cdot s_i(\vec{\theta})+b_i(\vec{\theta})]^{n_i}}{n_i!} e^{-[r\cdot s_i(\vec{\theta})+b_i(\vec{\theta})]} \prod_\kappa e^{-\frac{1}{2}\theta_\kappa^2}$$

  - It has three parameters: r, deltaS, and deltaB. "r" is the POI and is unconstrained (except by the observed data), while deltaS and deltaB are nuisance parameters which have external constraints. These three parameters are jointly fitted to get the value of "r".

Datacard: Realistic Counting Experiment

```
# Simple counting experiment, with one signal and a few background processes
# Simplified version of the 35/pb H->WW analysis for mH = 160 GeV
imax 1  number of channels
jmax 3  number of backgrounds
kmax 5  number of nuisance parameters (sources of systematical uncertainties)
------------
# we have just one channel, in which we observe 0 events
bin 1
observation 0
------------
# now we list the expected events for signal and all backgrounds in that bin
# the second 'process' line must have a positive number for backgrounds, and 0 for signal
# then we list the independent sources of uncertainties, and give their effect (syst. error)
# on each process and bin
bin              1     1     1     1
process         ggH  qqWW  ggWW  others
process          0     1     2     3
rate           1.47  0.63  0.06  0.22
------------
lumi    lnN    1.11    -   1.11    -    lumi affects both signal and gg->WW (mc-driven). lnN = lognormal
xs_ggH  lnN    1.16    -     -     -    gg->H cross section + signal efficiency + other minor ones.
WW_norm gmN 4    -   0.16    -     -    WW estimate of 0.64 comes from sidebands: 4 events in sideband times 0.16
xs_ggWW lnN      -     -   1.50    -    50% uncertainty on gg->WW cross section
bg_others lnN    -     -     -   1.30   30% uncertainty on the rest of the backgrounds
```

- Realistic datacards will have more processes and nuisance parameters, but we will end up with a similar likelihood function:

$$L(r,\vec{\theta}) = \prod_i \frac{[r\cdot s_i(\vec{\theta})+b_i(\vec{\theta})]^{n_i}}{n_i!} e^{-[r\cdot s_i(\vec{\theta})+b_i(\vec{\theta})]} \prod_\kappa e^{-\frac{1}{2}\theta_\kappa^2}$$

```
cat ../../CombineLimit/data/tutorials/realistic-counting-experiment.txt
```

Combination of Multiple Channels

```
imax 3   number of channels
jmax *   number of backgrounds ('*' = automatic)
kmax *   number of nuisance parameters (sources of systematical uncertainties)
------------
# three channels, each with it's number of observed events
bin          e_tau mu_tau e_mu
observation   517   540   101
------------
# now we list the expected events for signal and all backgrounds in those three bins
# the second 'process' line must have a positive number for backgrounds, and 0 for signal
# for the signal, we normalize the yields to an hypothetical cross section of 1/pb
# so that we get an absolute limit in cross section in units of pb.
# then we list the independent sources of uncertainties, and give their effect (syst. error)
# on each process and bin
bin             e_tau  e_tau  e_tau  mu_tau  mu_tau  mu_tau  e_mu   e_mu  e_mu
process         higgs   ZTT    QCD   higgs    ZTT     QCD    higgs   ZTT  other
process           0      1      2      0       1       2       0      1     2
rate            0.34    190    327    0.57    329     259    0.15    88    14
------------
lumi     lnN    1.11     -      -     1.11     -       -      1.11    -   1.11   A 11% lumi uncertainty, a
tauid    lnN    1.23   1.23     -     1.23   1.23      -       -      -     -    The infamous 23% tau id u
ZtoLL    lnN     -     1.04     -      -     1.04      -       -    1.04    -     4% uncertainty on lumi*Z
effic    lnN    1.04   1.04     -     1.04   1.04      -      1.04  1.04  1.04    4% uncertainty on effici
QCDel    lnN     -      -     1.20     -       -       -       -      -     -    20% uncertainty on QCD in
QCDmu    lnN     -      -      -       -       -      1.10     -      -     -    10% uncertainty on QCD in
other    lnN     -      -      -       -       -       -       -      -    1.1   10% uncertainty on non-Z
```

- Additional channels can be added easily (different “bin” label, same process labels)
  - Defining conventions for process/nuisance labels will make your life easier
- Can be done by hand or using a tool: `combineCards.py ch1.txt ch2.txt ch3.txt > comb.txt`

```
cat ../../data/tutorials/realistic-multi-channel.txt
```

Shape Experiment: Binned

```
imax 1
jmax 1
kmax *
---------------
shapes * * input-shapes-TH1.root $PROCESS $PROCESS_$SYSTEMATIC
---------------
bin 1
observation 85
------------------------------
bin             1          1
process         signal     background
process         0          1
rate            10         100
--------------------------------
lumi     lnN    1.10       1.0
bgnorm   lnN    1.00       1.3
alpha  shapeN2    -           1   uncertainty on background shape and normalization
sigma  shapeN2    0.5         -   uncertainty on signal resolution. Assume the histogram is a 2 sigma shift,
#                                so divide the unit gaussian by 2 before doing the interpolation
```

shapes ***process channel file histogram [histogram_with_systematics]***

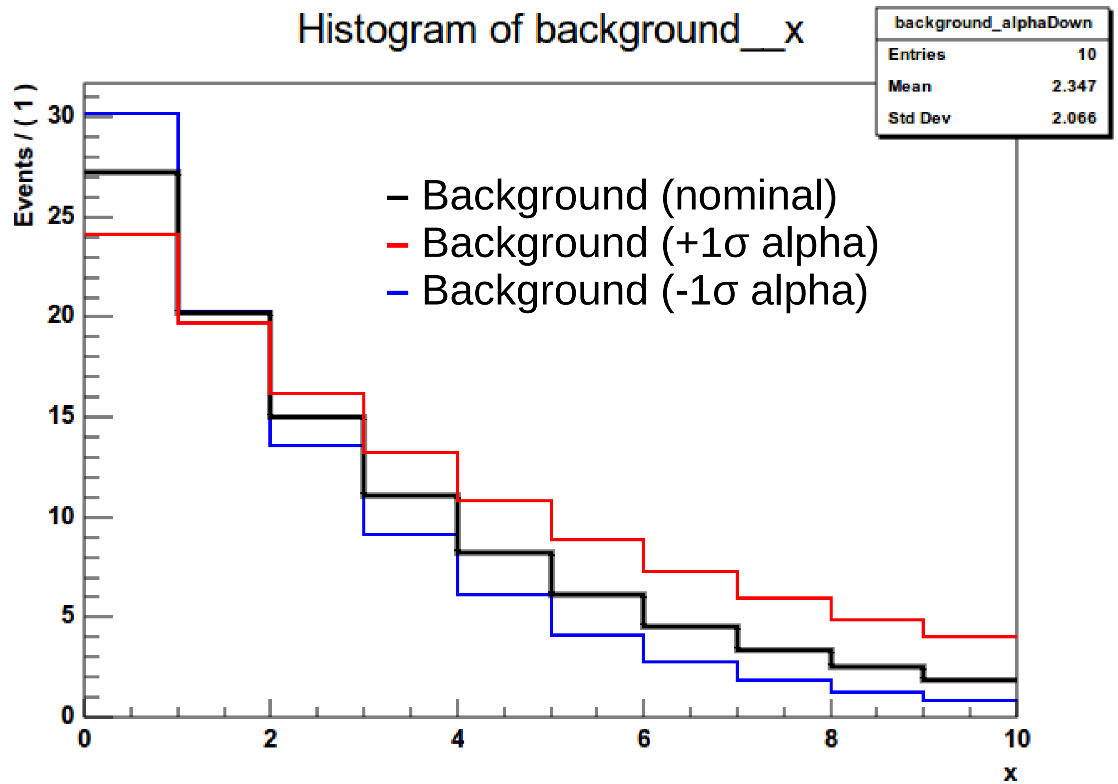
- In a shape experiment, a line pointing to a .root file is added
- For a binned experiment this .root file contains the shapes (histograms, PDFs, etc.) for the nominal distrubtion, systematic variations, and observed data
- Normalization of histograms can be used to simultaneously vary shape and rate

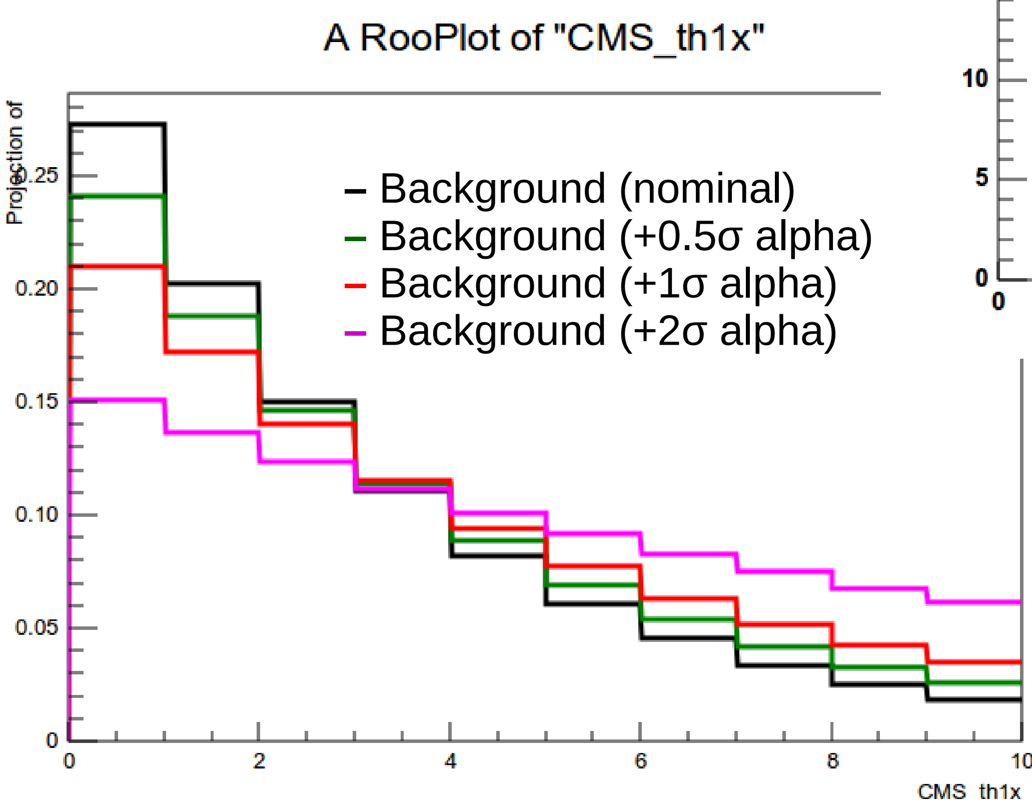
```
root [1] _file0->ls()
TFile**         data/benchmarks/shapes/simple-shapes-TH1.root
 TFile*         data/benchmarks/shapes/simple-shapes-TH1.root
  KEY: TH1F     signal;1        Histogram of signal__x
  KEY: TH1F     signal_sigmaUp;1        Histogram of signal__x
  KEY: TH1F     signal_sigmaDown;1      Histogram of signal__x
  KEY: TH1F     background;1    Histogram of background__x
  KEY: TH1F     background_alphaUp;1    Histogram of background__x
  KEY: TH1F     background_alphaDown;1  Histogram of background__x
  KEY: TH1F     data_obs;1      Histogram of data_obs__x
  KEY: TH1F     data_sig;1      Histogram of data_sig__x
```

```
cat simple-shapes-TH1.txt
root -l input-shapes-TH1.root
root [1] _file0->ls()
```

Shape Experiment: Morphing

- Given the histograms corresponding to +/- 1 sigma for a particular nuisance parameter as input...





- ...Combine creates a morphing pdf which provides a shape for any value of the nuisance parameter

(SWAN only)

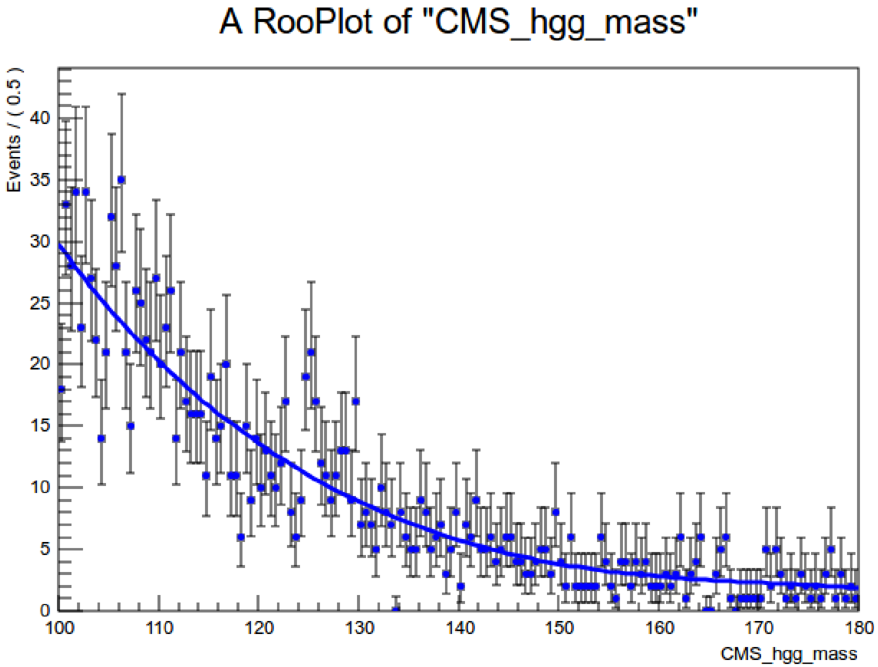
Shape Experiment: Parametric

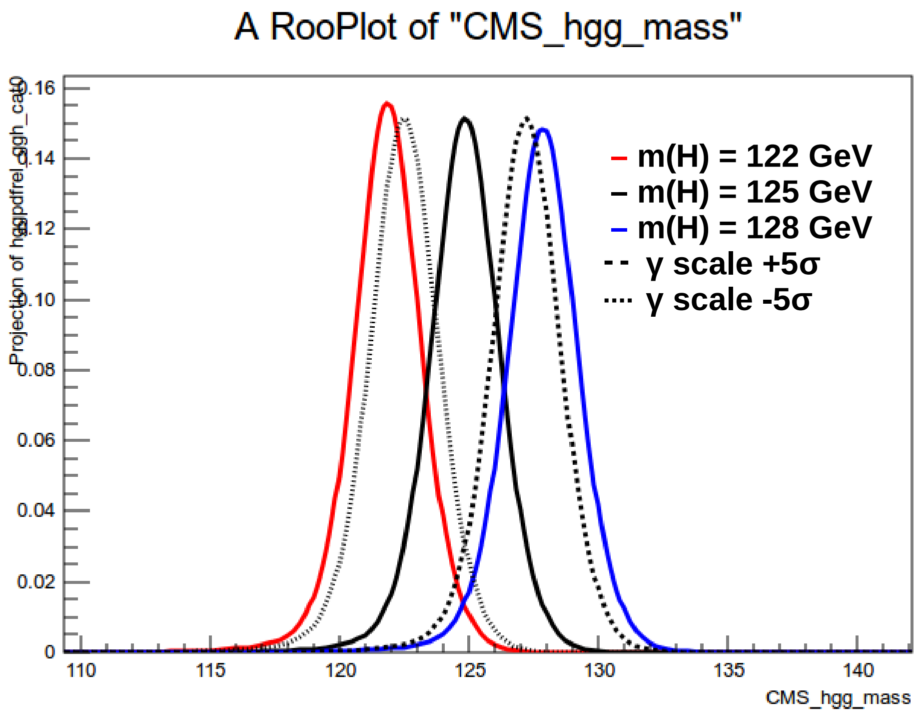
```
Combination of .=../couplings/hgg/hgg_8TeV_MVA.txt
imax 4 number of bins
jmax 5 number of processes minus 1
kmax * number of nuisance parameters
----------------------------------------------------------------------------------------------------------------------
shapes WH        cat0      hgg.inputsig_8TeV_MVA.root wsig_8TeV:hggpdfrel_wh_cat0
shapes ZH        cat0      hgg.inputsig_8TeV_MVA.root wsig_8TeV:hggpdfrel_zh_cat0
shapes bkg_mass  cat0      hgg.inputbkgdata_8TeV_MVA.root cms_hgg_workspace:pdf_data_pol_model_8TeV_cat0
shapes data_obs  cat0      hgg.inputbkgdata_8TeV_MVA.root cms_hgg_workspace:roohist_data_mass_cat0
shapes ggH       cat0      hgg.inputsig_8TeV_MVA.root wsig_8TeV:hggpdfrel_ggh_cat0
shapes qqH       cat0      hgg.inputsig_8TeV_MVA.root wsig_8TeV:hggpdfrel_vbf_cat0
shapes ttH       cat0      hgg.inputsig_8TeV_MVA.root wsig_8TeV:hggpdfrel_tth_cat0
[... similarly for cat1, cat4, cat5 ... ]
----------------------------------------------------------------------------------------------------------------------
bin          cat0         cat1         cat4         cat5
observation  -1.0         -1.0         -1.0         -1.0
----------------------------------------------------------------------------------------------------------------------
bin                                       cat0         cat0         cat0         cat0         cat0         cat0       [... cat1, cat4, cat5 ...]
process                                   ZH           qqH          WH           ttH          ggH          bkg_mass   [... cat1, cat4, cat5 ...]
process                                   -4           -3           -2           -1           0            1          [... cat1, cat4, cat5 ...]
rate                                      6867.0000    19620.0000   12753.0000   19620.0000   19620.0000   1.0000     [... cat1, cat4, cat5 ...]
----------------------------------------------------------------------------------------------------------------------
CMS_eff_j                lnN              0.999125     0.964688     0.999125     0.998262     0.996483     -          [... cat1, cat4, cat5 ...]
CMS_hgg_JECmigration     lnN              -            -            -            -            -            -          [... cat1, cat4, cat5 ...]
CMS_hgg_UEPSmigration    lnN              -            -            -            -            -            -          [... cat1, cat4, cat5 ...]
CMS_hgg_eff_MET          lnN              -            -            -            -            -            -          [... cat1, cat4, cat5 ...]
CMS_hgg_eff_e            lnN              -            -            -            -            -            -          [... cat1, cat4, cat5 ...]
CMS_hgg_eff_m            lnN              -            -            -            -            -            -          [... cat1, cat4, cat5 ...]
CMS_hgg_eff_trig         lnN              1.01         1.01         1.01         1.01         1.01         -          [... cat1, cat4, cat5 ...]
CMS_hgg_n_id             lnN              1.034/0.958  1.039/0.949  1.034/0.958  1.053/0.915  1.035/0.958  -          [... cat1, cat4, cat5 ...]
CMS_hgg_n_pdf_1          lnN              -            0.998/0.996  -            -            1.002/0.998  -          [... cat1, cat4, cat5 ...]
[... more lnN nuisances ...]
CMS_hgg_nuissancedeltamcat4  param  0.0 0.001458
CMS_hgg_nuissancedeltafracright_8TeV  param  1.0 0.002000
CMS_hgg_nuissancedeltamcat1  param  0.0 0.001470
CMS_hgg_nuissancedeltamcat0  param  0.0 0.001530
CMS_hgg_nuissancedeltasmearcat4  param  0.0 0.001122
CMS_hgg_nuissancedeltasmearcat1  param  0.0 0.001167
CMS_hgg_nuissancedeltasmearcat0  param  0.0 0.001230
CMS_hgg_globalscale  param  0.0 0.004717
```

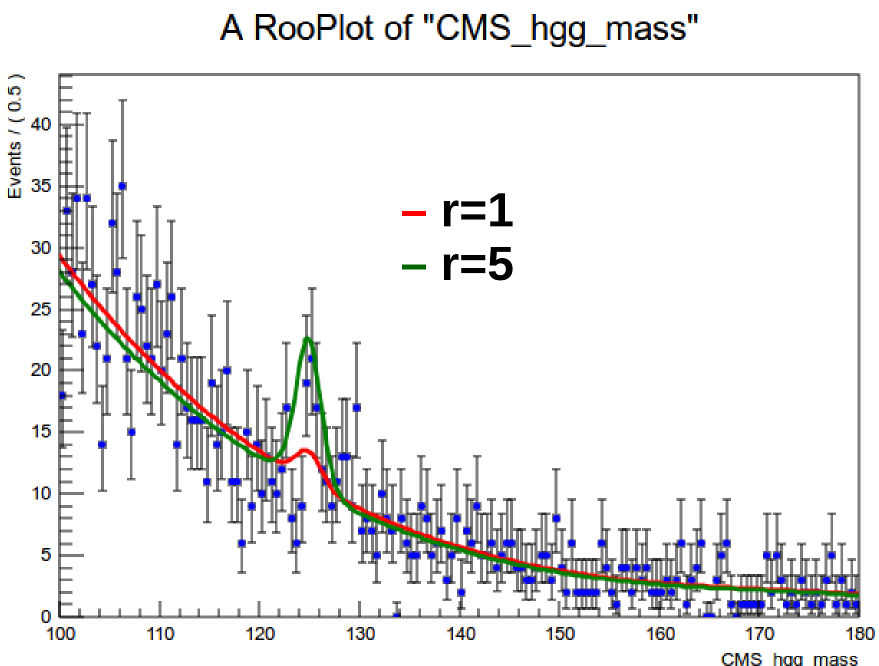
- In a parametric shape experiment, the “shapes” line points to a .root file which has a RooWorkspace which contains RooAbsPdf’s that describe the shape of each process

cat hgg_8TeV_MVA_cat0145.txt

Shape Experiment: Parametric





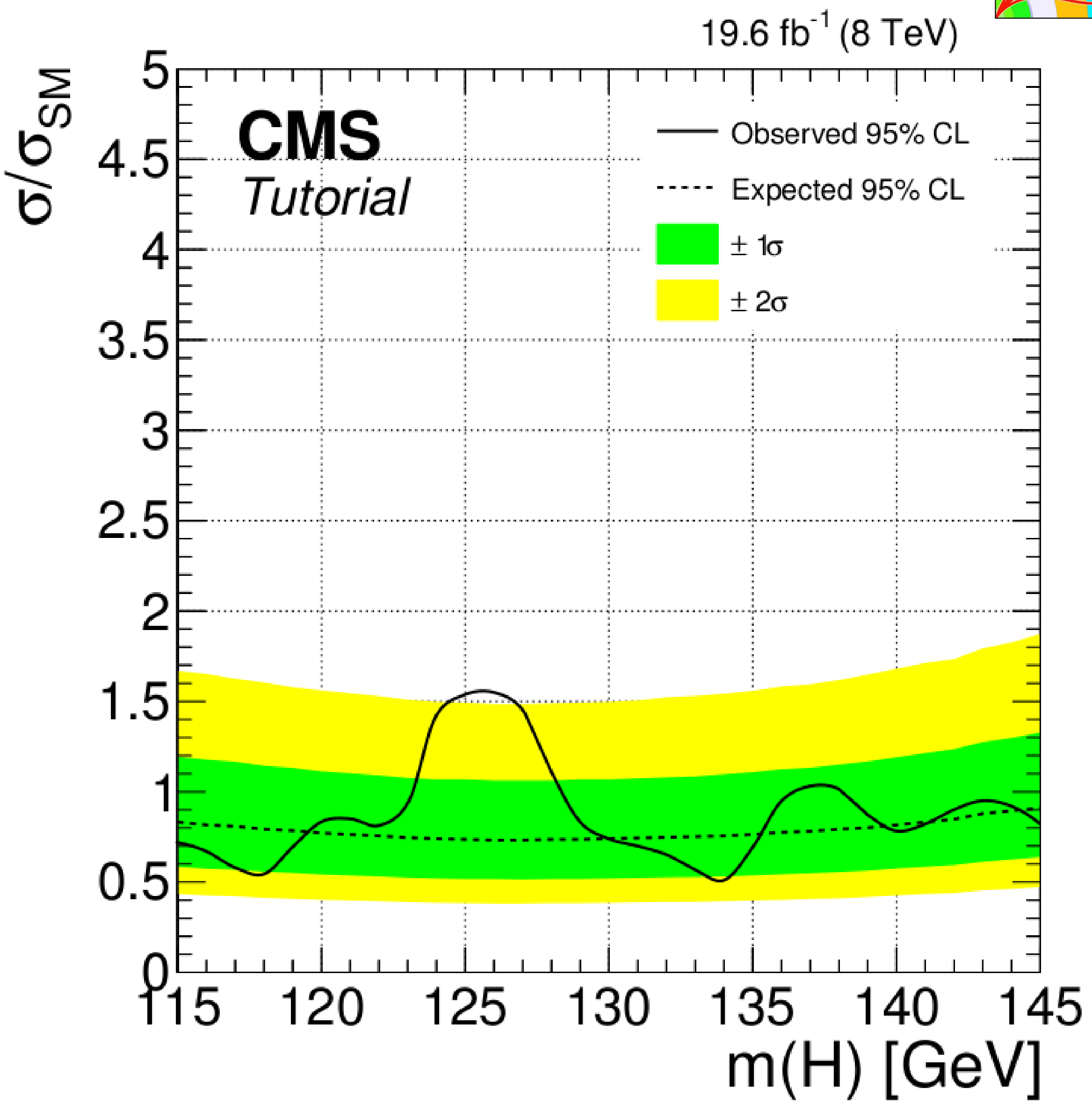


- Parametric experiments can be binned or unbinned (binned faster for larger datasets)
- How nuisance parameters affect the shape for a process can be defined in the workspace
- After converting to a workspace, one can draw the total signal+background PDF for any set of parameter values

(SWAN only)

Limit Setting

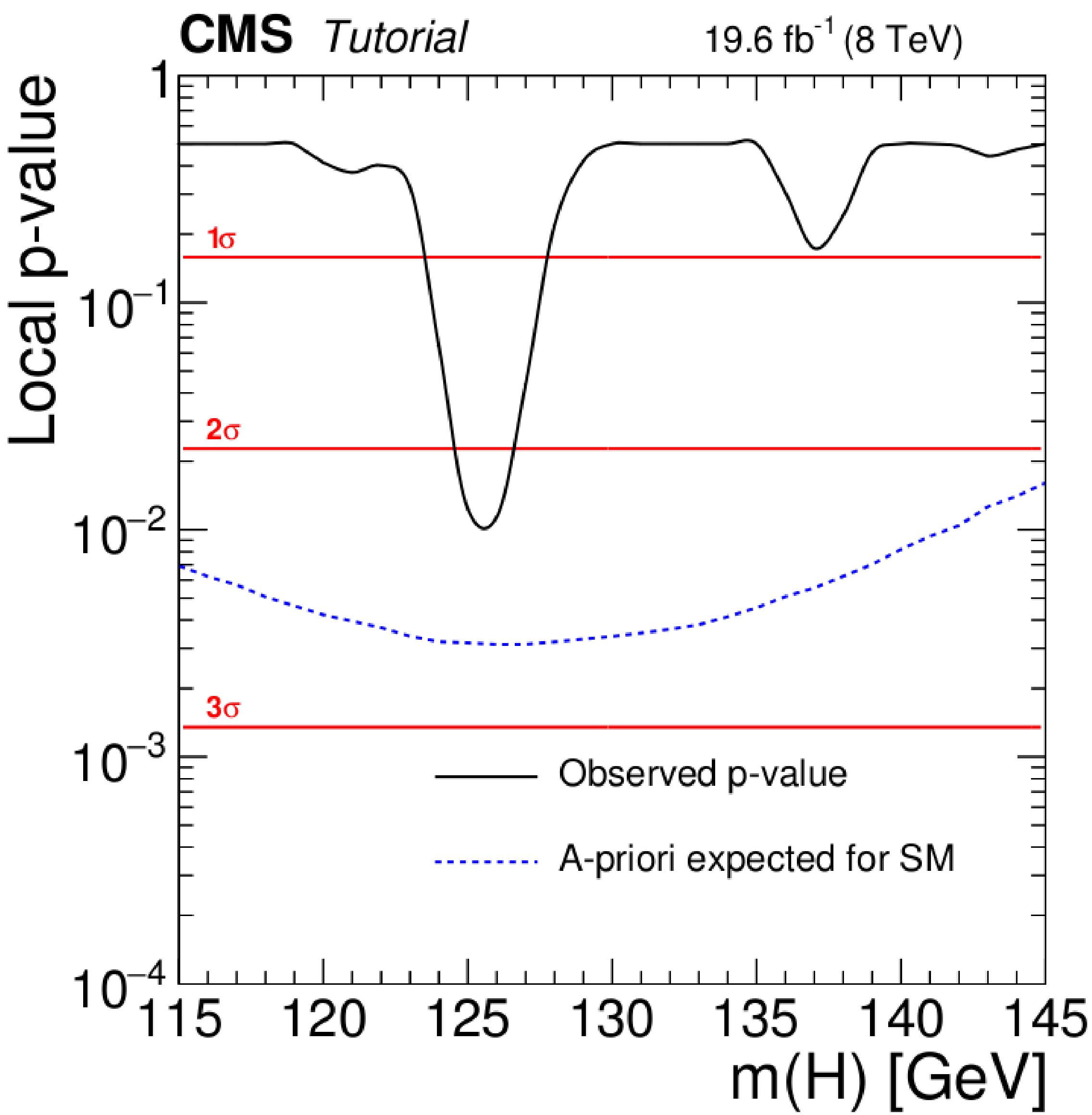
- Combine supports several methods for computation of limits on the model POIs
- Asymptotic CL_s limits: most common method used for setting limits in HIG PAG
- Uses the asymptotic approximation of the test-statistic distribution to quickly compute both observed and expected limits
- Other methods available:
  - Bayesian
  - Hybrid Bayesian-Frequentist
  - Fully Frequentist
  - 1 sided Feldman-Cousins Interval
    - More CPU intensive




```
chmod u+x run_hgg_asymptotic.sh
./run_hgg_asymptotic.sh
python plotLimits.py
```

Extracting Significance

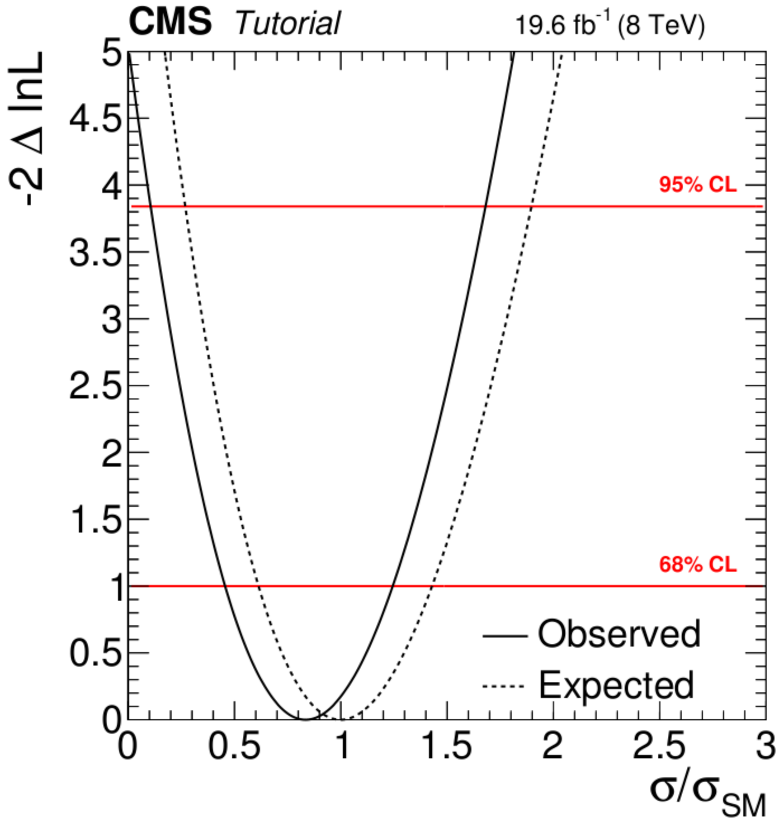
- Combine supports computation of the expected/observed significance of an excess
- Most common in HIG is to again use the profile likelihood approximation
  - ➔ For expected significance, can use the“Asimov” dataset or toys of signal+background
- Expected/Observed significance also supported for modified frequentist and fully frequentist methods



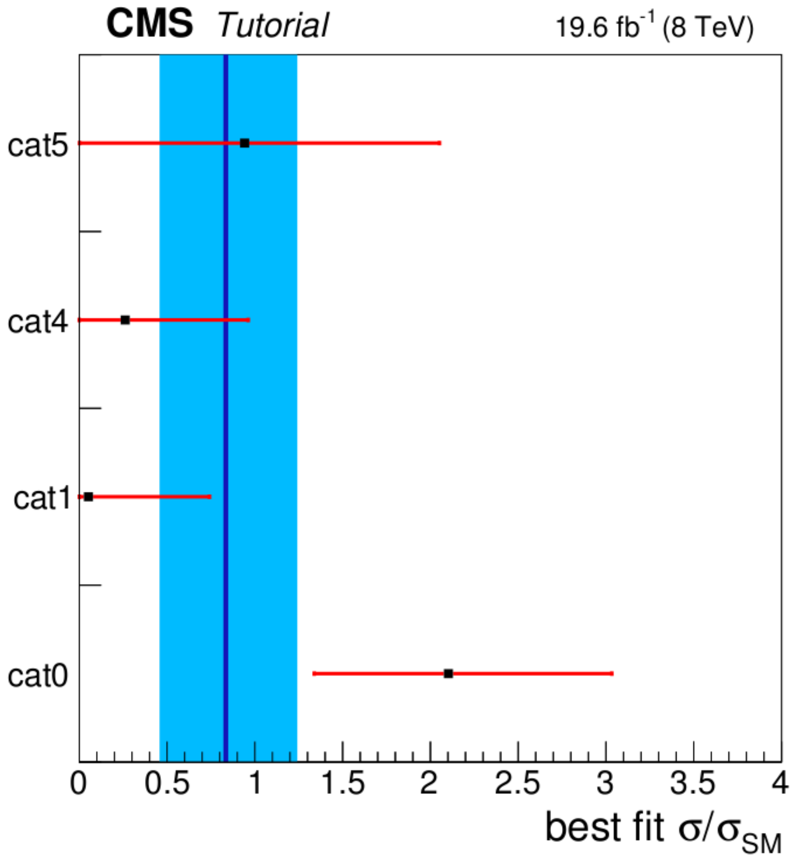

```
chmod u+x run_hgg_pvalue.sh
./run_hgg_pvalue.sh
python plotPvalue.py
```

Maximum Likelihood Fit

- Combine provides a Maximum Likelihood Fit method for extracting the (expected) best-fit and uncertainties for the POIs
  - Can produce likelihood scans for the POI



- Can fit channels simultaneously with full correlation of nuisance parameters




```
combine -n Obs -M MultiDimFit -m 125 hgg_8TeV_MVA_cat0145.root --algo=grid --points 300 --setPhysicsModelParameterRanges
r=0.0,3.0
combine -n Exp -M MultiDimFit -m 125 hgg_8TeV_MVA_cat0145.root -t -1 --expectSignal=1 --algo=grid --points 300 \
--setPhysicsModelParameterRanges r=0.0,3.0
python plotMuScan.py
combine -m 125 -M ChannelCompatibilityCheck hgg_8TeV_MVA_cat0145.root --saveFitResult
python cccPlot.py
```