Introduction to Combine

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CMS Topical Workshop on Off-shell Higgs Boson Production at LPC

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Resources

- Documentation: https://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/
  - Everything in this tutorial is also covered here
  - Your first stop for any combine questions
- cms-talk: https://cms-talk.web.cern.ch/c/physics/cat/cat-stats/279
  - Ask for help, submit bug reports, get notifications of updates
- Official paper (new!)
  - In final reading, to be submitted to CSBS
  - Cite this if you use combine in your analysis

Installing combine

To install current recommended version of combine:

```
cmssw-el7
cmsrel CMSSW_11_3_4
cd CMSSW_11_3_4/src
cmsenv
git clone https://github.com/cms-analysis/HiggsAnalysis-CombinedLimit.git HiggsAnalysis/CombinedLimit
cd HiggsAnalysis/CombinedLimit
git checkout v9.2.0
scramv1 b
```

- If you already have combine installed, it is probably ok for this tutorial … but no guarantees
- combine not yet transitioned to EL9 CMSSW —> run with singularity

Simple 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)
------------
bin bin1
observation 0
------------
bin             bin1 bin1  bin1  bin1
process          ggH  qqWW  ggWW  others
process          0     1     2     3
rate            1.47  0.64  0.06  0.22
------------
lumi    lnN    1.11    -   1.11    -
xs_ggH  lnN    1.16    -     -     -
WW_norm gmN 4    -   0.16    -     -
xs_ggWW lnN      -     -   1.50    -
bg_others lnN    -     -     -   1.30
```

Datacard: data/tutorials/counting/realistic_counting_experiment.txt

Simple 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
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bin             bin1 bin1  bin1  bin1
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process          0     1     2     3
rate           1.47  0.64  0.06  0.22
------------
lumi    lnN    1.11    -   1.11    -
xs_ggH  lnN    1.16    -     -     -
WW_norm gmN 4    -   0.16    -     -
xs_ggWW lnN      -     -   1.50    -
bg_others lnN    -     -     -   1.30
```

Single bin, with observation 0

Datacard: data/tutorials/counting/realistic_counting_experiment.txt

Simple Counting Experiment

```
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------------
bin             bin1 bin1  bin1  bin1
process         ggH  qqWW  ggWW  others
process          0     1     2     3
rate           1.47  0.64  0.06  0.22
------------
lumi    lnN    1.11    -   1.11    -
xs_ggH  lnN    1.16    -     -     -
WW_norm gmN 4    -   0.16    -     -
xs_ggWW lnN      -     -   1.50    -
bg_others lnN    -     -     -   1.30
```

Four processes contributing to bin1

Simple Counting Experiment

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rate            1.47 0.64  0.06  0.22
------------
lumi    lnN    1.11    -   1.11    -
xs_ggH  lnN    1.16    -     -     -
WW_norm gmN 4    -   0.16    -     -
xs_ggWW lnN      -     -   1.50    -
bg_others lnN    -     -     -   1.30
```

1 signal (process # ≤ 1) + 3 backgrounds

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Simple Counting Experiment

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------------
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bin             bin1 bin1  bin1  bin1
process          ggH  qqWW  ggWW  others
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rate             1.47  0.64  0.06  0.22
------------
lumi    lnN    1.11    -    1.11    -
xs_ggH  lnN    1.16    -      -     -
WW_norm gmN 4    -    0.16    -     -
xs_ggWW lnN      -      -    1.50    -
bg_others lnN    -      -      -    1.30
```

Expected yields of each process in bin 1

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Simple Counting Experiment

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bin             bin1 bin1  bin1  bin1
process          ggH  qqWW  ggWW  others
process          0     1     2     3
rate            1.47  0.64  0.06  0.22
------------
lumi    lnN    1.11    -    1.11    -
xs_ggH  lnN    1.16    -      -     -
WW_norm gmN 4    -    0.16   -     -
xs_ggWW lnN      -     -    1.50    -
bg_others lnN    -     -      -   1.30
```

Systematic uncertainties affecting each process
‘-‘ means no effect

Datacard: data/tutorials/counting/realistic_counting_experiment.txt

Simple Counting Experiment

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bin             bin1 bin1  bin1  bin1
process          ggH  qqWW  ggWW  others
process          0     1     2     3
rate            1.47  0.64  0.06  0.22
------------
lumi    lnN     1.11    -   1.11    -
xs_ggH  lnN     1.16    -     -     -
WW_norm gmN 4     -   0.16    -     -
xs_ggWW lnN       -     -   1.50    -
bg_others lnN     -     -     -   1.30
```

Lognormal rate uncertainties

Datacard: data/tutorials/counting/realistic_counting_experiment.txt

Simple Counting Experiment

```
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process         0     1     2     3
rate            1.47 0.64  0.06  0.22
------------
lumi    lnN     1.11    -   1.11    -
xs_ggH  lnN     1.16    -     -     -
WW_norm gmN 4     -   0.16    -     -
xs_ggWW lnN       -     -   1.50    -
bg_others lnN     -     -     -   1.30
```

Gamma uncertainty on yield extrapolated from CR
4 events in CR x 0.16 transfer factor = 0.64
This lets us account for the statistical uncertainty on a CR measurement (4) which does not directly enter the fit

Datacard: data/tutorials/counting/realistic_counting_experiment.txt

Simple Counting Experiment

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xs_ggH  lnN    1.16    -     -     -
WW_norm gmN 4    -   0.16    -     -
xs_ggWW lnN      -     -   1.50    -
bg_others lnN    -     -     -   1.30
```

Note that this can be inferred from rest of data card

Primarily a sanity check that you haven't missed anything elsewhere

Datacard: data/tutorials/counting/realistic_counting_experiment.txt

Simple 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 *  number of channels
jmax *  number of backgrounds
kmax *  number of nuisance parameters (sources of systematical uncertainties)
------------
bin bin1
observation 0
------------
bin             bin1 bin1  bin1  bin1
process         ggH  qqWW  ggWW  others
process          0     1     2     3
rate            1.47  0.64  0.06  0.22
------------
lumi    lnN    1.11    -   1.11    -
xs_ggH  lnN    1.16    -     -     -
WW_norm gmN 4    -   0.16    -     -
xs_ggWW lnN      -     -   1.50    -
bg_others lnN    -     -     -   1.30
```

Can replace with * and let combine infer correct values

Datacard: data/tutorials/counting/realistic_counting_experiment.txt

What does likelihood look like?

$$n_{ggH} = 1.47 * (1.16)^{\nu_{xs\_ggH}} * (1.11)^{\nu_{lumi}}$$
$$n_{ggWW} = 0.06 * (1.5)^{\nu_{xs\_ggWW}} * (1.11)^{\nu_{lumi}}$$
$$n_{others} = 0.22 * (1.3)^{\nu_{bg\_others}}$$
$$n_{qqWW} = 0.16 * \nu_{WW\_norm}$$
$$n_{exp} = r * n_{ggH} + n_{ggWW} + n_{qqWW} + n_{others}$$

$$L_{primary} = Poiss(0; n_{exp}) = e^{n_{exp}}$$

$$L_{auxiliary} = \frac{1}{(2\pi)^2} * e^{-\nu^2_{xs\_ggH}/2} * e^{-\nu^2_{xs\_ggWW}/2} * e^{-\nu^2_{bg\_others}/2} * e^{-\nu^2_{lumi}/2} * \frac{\nu^4_{WW\_norm} * e^{-\nu_{WW\_norm}}}{4!}$$

$$L = L_{primary} * L_{auxiliary}$$

Converting Datacard to Workspace

- What is a combine datacard?
  - 1) Description of a likelihood
  - 2) Instructions to construct a RooWorkspace
- Combine always does this conversion ‘under the hood’, but can do so explicitly with text2workspace.py

```
text2workspace.py data/tutorials/counting/realistic-counting-experiment.txt \
                  -o simple_counting.root
```

- Can then inspect workspace produced

```
root -l simple_counting.root
…
root [1] .ls
TFile**     simple_counting.root
 TFile*     simple_counting.root
  KEY: RooWorkspace w;1   w
  KEY: TProcessID ProcessID0;1   17771710-eb46-11ee-b4f6-660db9bcbeef
root [2] w->Print()
```

Inspecting the workspace

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

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

named sets
----------
ModelConfig_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_Observables:(n_obs_binbin1)
ModelConfig_POI:(r)
ModelConfig_bonly_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_bonly_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_bonly_Observables:(n_obs_binbin1)
ModelConfig_bonly_POI:(r)
POI:(r)
globalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
nuisances:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
observables:(n_obs_binbin1)

variables
---------
(WW_norm,WW_norm_In,bg_others,bg_others_In,lumi,lumi_In,n_obs_binbin1,r,xs_ggH,xs_ggH_In,xs_ggWW,
xs_ggWW_In)
```

Inspecting the workspace

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

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

named sets
----------
ModelConfig_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_Observables:(n_obs_binbin1)
ModelConfig_POI:(r)
ModelConfig_bonly_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_bonly_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_bonly_Observables:(n_obs_binbin1)
ModelConfig_bonly_POI:(r)
POI:(r)
globalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
nuisances:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
observables:(n_obs_binbin1)

variables
---------
(WW_norm,WW_norm_In,bg_others,bg_others_In,lumi,lumi_In,n_obs_binbin1,r,xs_ggH,xs_ggH_In,xs_ggWW,
xs_ggWW_In)
```

Workspace will contain s+b and b-only models

Inspecting the workspace

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

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

Dataset contains one observation

```
named sets
----------
ModelConfig_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_Observables:(n_obs_binbin1)
ModelConfig_POI:(r)
ModelConfig_bonly_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_bonly_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_bonly_Observables:(n_obs_binbin1)
ModelConfig_bonly_POI:(r)
POI:(r)
globalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
nuisances:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
observables:(n_obs_binbin1)

variables
---------
(WW_norm,WW_norm_In,bg_others,bg_others_In,lumi,lumi_In,n_obs_binbin1,r,xs_ggH,xs_ggH_In,xs_ggWW,
xs_ggWW_In)
```

Inspecting the workspace

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

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

named sets
----------
ModelConfig_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_Observables:(n_obs_binbin1)
ModelConfig_POI:(r)
ModelConfig_bonly_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_bonly_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_bonly_Observables:(n_obs_binbin1)
ModelConfig_bonly_POI:(r)
POI:(r)
globalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
nuisances:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
observables:(n_obs_binbin1)

variables
---------
(WW_norm,WW_norm_In,bg_others,bg_others_In,lumi,lumi_In,n_obs_binbin1,r,xs_ggH,xs_ggH_In,xs_ggWW,
xs_ggWW_In)
```

Model parameters — *_In are initial values

Inspecting the workspace

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

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

named sets
----------
ModelConfig_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_Observables:(n_obs_binbin1)
ModelConfig_POI:(r)
ModelConfig_bonly_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_bonly_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_bonly_Observables:(n_obs_binbin1)
ModelConfig_bonly_POI:(r)
POI:(r)
globalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
nuisances:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
observables:(n_obs_binbin1)

variables
---------
(WW_norm,WW_norm_In,bg_others,bg_others_In,lumi,lumi_In,n_obs_binbin1,r,xs_ggH,xs_ggH_In,xs_ggWW,
xs_ggWW_In)
```

All inputs and parameters

Inspecting the workspace

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

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

named sets
----------
ModelConfig_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_Observables:(n_obs_binbin1)
ModelConfig_POI:(r)
ModelConfig_bonly_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_bonly_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_bonly_Observables:(n_obs_binbin1)
ModelConfig_bonly_POI:(r)
POI:(r)
globalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
nuisances:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
observables:(n_obs_binbin1)

variables
---------
(WW_norm,WW_norm_In,bg_others,bg_others_In,lumi,lumi_In,n_obs_binbin1,r,xs_ggH,xs_ggH_In,xs_ggWW,
xs_ggWW_In)
```

Inputs and parameters for s+b model

Inspecting the workspace

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

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

named sets
----------
ModelConfig_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_Observables:(n_obs_binbin1)
ModelConfig_POI:(r)
ModelConfig_bonly_GlobalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
ModelConfig_bonly_NuisParams:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
ModelConfig_bonly_Observables:(n_obs_binbin1)
ModelConfig_bonly_POI:(r)
POI:(r)
globalObservables:(lumi_In,xs_ggH_In,WW_norm_In,xs_ggWW_In,bg_others_In)
nuisances:(lumi,xs_ggH,WW_norm,xs_ggWW,bg_others)
observables:(n_obs_binbin1)

variables
---------
(WW_norm,WW_norm_In,bg_others,bg_others_In,lumi,lumi_In,n_obs_binbin1,r,xs_ggH,xs_ggH_In,xs_ggWW,
xs_ggWW_In)
```

Inputs and parameters for b-only model

Inspecting the workspace

```
functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggH + n_exp_binbin1_proc_qqWW +
n_exp_binbin1_proc_ggWW + n_exp_binbin1_proc_others ] = 2.55
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_qqWW + n_exp_binbin1_proc_ggWW +
n_exp_binbin1_proc_others ] = 1.08
ProcessNormalization::n_exp_binbin1_proc_ggH[ thetaList=(lumi,xs_ggH) asymmThetaList=()
otherFactorList=(r) ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggWW[ thetaList=(lumi,xs_ggWW) asymmThetaList=()
otherFactorList=() ] = 0.06
ProcessNormalization::n_exp_binbin1_proc_others[ thetaList=(bg_others) asymmThetaList=()
otherFactorList=() ] = 0.22
ProcessNormalization::n_exp_binbin1_proc_qqWW[ thetaList=() asymmThetaList=()
otherFactorList=(WW_norm) ] = 0.8
```

```
p.d.f.s
-------
RooPoisson::WW_norm_Pdf[ x=WW_norm_In mean=WW_norm ] = 0.175467
SimpleGaussianConstraint::bg_others_Pdf[ x=bg_others mean=bg_others_In sigma=1 ] = 1
SimpleGaussianConstraint::lumi_Pdf[ x=lumi mean=lumi_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.339596
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.0780817
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.0595879
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.0137008
RooProdPdf::nuisancePdf[ xs_ggH_Pdf * bg_others_Pdf * WW_norm_Pdf * lumi_Pdf * xs_ggWW_Pdf ] =
0.175467
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.0780817
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.339596
SimpleGaussianConstraint::xs_ggH_Pdf[ x=xs_ggH mean=xs_ggH_In sigma=1 ] = 1
SimpleGaussianConstraint::xs_ggWW_Pdf[ x=xs_ggWW mean=xs_ggWW_In sigma=1 ] = 1
```

Inspecting the workspace

```
functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggH + n_exp_binbin1_proc_qqWW +
n_exp_binbin1_proc_ggWW + n_exp_binbin1_proc_others ] = 2.55
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_qqWW + n_exp_binbin1_proc_ggWW +
n_exp_binbin1_proc_others ] = 1.08
ProcessNormalization::n_exp_binbin1_proc_ggH[ thetaList=(lumi,xs_ggH) asymmThetaList=()
otherFactorList=(r) ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggWW[ thetaList=(lumi,xs_ggWW) asymmThetaList=()
otherFactorList=() ] = 0.06
ProcessNormalization::n_exp_binbin1_proc_others[ thetaList=(bg_others) asymmThetaList=()
otherFactorList=() ] = 0.22
ProcessNormalization::n_exp_binbin1_proc_qqWW[ thetaList=() asymmThetaList=()
otherFactorList=(WW_norm) ] = 0.8
```

N_exp for each process

```
p.d.f.s
-------
RooPoisson::WW_norm_Pdf[ x=WW_norm_In mean=WW_norm ] = 0.175467
SimpleGaussianConstraint::bg_others_Pdf[ x=bg_others mean=bg_others_In sigma=1 ] = 1
SimpleGaussianConstraint::lumi_Pdf[ x=lumi mean=lumi_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.339596
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.0780817
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.0595879
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.0137008
RooProdPdf::nuisancePdf[ xs_ggH_Pdf * bg_others_Pdf * WW_norm_Pdf * lumi_Pdf * xs_ggWW_Pdf ] =
0.175467
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.0780817
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.339596
SimpleGaussianConstraint::xs_ggH_Pdf[ x=xs_ggH mean=xs_ggH_In sigma=1 ] = 1
SimpleGaussianConstraint::xs_ggWW_Pdf[ x=xs_ggWW mean=xs_ggWW_In sigma=1 ] = 1
```

Inspecting the workspace

Total n_exp under s+b and b-only models

```
functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggH + n_exp_binbin1_proc_qqWW +
n_exp_binbin1_proc_ggWW + n_exp_binbin1_proc_others ] = 2.55
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_qqWW + n_exp_binbin1_proc_ggWW +
n_exp_binbin1_proc_others ] = 1.08
ProcessNormalization::n_exp_binbin1_proc_ggH[ thetaList=(lumi,xs_ggH) asymmThetaList=()
otherFactorList=(r) ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggWW[ thetaList=(lumi,xs_ggWW) asymmThetaList=()
otherFactorList=() ] = 0.06
ProcessNormalization::n_exp_binbin1_proc_others[ thetaList=(bg_others) asymmThetaList=()
otherFactorList=() ] = 0.22
ProcessNormalization::n_exp_binbin1_proc_qqWW[ thetaList=() asymmThetaList=()
otherFactorList=(WW_norm) ] = 0.8
```

```
p.d.f.s
-------
RooPoisson::WW_norm_Pdf[ x=WW_norm_In mean=WW_norm ] = 0.175467
SimpleGaussianConstraint::bg_others_Pdf[ x=bg_others mean=bg_others_In sigma=1 ] = 1
SimpleGaussianConstraint::lumi_Pdf[ x=lumi mean=lumi_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.339596
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.0780817
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.0595879
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.0137008
RooProdPdf::nuisancePdf[ xs_ggH_Pdf * bg_others_Pdf * WW_norm_Pdf * lumi_Pdf * xs_ggWW_Pdf ] =
0.175467
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.0780817
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.339596
SimpleGaussianConstraint::xs_ggH_Pdf[ x=xs_ggH mean=xs_ggH_In sigma=1 ] = 1
SimpleGaussianConstraint::xs_ggWW_Pdf[ x=xs_ggWW mean=xs_ggWW_In sigma=1 ] = 1
```

Inspecting the workspace

```
functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggH + n_exp_binbin1_proc_qqWW +
n_exp_binbin1_proc_ggWW + n_exp_binbin1_proc_others ] = 2.55
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_qqWW + n_exp_binbin1_proc_ggWW +
n_exp_binbin1_proc_others ] = 1.08
ProcessNormalization::n_exp_binbin1_proc_ggH[ thetaList=(lumi,xs_ggH) asymmThetaList=()
otherFactorList=(r) ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggWW[ thetaList=(lumi,xs_ggWW) asymmThetaList=()
otherFactorList=() ] = 0.06
ProcessNormalization::n_exp_binbin1_proc_others[ thetaList=(bg_others) asymmThetaList=()
otherFactorList=() ] = 0.22
ProcessNormalization::n_exp_binbin1_proc_qqWW[ thetaList=() asymmThetaList=()
otherFactorList=(WW_norm) ] = 0.8
```

```
p.d.f.s
-------
RooPoisson::WW_norm_Pdf[ x=WW_norm_In mean=WW_norm ] = 0.175467
SimpleGaussianConstraint::bg_others_Pdf[ x=bg_others mean=bg_others_In sigma=1 ] = 1
SimpleGaussianConstraint::lumi_Pdf[ x=lumi mean=lumi_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.339596
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.0780817
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.0595879
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.0137008
RooProdPdf::nuisancePdf[ xs_ggH_Pdf * bg_others_Pdf * WW_norm_Pdf * lumi_Pdf * xs_ggWW_Pdf ] =
0.175467
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.0780817
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.339596
SimpleGaussianConstraint::xs_ggH_Pdf[ x=xs_ggH mean=xs_ggH_In sigma=1 ] = 1
SimpleGaussianConstraint::xs_ggWW_Pdf[ x=xs_ggWW mean=xs_ggWW_In sigma=1 ] = 1
```

poisson part of likelihood for bin 1

Inspecting the workspace

```
functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggH + n_exp_binbin1_proc_qqWW +
n_exp_binbin1_proc_ggWW + n_exp_binbin1_proc_others ] = 2.55
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_qqWW + n_exp_binbin1_proc_ggWW +
n_exp_binbin1_proc_others ] = 1.08
ProcessNormalization::n_exp_binbin1_proc_ggH[ thetaList=(lumi,xs_ggH) asymmThetaList=()
otherFactorList=(r) ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggWW[ thetaList=(lumi,xs_ggWW) asymmThetaList=()
otherFactorList=() ] = 0.06
ProcessNormalization::n_exp_binbin1_proc_others[ thetaList=(bg_others) asymmThetaList=()
otherFactorList=() ] = 0.22
ProcessNormalization::n_exp_binbin1_proc_qqWW[ thetaList=() asymmThetaList=()
otherFactorList=(WW_norm) ] = 0.8
```

```
p.d.f.s
-------
RooPoisson::WW_norm_Pdf[ x=WW_norm_In mean=WW_norm ] = 0.175467
SimpleGaussianConstraint::bg_others_Pdf[ x=bg_others mean=bg_others_In sigma=1 ] = 1
SimpleGaussianConstraint::lumi_Pdf[ x=lumi mean=lumi_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.339596
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.0780817
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.0595879
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.0137008
RooProdPdf::nuisancePdf[ xs_ggH_Pdf * bg_others_Pdf * WW_norm_Pdf * lumi_Pdf * xs_ggWW_Pdf ] =
0.175467
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.0780817
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.339596
SimpleGaussianConstraint::xs_ggH_Pdf[ x=xs_ggH mean=xs_ggH_In sigma=1 ] = 1
SimpleGaussianConstraint::xs_ggWW_Pdf[ x=xs_ggWW mean=xs_ggWW_In sigma=1 ] = 1
```

poisson part of likelihood for all bins

Inspecting the workspace

```
functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggH + n_exp_binbin1_proc_qqWW +
n_exp_binbin1_proc_ggWW + n_exp_binbin1_proc_others ] = 2.55
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_qqWW + n_exp_binbin1_proc_ggWW +
n_exp_binbin1_proc_others ] = 1.08
ProcessNormalization::n_exp_binbin1_proc_ggH[ thetaList=(lumi,xs_ggH) asymmThetaList=()
otherFactorList=(r) ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggWW[ thetaList=(lumi,xs_ggWW) asymmThetaList=()
otherFactorList=() ] = 0.06
ProcessNormalization::n_exp_binbin1_proc_others[ thetaList=(bg_others) asymmThetaList=()
otherFactorList=() ] = 0.22
ProcessNormalization::n_exp_binbin1_proc_qqWW[ thetaList=() asymmThetaList=()
otherFactorList=(WW_norm) ] = 0.8
```

```
p.d.f.s
-------
RooPoisson::WW_norm_Pdf[ x=WW_norm_In mean=WW_norm ] = 0.175467
SimpleGaussianConstraint::bg_others_Pdf[ x=bg_others mean=bg_others_In sigma=1 ] = 1
SimpleGaussianConstraint::lumi_Pdf[ x=lumi mean=lumi_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.339596
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.0780817
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.0595879
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.0137008
RooProdPdf::nuisancePdf[ xs_ggH_Pdf * bg_others_Pdf * WW_norm_Pdf * lumi_Pdf * xs_ggWW_Pdf ] =
0.175467
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.0780817
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.339596
SimpleGaussianConstraint::xs_ggH_Pdf[ x=xs_ggH mean=xs_ggH_In sigma=1 ] = 1
SimpleGaussianConstraint::xs_ggWW_Pdf[ x=xs_ggWW mean=xs_ggWW_In sigma=1 ] = 1
```

constraint terms on lnN nuisances

Inspecting the workspace

```
functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggH + n_exp_binbin1_proc_qqWW +
n_exp_binbin1_proc_ggWW + n_exp_binbin1_proc_others ] = 2.55
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_qqWW + n_exp_binbin1_proc_ggWW +
n_exp_binbin1_proc_others ] = 1.08
ProcessNormalization::n_exp_binbin1_proc_ggH[ thetaList=(lumi,xs_ggH) asymmThetaList=()
otherFactorList=(r) ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggWW[ thetaList=(lumi,xs_ggWW) asymmThetaList=()
otherFactorList=() ] = 0.06
ProcessNormalization::n_exp_binbin1_proc_others[ thetaList=(bg_others) asymmThetaList=()
otherFactorList=() ] = 0.22
ProcessNormalization::n_exp_binbin1_proc_qqWW[ thetaList=() asymmThetaList=()
otherFactorList=(WW_norm) ] = 0.8
```

```
p.d.f.s
-------
RooPoisson::WW_norm_Pdf[ x=WW_norm_In mean=WW_norm ] = 0.175467
SimpleGaussianConstraint::bg_others_Pdf[ x=bg_others mean=bg_others_In sigma=1 ] = 1
SimpleGaussianConstraint::lumi_Pdf[ x=lumi mean=lumi_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.339596
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.0780817
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.0595879
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.0137008
RooProdPdf::nuisancePdf[ xs_ggH_Pdf * bg_others_Pdf * WW_norm_Pdf * lumi_Pdf * xs_ggWW_Pdf ] =
0.175467
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.0780817
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.339596
SimpleGaussianConstraint::xs_ggH_Pdf[ x=xs_ggH mean=xs_ggH_In sigma=1 ] = 1
SimpleGaussianConstraint::xs_ggWW_Pdf[ x=xs_ggWW mean=xs_ggWW_In sigma=1 ] = 1
```

constraint term on gamma nuisance

Inspecting the workspace

```
functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggH + n_exp_binbin1_proc_qqWW +
n_exp_binbin1_proc_ggWW + n_exp_binbin1_proc_others ] = 2.55
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_qqWW + n_exp_binbin1_proc_ggWW +
n_exp_binbin1_proc_others ] = 1.08
ProcessNormalization::n_exp_binbin1_proc_ggH[ thetaList=(lumi,xs_ggH) asymmThetaList=()
otherFactorList=(r) ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggWW[ thetaList=(lumi,xs_ggWW) asymmThetaList=()
otherFactorList=() ] = 0.06
ProcessNormalization::n_exp_binbin1_proc_others[ thetaList=(bg_others) asymmThetaList=()
otherFactorList=() ] = 0.22
ProcessNormalization::n_exp_binbin1_proc_qqWW[ thetaList=() asymmThetaList=()
otherFactorList=(WW_norm) ] = 0.8
```

```
p.d.f.s
-------
RooPoisson::WW_norm_Pdf[ x=WW_norm_In mean=WW_norm ] = 0.175467
SimpleGaussianConstraint::bg_others_Pdf[ x=bg_others mean=bg_others_In sigma=1 ] = 1
SimpleGaussianConstraint::lumi_Pdf[ x=lumi mean=lumi_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.339596
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.0780817
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.0595879
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.0137008
RooProdPdf::nuisancePdf[ xs_ggH_Pdf * bg_others_Pdf * WW_norm_Pdf * lumi_Pdf * xs_ggWW_Pdf ] =
0.175467
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.0780817
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.339596
SimpleGaussianConstraint::xs_ggH_Pdf[ x=xs_ggH mean=xs_ggH_In sigma=1 ] = 1
SimpleGaussianConstraint::xs_ggWW_Pdf[ x=xs_ggWW mean=xs_ggWW_In sigma=1 ] = 1
```

constraint term for all nuisances

Inspecting the workspace

```
functions
--------
RooAddition::n_exp_binbin1[ n_exp_binbin1_proc_ggH + n_exp_binbin1_proc_qqWW +
n_exp_binbin1_proc_ggWW + n_exp_binbin1_proc_others ] = 2.55
RooAddition::n_exp_binbin1_bonly[ n_exp_binbin1_proc_qqWW + n_exp_binbin1_proc_ggWW +
n_exp_binbin1_proc_others ] = 1.08
ProcessNormalization::n_exp_binbin1_proc_ggH[ thetaList=(lumi,xs_ggH) asymmThetaList=()
otherFactorList=(r) ] = 1.47
ProcessNormalization::n_exp_binbin1_proc_ggWW[ thetaList=(lumi,xs_ggWW) asymmThetaList=()
otherFactorList=() ] = 0.06
ProcessNormalization::n_exp_binbin1_proc_others[ thetaList=(bg_others) asymmThetaList=()
otherFactorList=() ] = 0.22
ProcessNormalization::n_exp_binbin1_proc_qqWW[ thetaList=() asymmThetaList=()
otherFactorList=(WW_norm) ] = 0.8
```

```
p.d.f.s
-------
RooPoisson::WW_norm_Pdf[ x=WW_norm_In mean=WW_norm ] = 0.175467
SimpleGaussianConstraint::bg_others_Pdf[ x=bg_others mean=bg_others_In sigma=1 ] = 1
SimpleGaussianConstraint::lumi_Pdf[ x=lumi mean=lumi_In sigma=1 ] = 1
RooProdPdf::modelObs_b[ pdf_binbin1_bonly ] = 0.339596
RooProdPdf::modelObs_s[ pdf_binbin1 ] = 0.0780817
RooProdPdf::model_b[ modelObs_b * nuisancePdf ] = 0.0595879
RooProdPdf::model_s[ modelObs_s * nuisancePdf ] = 0.0137008
RooProdPdf::nuisancePdf[ xs_ggH_Pdf * bg_others_Pdf * WW_norm_Pdf * lumi_Pdf * xs_ggWW_Pdf ] =
0.175467
RooPoisson::pdf_binbin1[ x=n_obs_binbin1 mean=n_exp_binbin1 ] = 0.0780817
RooPoisson::pdf_binbin1_bonly[ x=n_obs_binbin1 mean=n_exp_binbin1_bonly ] = 0.339596
SimpleGaussianConstraint::xs_ggH_Pdf[ x=xs_ggH mean=xs_ggH_In sigma=1 ] = 1
SimpleGaussianConstraint::xs_ggWW_Pdf[ x=xs_ggWW mean=xs_ggWW_In sigma=1 ] = 1
```

full likelihood for s+b and b-only models

Workspaces vs. datacards

- This is a very simple model, but workspace is already complicated!
- Realistic analyses will have multiple bins, many nuisance parameters, more complicated physics models…
- Benefit of datacards — simple / human-readable description of complicated likelihood
  - Could build workspace by hand if you wanted, but not necessary save in very particular scenarios

Full combine likelihood

$$\mathcal{L}(\vec{\mu},\vec{\nu}) = \prod_{c=1}^{N_C}\prod_{b=1}^{N_B^c} \mathrm{Poiss}(n_{cb}; n_{cb}^{\mathrm{exp}}(\vec{\mu},\vec{\nu})) \prod_{e=1}^{N_E} p_e(y_e;\nu_e)$$

Exp. events per bin

NP constraints

$$p_{\mathrm{L,S}} = \mathcal{N}(y_{\mathrm{L,S}};\nu_{\mathrm{L,S}},1)$$

$$p_{\mathrm{G}} = \mathrm{Poiss}(y_{\mathrm{G}};\nu_{\mathrm{G}})$$

$$p_{\mathrm{B}} = \begin{cases} \mathcal{N}(y_{\mathrm{B}};\nu_{\mathrm{B}},1) & \nu_{\mathrm{B}} \in \text{Gaussian} \\ \mathrm{Poiss}(y_{\mathrm{B}};\nu_{\mathrm{B}}) & \nu_{\mathrm{B}} \in \text{Poisson} \end{cases}$$

$$p_\rho = \begin{cases} \mathcal{N}(y_\rho;\nu_\rho,\sigma_\nu) \\ \text{Uniform on [a, b]} \end{cases}$$

$$n_{cb}^{\mathrm{exp}} = \max(0, \sum_p M_{cp}(\vec{\mu}) N_{cp}(\vec{\nu}_L,\vec{\nu}_S,\vec{\nu}_G,\vec{\nu}_\rho) \omega_{cbp}(\vec{\nu}_S) + E_{cb}(\vec{\nu}_B))$$

Physics model scaling · Process norm. · Process templates · MC stats

Barlow-Beeston "lite"

$$E_{cb}(\vec{\mu},\vec{\nu},\nu) = \nu \left(\sum_p (e_{cpb} N_{cp} M_{cp}(\vec{\mu},\vec{\nu}))^2\right)^{\frac{1}{2}}$$

full

$$E_{cb}(\vec{\mu},\vec{\nu},\vec{\nu}_\alpha,\vec{\nu}_\beta) = \sum_\alpha^{\text{Poisson}} \left(\frac{\nu_\alpha}{y_\alpha} - 1\right) \omega_{c\alpha b} N_{c\alpha} M_{c\alpha}(\vec{\mu},\vec{\nu}) + \sum_\beta^{\text{Gaussian}} \nu_\beta e_{c\beta b} N_{c\beta} M_{c\beta}(\vec{\mu},\vec{\nu}),$$

Gamma · Log-normal · Asymmetric log-normal · rateParams

$$N = N_0(\nu_G) \prod_n {\kappa_n}^{\nu_{L,n}} \prod_a \kappa_a^{\mathrm{A}}(\nu_{L(S)}^a, \kappa_a^+, \kappa_a^-)^{\nu_{L(S)}^a} \prod_r F_r(\nu_{\rho,r})$$

$$N_0 = \frac{\nu_G}{y_G}$$

$$\kappa^{\mathrm{A}}(\nu,\kappa^+,\kappa^-) = \begin{cases} \kappa^+, & \text{for } \nu \geq 0.5 \\ \kappa^-, & \text{for } \nu \leq -0.5 \\ \exp\left(\frac{1}{2}\left((\ln\kappa^+ + \ln\kappa^+) + \frac{1}{4}(\ln\kappa^+ - \ln\kappa^-) I(\nu)\right)\right. & \text{otherwise} \end{cases}$$

Interpolation between up and down variations (norm)

$$I(\nu) = 48\nu^5 - 40\nu^3 + 15\nu$$

$$\kappa_s^\pm = \frac{\sum_b \omega_b^{s,\pm}}{\sum_b \omega_b^0}.$$

Shape uncert. norm. change factored out

$$\omega_b(\vec{\nu}_S) = \begin{cases} \max\left(0, \omega^0 \left(f_b^0 + \sum_s F\left(\nu_s, \delta_b^{s,+}, \delta_b^{s,-}, \epsilon_s\right)\right)\right) & \text{(direct)}, \\ \max\left(0, \omega^0 \exp\left(\ln(f_b^0) + \sum_s F(\nu_s, \Delta_b^{s,+}, \Delta_b^{s,-}, \epsilon_s)\right)\right) & \text{(logarithmic)}, \end{cases}$$

Vertical morphing

$$f_b = \omega_b / \sum \omega_b$$

$$\omega^0 = \sum \omega_b^0,\ \delta^\pm = f_i^\pm - f_i^0,\ \text{and}\ \Delta^\pm = \ln(\tfrac{f_i^\pm}{f_i^0})$$

$$F(\nu,\delta^+,\delta^-,\epsilon_s) = \begin{cases} \frac{1}{2}\nu' \left((\delta^+ - \delta^-) + \frac{1}{8}(\delta^+ + \delta^-)(3\bar{\nu}^5 - 10\bar{\nu}^3 + 15\bar{\nu})\right), & \text{for } -q < \nu' < q; \\ \nu'\delta^+, & \text{for } \nu' \geq q; \\ -\nu'\delta^-, & \text{for } \nu' \leq -q; \end{cases}$$

Interpolation between up and down variations (shape)

$$\nu' = \nu\epsilon_s$$

$$\bar{\nu} = \frac{\nu'}{q}$$

$$q = \min_s \epsilon_s$$

Running fits

- What measurements could we do with this model?

    1. Best fit value of r

```
combine -M MultiDimFit --algo singles simple_counting.root
```

What do we expect?

Running fits

- What measurements could we do with this model?

  1. Best fit value of r

```
combine -M MultiDimFit --algo singles simple_counting.root
```

```
<<< Combine >>>
 <<< v9.2.0 >>>
>>> Random number generator seed is 123456
>>> Method used is MultiDimFit
Doing initial fit:
Error in <ROOT::Math::Fitter::CalculateMinosErrors>: Minos error calculation
failed for all the selected parameters

 --- MultiDimFit ---
best fit parameter values and profile-likelihood uncertainties:
 Warning - No valid low-error found, will report difference to minimum of
range for : r
   r :    +0.000   -0.000/+0.335 (68%)
Done in 0.00 min (cpu), 0.00 min (real)
```

Running fits

- What measurements could we do with this model?

  1. Best fit value of r

```
combine -M MultiDimFit --algo singles simple_counting.root
```

```
<<< Combine >>>
 <<< v9.2.0 >>>
>>> Random number generator seed is 123456
>>> Method used is MultiDimFit
Doing initial fit:
Error in <ROOT::Math::Fitter::CalculateMinosErrors>: Minos error calculation
failed for all the selected parameters

 --- MultiDimFit ---
best fit parameter values and profile-likelihood uncertainties:
 Warning - No valid low-error found, will report difference to minimum of
ra

Do
```

These are Minos errors — fit is walking along r until it hits the 68% CI bound (from log profile likelihood ratio)
Require r ≥ 0 due to physics constraints
Best fit value of r is 0 —> cannot ‘walk’ lower without hitting wall

Running fits

- What measurements could we do with this model?

  1. Best fit value of r

  2. Limit on r

```
combine -M AsymptoticLimits simple_counting.root
```

Running fits

- What measurements could we do with this model?

  1. Best fit value of r

  2. Limit on r

```
combine -M AsymptoticLimits simple_counting.root
```

```
 <<< Combine >>>
 <<< v9.2.0 >>>
>>> Random number generator seed is 123456
>>> Method used is AsymptoticLimits

 -- AsymptoticLimits ( CLs ) --
Observed Limit: r < 1.6281
Expected  2.5%: r < 0.9640
Expected 16.0%: r < 1.4329
Expected 50.0%: r < 2.3281
Expected 84.0%: r < 3.9800
Expected 97.5%: r < 6.6194

Done in 0.00 min (cpu), 0.00 min (real)
```

→ 95% CL

→ Expected limit is weaker

Shape Analysis

- Realistic physics analyses are not cut-and-count — instead comparing shapes of some discriminant for signal and background

- Two types of shape analyses in combine:

  - Binned (histograms) —> likelihood is product of likelihoods per bin, e.g. multibin counting experiment

  - Unbinned (parametric) —> likelihood is product of pdf likelihoods per bin times overall poisson yield term (extended likelihood)

Binned Shape Analysis

Datacard: data/tutorials/longexercise/datacard_part3.txt

```
imax    1 number of bins
jmax    4 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes *         signal_region datacard_part3.shapes.root signal_region/$PROCESS signal_region/$PROCESS_$SYSTEMATIC
shapes bbHtautau signal_region datacard_part3.shapes.root signal_region/bbHtautau$MASS signal_region/
bbHtautau$MASS_$SYSTEMATIC
--------------------------------------------------------------------------------
bin          signal_region
observation  3416.0
--------------------------------------------------------------------------------
bin                                   signal_region   signal_region   signal_region   signal_region   signal_region
process                               ttbar           diboson         Ztautau         jetFakes        bbHtautau
process                               1               2               3               4               0
rate                                  683.017         96.5185         742.649         2048.94         198.521
--------------------------------------------------------------------------------
CMS_eff_b                     lnN     1.02            1.02            1.02            -               1.02
CMS_eff_t                     lnN     1.12            1.12            1.12            -               1.12
CMS_eff_t_highpt              shape   1               1               1               -               1
CMS_scale_t_1prong0pi0_13TeV  shape   1               1               1               -               1
CMS_scale_t_1prong1pi0_13TeV  shape   1               1               1               -               1
CMS_scale_t_3prong0pi0_13TeV  shape   1               1               1               -               1
acceptance_bbH                lnN     -               -               -               -               1.05
lumi_13TeV                    lnN     1.025           1.025           1.025           -               1.025
norm_jetFakes                 lnN     -               -               -               1.2             -
top_pt_ttbar_shape            shape   1               -               -               -               -
xsec_diboson                  lnN     -               1.05            -               -               -
* autoMCStats 0
```

Binned Shape Analysis

Tells combine 1) root file containing shape histograms and 2) names of histograms for specific processes

```
imax    1 number of bins
jmax    4 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes *         signal_region datacard_part3.shapes.root signal_region/$PROCESS signal_region/$PROCESS_$SYSTEMATIC
shapes bbHtautau signal_region datacard_part3.shapes.root signal_region/bbHtautau$MASS signal_region/
bbHtautau$MASS_$SYSTEMATIC
--------------------------------------------------------------------------------
bin          signal_region
observation  3416.0
--------------------------------------------------------------------------------
bin                                  signal_region   signal_region   signal_region   signal_region   signal_region
process                              ttbar           diboson         Ztautau         jetFakes        bbHtautau
process                              1               2               3               4               0
rate                                 683.017         96.5185         742.649         2048.94         198.521
--------------------------------------------------------------------------------
CMS_eff_b                    lnN     1.02            1.02            1.02            -               1.02
CMS_eff_t                    lnN     1.12            1.12            1.12            -               1.12
CMS_eff_t_highpt             shape   1               1               1               -               1
CMS_scale_t_1prong0pi0_13TeV shape   1               1               1               -               1
CMS_scale_t_1prong1pi0_13TeV shape   1               1               1               -               1
CMS_scale_t_3prong0pi0_13TeV shape   1               1               1               -               1
acceptance_bbH               lnN     -               -               -               -               1.05
lumi_13TeV                   lnN     1.025           1.025           1.025           -               1.025
norm_jetFakes                lnN     -               -               -               1.2             -
top_pt_ttbar_shape           shape   1               -               -               -               -
xsec_diboson                 lnN     -               1.05            -               -               -
* autoMCStats 0
```

Binned Shape Analysis

Variables $PROCESS and $SYSTEMATIC match process name and systematic name in data card
Later commands override previous — we first define a naming pattern for all histograms, then override for bbHtautau

```
imax    1 number of bins
jmax    4 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes *         signal_region datacard_part3.shapes.root signal_region/$PROCESS signal_region/$PROCESS_$SYSTEMATIC
shapes bbHtautau signal_region datacard_part3.shapes.root signal_region/bbHtautau$MASS signal_region/
bbHtautau$MASS_$SYSTEMATIC
--------------------------------------------------------------------------------
bin          signal_region
observation  3416.0
--------------------------------------------------------------------------------
bin                                  signal_region   signal_region   signal_region   signal_region   signal_region
process                              ttbar           diboson         Ztautau         jetFakes        bbHtautau
process                              1               2               3               4               0
rate                                 683.017         96.5185         742.649         2048.94         198.521
--------------------------------------------------------------------------------
CMS_eff_b                    lnN     1.02            1.02            1.02            -               1.02
CMS_eff_t                    lnN     1.12            1.12            1.12            -               1.12
CMS_eff_t_highpt             shape   1               1               1               -               1
CMS_scale_t_1prong0pi0_13TeV shape   1               1               1               -               1
CMS_scale_t_1prong1pi0_13TeV shape   1               1               1               -               1
CMS_scale_t_3prong0pi0_13TeV shape   1               1               1               -               1
acceptance_bbH               lnN     -               -               -               -               1.05
lumi_13TeV                   lnN     1.025           1.025           1.025           -               1.025
norm_jetFakes                lnN     -               -               -               1.2             -
top_pt_ttbar_shape           shape   1               -               -               -               -
xsec_diboson                 lnN     -               1.05            -               -               -
* autoMCStats 0
```

Binned Shape Analysis

```
imax    1 number of bins
jmax    4 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes *         signal_region datacard_part3.shapes.root signal_region/$PROCESS signal_region/$PROCESS_$SYSTEMATIC
shapes bbHtautau signal_region datacard_part3.shapes.root signal_region/bbHtautau$MASS signal_region/
bbHtautau$MASS_$SYSTEMATIC
--------------------------------------------------------------------------------
bin          signal_region
observation  3416.0
--------------------------------------------------------------------------------
bin                                   signal_region   signal_region   signal_region   signal_region   signal_region
process                               ttbar           diboson         Ztautau         jetFakes        bbHtautau
process                               1               2               3               4               0
rate                                  683.017         96.5185         742.649         2048.94         198.521
--------------------------------------------------------------------------------
CMS_eff_b                      lnN    1.02            1.02            1.02            -               1.02
CMS_eff_t                      lnN    1.12            1.12            1.12            -               1.12
CMS_eff_t_highpt               shape  1               1               1               -               1
CMS_scale_t_1prong0pi0_13TeV   shape  1               1               1               -               1
CMS_scale_t_1prong1pi0_13TeV   shape  1               1               1               -               1
CMS_scale_t_3prong0pi0_13TeV   shape  1               1               1               -               1
acceptance_bbH                 lnN    -               -               -               -               1.05
lumi_13TeV                     lnN    1.025           1.025           1.025           -               1.025
norm_jetFakes                  lnN    -               -               -               1.2             -
top_pt_ttbar_shape             shape  1               -               -               -               -
xsec_diboson                   lnN    -               1.05            -               -               -
* autoMCStats 0
```

1 —> up and down shapes are ±1 sigma variations

Binned Shape Analysis

```
imax    1 number of bins
jmax    4 number of processes minus 1
kmax    * number of nuisance parameters
--------------------------------------------------------------------------------
shapes *         signal_region datacard_part3.shapes.root signal_region/$PROCESS signal_region/$PROCESS_$SYSTEMATIC
shapes bbHtautau signal_region datacard_part3.shapes.root signal_region/bbHtautau$MASS signal_region/
bbHtautau$MASS_$SYSTEMATIC
--------------------------------------------------------------------------------
bin          signal_region
observation  3416.0
--------------------------------------------------------------------------------
bin                                   signal_region   signal_region   signal_region   signal_region   signal_region
process                               ttbar           diboson         Ztautau         jetFakes        bbHtautau
process                               1               2               3               4               0
rate                                  683.017         96.5185         742.649         2048.94         198.521
--------------------------------------------------------------------------------
CMS_eff_b                      lnN    1.02            1.02            1.02            -               1.02
CMS_eff_t                      lnN    1.12            1.12            1.12            -               1.12
CMS_eff_t_highpt               shape  1               1               1               -               1
CMS_scale_t_1prong0pi0_13TeV   shape  1               1               1               -               1
CMS_scale_t_1prong1pi0_13TeV   shape  1               1               1               -               1
CMS_scale_t_3prong0pi0_13TeV   shape  1               1               1               -               1
acceptance_bbH                 lnN    -               -               -               -               1.05
lumi_13TeV                     lnN    1.025           1.025           1.025           -               1.025
norm_jetFakes                  lnN    -               -               -               1.2             -
top_pt_ttbar_shape             shape  1               -               -               -               -
xsec_diboson                   lnN    -               1.05            -               -               -
* autoMCStats 0
```

Tells combine how to handle MC stat. unc. — full description here

Syntax: `[channel] autoMCStats [threshold] [include-signal = 0] [hist-mode = 1]`

In this case: assign single nuisance parameter per bin, corresponding to total MC stat. unc. of all bkg processes

Binned Shape Analysis: Workspace

```
text2workspace.py data/tutorials/longexercise/datacard_part3.txt \
                  -o simple_shape.root \
                  --mass 200
```

Binned Shape Analysis: Running Fits

- What measurements could we do with this model?

    1. Best fit value of r

```
combine -M MultiDimFit --algo singles simple_shape.root
```

Binned Shape Analysis: Running Fits

- What measurements could we do with this model?

  1. Best fit value of r

```
combine -M MultiDimFit --algo singles simple_shape.root
```

```
 <<< Combine >>>
 <<< v9.2.0 >>>
>>> Random number generator seed is 123456
>>> Method used is MultiDimFit
Doing initial fit:

 --- MultiDimFit ---
best fit parameter values and profile-likelihood uncertainties:
   r :    +0.480   -0.431/+0.448 (68%)
Done in 0.00 min (cpu), 0.00 min (real)
```

Binned Shape Analysis: Running Fits

- What measurements could we do with this model?

  1. Best fit value of r

  2. Significance

```
combine -M Significance simple_shape.root
```

Binned Shape Analysis: Running Fits

- What measurements could we do with this model?
  1. Best fit value of r
  2. Significance

```
combine -M Significance simple_shape.root
```

```
 <<< Combine >>>
 <<< v9.2.0 >>>
>>> Random number generator seed is 123456
>>> Method used is Significance

 -- Significance --
Significance: 1.11272
Done in 0.00 min (cpu), 0.00 min (real)
```

Binned Shape Analysis: Running Fits

- What measurements could we do with this model?

  1. Best fit value of r

  2. Significance

  3. Best fit values of nuisance parameters

```
combine -M FitDiagnostics simple_shape.root
```

Binned Shape Analysis: Running Fits

- What measurements could we do with this model?

1. Best fit value of r
2. Significance
3. Best fit values of nuisance parameters

```
combine -M FitDiagnostics simple_shape.root
```

```
 <<< Combine >>>
 <<< v9.2.0 >>>
>>> Random number generator seed is 123456
>>> Method used is FitDiagnostics

 --- FitDiagnostics ---
Best fit r: 0.479467  -0.431232/+0.448341  (68% CL)
Done in 0.00 min (cpu), 0.00 min (real)
```

Inspecting FitDiagnostics output

```
root -l fitDiagnosticsTest.root
…
root [1] .ls
TFile**     fitDiagnosticsTest.root
 TFile*     fitDiagnosticsTest.root
KEY: RooFitResult  nuisances_prefit_res;1
KEY: TProcessID ProcessID0;1   9d2bbadc-eb64-11ee-9108-660db9bcbeef
KEY: RooArgSet  nuisances_prefit;1Set of RooAbsArg objects
KEY: RooFitResult  fit_b;1
KEY: RooFitResult  fit_s;1
KEY: TTree   tree_fit_sb;1  tree_fit_sb
KEY: TTree   tree_fit_b;1   tree_fit_b
KEY: TTree   tree_prefit;1  tree_prefit
```

Inspecting FitDiagnostics output

```
root -l fitDiagnosticsTest.root
…
root [1] .ls
TFile**     fitDiagnosticsTest.root
 TFile*     fitDiagnosticsTest.root
KEY: RooFitResult  nuisances_prefit_res;1
KEY: TProcessID ProcessID0;1   9d2bbadc-eb64-11ee-9108-660db9bcbeef
KEY: RooArgSet  nuisances_prefit;1Set of RooAbsArg objects
KEY: RooFitResult  fit_b;1
KEY: RooFitResult  fit_s;1
KEY: TTree   tree_fit_sb;1  tree_fit_sb
KEY: TTree   tree_fit_b;1   tree_fit_b
KEY: TTree   tree_prefit;1  tree_prefit
```

s+b and b-only fit results

Inspecting FitDiagnostics output

```
root -l fitDiagnosticsTest.root
…
root [1] .ls
TFile**     fitDiagnosticsTest.root
 TFile*     fitDiagnosticsTest.root
KEY: RooFitResult  nuisances_prefit_res;1
KEY: TProcessID ProcessID0;1   9d2bbadc-eb64-11ee-9108-660db9bcbeef
KEY: RooArgSet  nuisances_prefit;1Set of RooAbsArg objects
KEY: RooFitResult  fit_b;1
KEY: RooFitResult  fit_s;1
KEY: TTree   tree_fit_sb;1  tree_fit_sb
KEY: TTree   tree_fit_b;1   tree_fit_b
KEY: TTree   tree_prefit;1  tree_prefit
```

Prefit, s+b fit, and b-only fit values of nuisance parameters

Inspecting FitDiagnostics output

```
root [2] fit_s->Print()

  RooFitResult: minimized FCN value: -2.19244e-06, estimated distance to minimum: 3.12019e-06
                covariance matrix quality: Full, accurate covariance matrix
                Status : MINIMIZE=0 HESSE=0

    Floating Parameter    FinalValue +/-  Error
  --------------------  --------------------------
             CMS_eff_b   -5.0091e-02 +/-  9.93e-01
             CMS_eff_t   -2.8360e-01 +/-  7.09e-01
      CMS_eff_t_highpt   -5.5729e-01 +/-  9.41e-01
  CMS_scale_t_1prong0pi0_13TeV   -1.3804e-01 +/-  6.36e-01
  CMS_scale_t_1prong1pi0_13TeV   -1.1440e-01 +/-  5.31e-01
  CMS_scale_t_3prong0pi0_13TeV   -2.4910e-01 +/-  6.81e-01
        acceptance_bbH   -4.1198e-04 +/-  1.00e+00
            lumi_13TeV   -6.1256e-02 +/-  9.88e-01
         norm_jetFakes   -3.3203e-01 +/-  3.45e-01
  prop_binsignal_region_bin0   -4.7165e-01 +/-  8.19e-01
  prop_binsignal_region_bin1   -6.4677e-03 +/-  8.34e-01
  prop_binsignal_region_bin10    5.6409e-01 +/-  8.89e-01
  prop_binsignal_region_bin11   -9.4163e-01 +/-  8.98e-01
  prop_binsignal_region_bin12    3.1562e-05 +/-  8.70e-01
  prop_binsignal_region_bin13    4.1191e-01 +/-  8.45e-01
  prop_binsignal_region_bin14    1.8375e-01 +/-  8.07e-01
  prop_binsignal_region_bin15   -2.6847e-01 +/-  9.23e-01
  prop_binsignal_region_bin16   -6.2880e-01 +/-  1.00e+00
  prop_binsignal_region_bin17   -8.3528e-01 +/-  1.00e+00
  prop_binsignal_region_bin2   -1.0385e+00 +/-  8.55e-01
  prop_binsignal_region_bin3    1.2987e+00 +/-  8.48e-01
  prop_binsignal_region_bin4   -5.7833e-01 +/-  8.76e-01
  prop_binsignal_region_bin5   -7.3025e-02 +/-  9.01e-01
  prop_binsignal_region_bin6    3.8000e-01 +/-  8.93e-01
  prop_binsignal_region_bin7   -2.7112e-02 +/-  8.78e-01
  prop_binsignal_region_bin8   -2.9982e-01 +/-  9.27e-01
  prop_binsignal_region_bin9   -1.5786e-01 +/-  8.87e-01
                     r    4.7947e-01 +/-  4.35e-01
    top_pt_ttbar_shape    4.2553e-01 +/-  7.33e-01
          xsec_diboson   -1.2748e-02 +/-  9.99e-01
```

Inspecting FitDiagnostics output

```
root [2] fit_s->Print()

  RooFitResult: minimized FCN value: -2.19244e-06, estimated distance to minimum: 3.12019e-06
                covariance matrix quality: Full, accurate covariance matrix
                Status : MINIMIZE=0 HESSE=0

    Floating Parameter    FinalValue +/-  Error
  --------------------  --------------------------
             CMS_eff_b   -5.0091e-02 +/-  9.93e-01
             CMS_eff_t   -2.8360e-01 +/-  7.09e-01
      CMS_eff_t_highpt   -5.5729e-01 +/-  9.41e-01
  CMS_scale_t_1prong0pi0_13TeV   -1.3804e-01 +/-  6.36e-01
  CMS_scale_t_1prong1pi0_13TeV   -1.1440e-01 +/-  5.31e-01
  CMS_scale_t_3prong0pi0_13TeV   -2.4910e-01 +/-  6.81e-01
        acceptance_bbH   -4.1198e-04 +/-  1.00e+00
            lumi_13TeV   -6.1256e-02 +/-  9.88e-01
         norm_jetFakes   -3.3203e-01 +/-  3.45e-01
  prop_binsignal_region_bin0   -4.7165e-01 +/-  8.19e-01
  prop_binsignal_region_bin1   -6.4677e-03 +/-  8.34e-01
  prop_binsignal_region_bin10    5.6409e-01 +/-  8.89e-01
  prop_binsignal_region_bin11   -9.4163e-01 +/-  8.98e-01
  prop_binsignal_region_bin12    3.1562e-05 +/-  8.70e-01
  prop_binsignal_region_bin13    4.1191e-01 +/-  8.45e-01
  prop_binsignal_region_bin14    1.8375e-01 +/-  8.07e-01
  prop_binsignal_region_bin15   -2.6847e-01 +/-  9.23e-01
  prop_binsignal_region_bin16   -6.2880e-01 +/-  1.00e+00
  prop_binsignal_region_bin17   -8.3528e-01 +/-  1.00e+00
  prop_binsignal_region_bin2   -1.0385e+00 +/-  8.55e-01
  prop_binsignal_region_bin3    1.2987e+00 +/-  8.48e-01
  prop_binsignal_region_bin4   -5.7833e-01 +/-  8.76e-01
  prop_binsignal_region_bin5   -7.3025e-02 +/-  9.01e-01
  prop_binsignal_region_bin6    3.8000e-01 +/-  8.93e-01
  prop_binsignal_region_bin7   -2.7112e-02 +/-  8.78e-01
  prop_binsignal_region_bin8   -2.9982e-01 +/-  9.27e-01
  prop_binsignal_region_bin9   -1.5786e-01 +/-  8.87e-01
                     r    4.7947e-01 +/-  4.35e-01
    top_pt_ttbar_shape    4.2553e-01 +/-  7.33e-01
          xsec_diboson   -1.2748e-02 +/-  9.99e-01
```

Fit converged and covariance matrix (e.g. nuisance parameter uncertainties) is valid

Inspecting FitDiagnostics output

```
root [2] fit_s->Print()

  RooFitResult: minimized FCN value: -2.19244e-06, estimated distance to minimum: 3.12019e-06
                covariance matrix quality: Full, accurate covariance matrix
                Status : MINIMIZE=0 HESSE=0

    Floating Parameter    FinalValue +/-  Error
  --------------------  --------------------------
             CMS_eff_b   -5.0091e-02 +/-  9.93e-01
             CMS_eff_t   -2.8360e-01 +/-  7.09e-01
      CMS_eff_t_highpt   -5.5729e-01 +/-  9.41e-01
  CMS_scale_t_1prong0pi0_13TeV   -1.3804e-01 +/-  6.36e-01
  CMS_scale_t_1prong1pi0_13TeV   -1.1440e-01 +/-  5.31e-01
  CMS_scale_t_3prong0pi0_13TeV   -2.4910e-01 +/-  6.81e-01
        acceptance_bbH   -4.1198e-04 +/-  1.00e+00
            lumi_13TeV   -6.1256e-02 +/-  9.88e-01
         norm_jetFakes   -3.3203e-01 +/-  3.45e-01
  prop_binsignal_region_bin0   -4.7165e-01 +/-  8.19e-01
  prop_binsignal_region_bin1   -6.4677e-03 +/-  8.34e-01
  prop_binsignal_region_bin10    5.6409e-01 +/-  8.89e-01
  prop_binsignal_region_bin11   -9.4163e-01 +/-  8.98e-01
  prop_binsignal_region_bin12    3.1562e-05 +/-  8.70e-01
  prop_binsignal_region_bin13    4.1191e-01 +/-  8.45e-01
  prop_binsignal_region_bin14    1.8375e-01 +/-  8.07e-01
  prop_binsignal_region_bin15   -2.6847e-01 +/-  9.23e-01
  prop_binsignal_region_bin16   -6.2880e-01 +/-  1.00e+00
  prop_binsignal_region_bin17   -8.3528e-01 +/-  1.00e+00
  prop_binsignal_region_bin2   -1.0385e+00 +/-  8.55e-01
  prop_binsignal_region_bin3    1.2987e+00 +/-  8.48e-01
  prop_binsignal_region_bin4   -5.7833e-01 +/-  8.76e-01
  prop_binsignal_region_bin5   -7.3025e-02 +/-  9.01e-01
  prop_binsignal_region_bin6    3.8000e-01 +/-  8.93e-01
  prop_binsignal_region_bin7   -2.7112e-02 +/-  8.78e-01
  prop_binsignal_region_bin8   -2.9982e-01 +/-  9.27e-01
  prop_binsignal_region_bin9   -1.5786e-01 +/-  8.87e-01
                         r    4.7947e-01 +/-  4.35e-01
    top_pt_ttbar_shape    4.2553e-01 +/-  7.33e-01
          xsec_diboson   -1.2748e-02 +/-  9.99e-01
```

Postfit values for MC stat uncertainties (per-bin nuisance generated by autoMCStat)
Prefit values are 0 ± 1
Shift in central value —> pull
Uncertainty smaller than 1 —> constraint

Inspecting FitDiagnostics output

```
root [2] fit_s->Print()

  RooFitResult: minimized FCN value: -2.19244e-06, estimated distance to minimum: 3.12019e-06
                covariance matrix quality: Full, accurate covariance matrix
                Status : MINIMIZE=0 HESSE=0

    Floating Parameter    FinalValue +/-  Error
  --------------------  --------------------------
             CMS_eff_b   -5.0091e-02 +/-  9.93e-01
             CMS_eff_t   -2.8360e-01 +/-  7.09e-01
      CMS_eff_t_highpt   -5.5729e-01 +/-  9.41e-01
  CMS_scale_t_1prong0pi0_13TeV   -1.3804e-01 +/-  6.36e-01
  CMS_scale_t_1prong1pi0_13TeV   -1.1440e-01 +/-  5.31e-01
  CMS_scale_t_3prong0pi0_13TeV   -2.4910e-01 +/-  6.81e-01
        acceptance_bbH   -4.1198e-04 +/-  1.00e+00
            lumi_13TeV   -6.1256e-02 +/-  9.88e-01
         norm_jetFakes   -3.3203e-01 +/-  3.45e-01
  prop_binsignal_region_bin0   -4.7165e-01 +/-  8.19e-01
  prop_binsignal_region_bin1   -6.4677e-03 +/-  8.34e-01
  prop_binsignal_region_bin10    5.6409e-01 +/-  8.89e-01
  prop_binsignal_region_bin11   -9.4163e-01 +/-  8.98e-01
  prop_binsignal_region_bin12    3.1562e-05 +/-  8.70e-01
  prop_binsignal_region_bin13    4.1191e-01 +/-  8.45e-01
  prop_binsignal_region_bin14    1.8375e-01 +/-  8.07e-01
  prop_binsignal_region_bin15   -2.6847e-01 +/-  9.23e-01
  prop_binsignal_region_bin16   -6.2880e-01 +/-  1.00e+00
  prop_binsignal_region_bin17   -8.3528e-01 +/-  1.00e+00
  prop_binsignal_region_bin2   -1.0385e+00 +/-  8.55e-01
  prop_binsignal_region_bin3    1.2987e+00 +/-  8.48e-01
  prop_binsignal_region_bin4   -5.7833e-01 +/-  8.76e-01
  prop_binsignal_region_bin5   -7.3025e-02 +/-  9.01e-01
  prop_binsignal_region_bin6    3.8000e-01 +/-  8.93e-01
  prop_binsignal_region_bin7   -2.7112e-02 +/-  8.78e-01
  prop_binsignal_region_bin8   -2.9982e-01 +/-  9.27e-01
  prop_binsignal_region_bin9   -1.5786e-01 +/-  8.87e-01
                         r    4.7947e-01 +/-  4.35e-01
    top_pt_ttbar_shape    4.2553e-01 +/-  7.33e-01
          xsec_diboson   -1.2748e-02 +/-  9.99e-01
```

Postfit values for log-normal and shape nuisances

Prefit values are 0 ± 1

Shift in central value —> pull

Uncertainty smaller than 1 —> constraint

Physics Models

- By default, combine assumes you have one POI (signal strength r) which uniformly scales all signals (processes with ID ≤ 0 in data card)
- However, we often want to do something more complicated
  - Multiple signals with different signal strengths
  - Mass, width, etc. of resonance as POI
  - Interference
  - etc…
- Solution: physics models
- combine maintains a selection of commonly used physics models
  - See documentation and links here
  - Can also build your own

Physics Models

- By default, combine assumes you have one POI (signal strength r) which uniformly scales all signals (processes with ID ≤ 0 in data card)
- However, we often want to do something more complicated
  - Multiple signals with different signal strengths
    - Mass, width, etc. of resonance as POI
    - Interference
    - etc…
  - Solution: physics models
  - combine maintains a selection of commonly used physics models
    - See documentation and links here
    - Can also build your own

Let's test out this one

Physics Models: Datacard

```
Combination of htt_tt_0_8TeV=htt_tt_0_8TeV.txt  htt_tt_1_8TeV=htt_tt_1_8TeV.txt  htt_tt_2_8TeV=htt_tt_2_8TeV.txt
imax 3 number of bins
jmax 10 number of processes minus 1
kmax 66 number of nuisance parameters
----------------------------------------------------------------------------------------------------------------
-
shapes *              htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/$PROCESS htt_tt_0_8TeV/$PROCESS_$SYSTEMATIC
shapes WH             htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/WH$MASS htt_tt_0_8TeV/WH$MASS_$SYSTEMATIC
shapes ZH             htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/ZH$MASS htt_tt_0_8TeV/ZH$MASS_$SYSTEMATIC
shapes ggH            htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/ggH$MASS htt_tt_0_8TeV/ggH$MASS_$SYSTEMATIC
shapes qqH            htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/qqH$MASS htt_tt_0_8TeV/qqH$MASS_$SYSTEMATIC
shapes *              htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/$PROCESS htt_tt_1_8TeV/$PROCESS_$SYSTEMATIC
shapes WH             htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/WH$MASS htt_tt_1_8TeV/WH$MASS_$SYSTEMATIC
shapes ZH             htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/ZH$MASS htt_tt_1_8TeV/ZH$MASS_$SYSTEMATIC
shapes ggH            htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/ggH$MASS htt_tt_1_8TeV/ggH$MASS_$SYSTEMATIC
shapes qqH            htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/qqH$MASS htt_tt_1_8TeV/qqH$MASS_$SYSTEMATIC
shapes *              htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/$PROCESS htt_tt_2_8TeV/$PROCESS_$SYSTEMATIC
shapes WH             htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/WH$MASS htt_tt_2_8TeV/WH$MASS_$SYSTEMATIC
shapes ZH             htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/ZH$MASS htt_tt_2_8TeV/ZH$MASS_$SYSTEMATIC
shapes ggH            htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/ggH$MASS htt_tt_2_8TeV/ggH$MASS_$SYSTEMATIC
shapes qqH            htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/qqH$MASS htt_tt_2_8TeV/qqH$MASS_$SYSTEMATIC
----------------------------------------------------------------------------------------------------------------
-
bin          htt_tt_0_8TeV  htt_tt_1_8TeV  htt_tt_2_8TeV
observation  1120.0         366.0          34.0
----------------------------------------------------------------------------------------------------------------
-
bin                                                          htt_tt_0_8TeV  htt_tt_0_8TeV  htt_tt_0_8TeV  …
process                                                      ZH             qqH            WH             …
process                                                      -3             -2             -1             …
rate                                                         0.6295         1.9520         0.2948         …
----------------------------------------------------------------------------------------------------------------
-
CMS_eff_b_8TeV          lnN                                  -              -              -              …
CMS_eff_t_tt_8TeV       lnN                                  1.19           1.19           1.19           …
…
```

Physics Models: Datacard

```
Combination of htt_tt_0_8TeV=htt_tt_0_8TeV.txt  htt_tt_1_8TeV=htt_tt_1_8TeV.txt  htt_tt_2_8TeV=htt_tt_2_8TeV.txt
imax 3 number of bins
jmax 10 number of processes minus 1
kmax 66 number of nuisance parameters
----------------------------------------------------------------------------------------------------------------
shapes *              htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/$PROCESS htt_tt_0_8TeV/$PROCESS_$SYSTEMATIC
shapes WH             htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/WH$MASS htt_tt_0_8TeV/WH$MASS_$SYSTEMATIC
shapes ZH             htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/ZH$MASS htt_tt_0_8TeV/ZH$MASS_$SYSTEMATIC
shapes ggH            htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/ggH$MASS htt_tt_0_8TeV/ggH$MASS_$SYSTEMATIC
shapes qqH            htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/qqH$MASS htt_tt_0_8TeV/qqH$MASS_$SYSTEMATIC
shapes *              htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/$PROCESS htt_tt_1_8TeV/$PROCESS_$SYSTEMATIC
shapes WH             htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/WH$MASS htt_tt_1_8TeV/WH$MASS_$SYSTEMATIC
shapes ZH             htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/ZH$MASS htt_tt_1_8TeV/ZH$MASS_$SYSTEMATIC
shapes ggH            htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/ggH$MASS htt_tt_1_8TeV/ggH$MASS_$SYSTEMATIC
shapes qqH            htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/qqH$MASS htt_tt_1_8TeV/qqH$MASS_$SYSTEMATIC
shapes *              htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/$PROCESS htt_tt_2_8TeV/$PROCESS_$SYSTEMATIC
shapes WH             htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/WH$MASS htt_tt_2_8TeV/WH$MASS_$SYSTEMATIC
shapes ZH             htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/ZH$MASS htt_tt_2_8TeV/ZH$MASS_$SYSTEMATIC
shapes ggH            htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/ggH$MASS htt_tt_2_8TeV/ggH$MASS_$SYSTEMATIC
shapes qqH            htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/qqH$MASS htt_tt_2_8TeV/qqH$MASS_$SYSTEMATIC
----------------------------------------------------------------------------------------------------------------
bin          htt_tt_0_8TeV  htt_tt_1_8TeV  htt_tt_2_8TeV
observation  1120.0         366.0          34.0
----------------------------------------------------------------------------------------------------------------
bin                                                    htt_tt_0_8TeV  htt_tt_0_8TeV  htt_tt_0_8TeV  …
process                                                ZH             qqH            WH             …
process                                                -3             -2             -1             …
rate                                                   0.6295         1.9520         0.2948         …
----------------------------------------------------------------------------------------------------------------
CMS_eff_b_8TeV          lnN                            -              -              -              …
CMS_eff_t_tt_8TeV       lnN                            1.19           1.19           1.19           …
…
```

Multiple bins

Physics Models: Datacard

```
Combination of htt_tt_0_8TeV=htt_tt_0_8TeV.txt  htt_tt_1_8TeV=htt_tt_1_8TeV.txt  htt_tt_2_8TeV=htt_tt_2_8TeV.txt
imax 3 number of bins
jmax 10 number of processes minus 1
kmax 66 number of nuisance parameters
----------------------------------------------------------------------------------------------------------------
shapes *              htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/$PROCESS htt_tt_0_8TeV/$PROCESS_$SYSTEMATIC
shapes WH             htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/WH$MASS htt_tt_0_8TeV/WH$MASS_$SYSTEMATIC
shapes ZH             htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/ZH$MASS htt_tt_0_8TeV/ZH$MASS_$SYSTEMATIC
shapes ggH            htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/ggH$MASS htt_tt_0_8TeV/ggH$MASS_$SYSTEMATIC
shapes qqH            htt_tt_0_8TeV  ../common/htt_tt.input.root htt_tt_0_8TeV/qqH$MASS htt_tt_0_8TeV/qqH$MASS_$SYSTEMATIC
shapes *              htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/$PROCESS htt_tt_1_8TeV/$PROCESS_$SYSTEMATIC
shapes WH             htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/WH$MASS htt_tt_1_8TeV/WH$MASS_$SYSTEMATIC
shapes ZH             htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/ZH$MASS htt_tt_1_8TeV/ZH$MASS_$SYSTEMATIC
shapes ggH            htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/ggH$MASS htt_tt_1_8TeV/ggH$MASS_$SYSTEMATIC
shapes qqH            htt_tt_1_8TeV  ../common/htt_tt.input.root htt_tt_1_8TeV/qqH$MASS htt_tt_1_8TeV/qqH$MASS_$SYSTEMATIC
shapes *              htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/$PROCESS htt_tt_2_8TeV/$PROCESS_$SYSTEMATIC
shapes WH             htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/WH$MASS htt_tt_2_8TeV/WH$MASS_$SYSTEMATIC
shapes ZH             htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/ZH$MASS htt_tt_2_8TeV/ZH$MASS_$SYSTEMATIC
shapes ggH            htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/ggH$MASS htt_tt_2_8TeV/ggH$MASS_$SYSTEMATIC
shapes qqH            htt_tt_2_8TeV  ../common/htt_tt.input.root htt_tt_2_8TeV/qqH$MASS htt_tt_2_8TeV/qqH$MASS_$SYSTEMATIC
----------------------------------------------------------------------------------------------------------------
bin          htt_tt_0_8TeV  htt_tt_1_8TeV  htt_tt_2_8TeV
observation  1120.0         366.0          34.0
----------------------------------------------------------------------------------------------------------------
bin                                                    htt_tt_0_8TeV  htt_tt_0_8TeV  htt_tt_0_8TeV  …
process                                                ZH             qqH            WH             …
process                                                -3             -2             -1             …
rate                                                   0.6295         1.9520         0.2948         …
----------------------------------------------------------------------------------------------------------------
CMS_eff_b_8TeV          lnN                            -              -              -              …
CMS_eff_t_tt_8TeV       lnN                            1.19           1.19           1.19           …
…
```

Multiple signals

Physics Models: Making Workspace

```
cd data/tutorials/htt/125
text2workspace.py -P HiggsAnalysis.CombinedLimit.PhysicsModel:multiSignalModel \
                  --PO 'map=.*/ggH:r_ggH[1, -10, 10]' \
                  --PO 'map=.*/qqH:r_qqH[1, -10, 10]' \
                  --PO 'map=.*/WH:r_WH[1, -10, 10]' \
                  --PO 'map=.*/ZH:r_ZH[1, -10, 10]' \
                  --mass 125 \
                  htt_tt.txt -o ../../../../htt_tt.root
cd ../../../../
```

-P loads physics model

--P0 arguments map individual signal strengths to individual processes

Check the printout … are the signal strengths assigned correctly?

Expected Fit Results

- Until now, we have done statistical tests against real data observation
- However, we usually want to know how we expect a analysis to perform before we look at data
    - Blinding: develop analysis while agnostic to data, so as not to bias results
- To do this, can compute expected signal strength, significance, etc.
- Use Asimov toy dataset
    - ‘Representative dataset’ — single toy giving median expectation
    - Central values of observation will exactly match model

Expected Signal Strength

```
combine -M MultiDimFit --algo singles htt_tt.root \
        -t -1 \
        --setParameters r_ggH=1,r_qqH=1,r_WH=1,r_ZH=1 \
        --mass 125
```

-t -1 : do a fit to the Asimov toy
--setParameters : use these parameter values when generating the toy

What do you expect?

Expected Signal Strength

```
combine -M MultiDimFit --algo singles htt_tt.root \
        -t -1 \
        --setParameters r_ggH=1,r_qqH=1,r_WH=1,r_ZH=1 \
        --mass 125
```

```
 <<< Combine >>>
 <<< v9.2.0 >>>
>>> Random number generator seed is 123456
>>> Method used is MultiDimFit
ModelConfig 'ModelConfig' defines more than one parameter of interest. This is not supported in some
statistical methods.
Set Default Value of Parameter r_ggH To : 1
Set Default Value of Parameter r_qqH To : 1
Set Default Value of Parameter r_WH To : 1
Set Default Value of Parameter r_ZH To : 1
Doing initial fit:

 --- MultiDimFit ---
best fit parameter values and profile-likelihood uncertainties:
   r_ggH :    +1.000   -3.126/+3.730 (68%)
   r_qqH :    +1.000   -1.521/+1.797 (68%)
    r_WH :    +1.000   -11.000/+9.000 (68%)
    r_ZH :    +1.000   -11.000/+9.000 (68%)
Done in 0.00 min (cpu), 0.01 min (real)
```

Expected Significance

```
combine -M Significance htt_tt.root --mass 125 \
        -t -1 --setParameters r_ggH=1,r_qqH=1,r_WH=1,r_ZH=1
```

```
 <<< Combine >>>
 <<< v9.2.0 >>>
>>> Random number generator seed is 123456
>>> Method used is Significance
ModelConfig 'ModelConfig' defines more than one parameter of interest. This is not supported in some
statistical methods.
Set Default Value of Parameter r_ggH To : 1
Set Default Value of Parameter r_qqH To : 1
Set Default Value of Parameter r_WH To : 1
Set Default Value of Parameter r_ZH To : 1

 -- Significance --
Significance: 0.194094
Done in 0.00 min (cpu), 0.00 min (real)
```

What significance did you compute?

Expected Significance

```
combine -M Significance htt_tt.root --mass 125 \
        -t -1 --setParameters r_ggH=1,r_qqH=1,r_WH=1,r_ZH=1 --redefineSignalPOIs r_ggH
```

```
 <<< Combine >>>
 <<< v9.2.0 >>>
>>> Random number generator seed is 123456
>>> Method used is Significance
ModelConfig 'ModelConfig' defines more than one parameter of interest. This is not supported in some
statistical methods.
Set Default Value of Parameter r_ggH To : 1
Set Default Value of Parameter r_qqH To : 1
Set Default Value of Parameter r_WH To : 1
Set Default Value of Parameter r_ZH To : 1

 -- Significance --
Significance: 0.194094
Done in 0.00 min (cpu), 0.00 min (real)
```

What significance do you get for other POIs?

Expected Nuisance Parameter Uncertainties

```
combine -M FitDiagnostics htt_tt.root --mass 125 -n htt \
        -t -1 --setParameters r_ggH=1,r_qqH=1,r_WH=1,r_ZH=1
```

This produces a file name fitDiagnosticshtt.root

Open and inspect the fit_s result — are the nuisance parameters as you expect?

Expected Nuisance Parameter Uncertainties

```
combine -M FitDiagnostics htt_tt.root --mass 125 -n htt \
        -t -1 --setParameters r_ggH=1,r_qqH=1,r_WH=1,r_ZH=1
```

This produces a file name fitDiagnosticshtt.root

Open and inspect the fit_s result — are the nuisance parameters as you expect?

```
 RooFitResult: minimized FCN value: 0, estimated distance to minimum: 7.07224e-12
                covariance matrix quality: Full, accurate covariance matrix
                Status : MINIMIZE=0 HESSE=0

  Floating Parameter    FinalValue +/-  Error
--------------------  --------------------------
      CMS_eff_b_8TeV    0.0000e+00 +/-  9.98e-01
    CMS_eff_t_tt_8TeV    0.0000e+00 +/-  3.37e-01
     CMS_fake_b_8TeV    0.0000e+00 +/-  9.98e-01
CMS_htt_DiBosonNorm_8TeV                                    0.0000e+00 +/-  9.99e-01
CMS_htt_DiBosonNorm_tauTau_1jet_high_highhiggs_8TeV         0.0000e+00 +/-  9.98e-01
CMS_htt_DiBosonNorm_tauTau_1jet_high_mediumhiggs_8TeV       0.0000e+00 +/-  9.99e-01
CMS_htt_DiBosonNorm_tauTau_vbf_8TeV                         0.0000e+00 +/-  1.00e+00
CMS_htt_QCDSyst_tauTau_1jet_high_highhiggs_8TeV             0.0000e+00 +/-  8.54e-01
CMS_htt_QCDSyst_tauTau_1jet_high_mediumhiggs_8TeV           0.0000e+00 +/-  2.33e-01
CMS_htt_QCDSyst_tauTau_vbf_8TeV                             0.0000e+00 +/-  8.32e-01
CMS_htt_WNorm_tauTau_1jet_high_highhiggs_8TeV               0.0000e+00 +/-  9.77e-01
CMS_htt_WNorm_tauTau_1jet_high_mediumhiggs_8TeV             0.0000e+00 +/-  9.68e-01
CMS_htt_WNorm_tauTau_vbf_8TeV                               0.0000e+00 +/-  9.98e-01
```