CONTUR: a tutorial

by
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Using material provided by the →CONTUR team
MCnet School Zakopane Workshop 19-25 June 2022

→video tutorial @ RiF workshop 2021

Illustration by Chris Wormell from "A Map of the Invisible"

Prerequisites


```
$ docker pull hepstore/contur-herwig:latest

[...]

$ unzip contur_tutorial.zip -d contur_tutorial
$ cd contur_tutorial
$ docker run -it -v ${PWD}:/contur_tutorial hepstore/contur-herwig:latest
---------------------------------------
Contur environment successfully enabled
---------------------------------------
root@34d102de55ac:/contur#
```

pull docker image
(we're going to generate events as well, so make sure to use `contur-herwig` instead of only `contur`

(download and) extract tutorial files

run docker image, binding directories

ready to go!

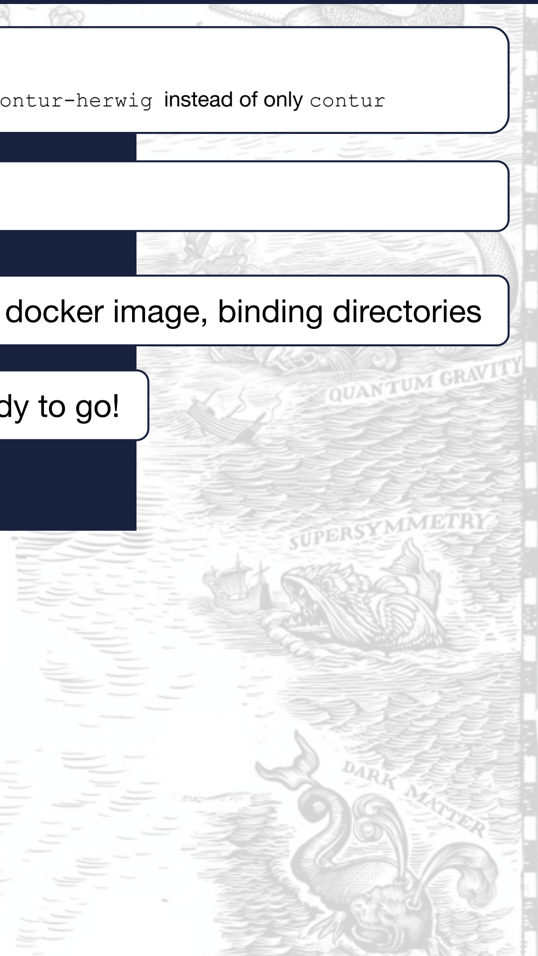


Illustration by Chris Wormell from "A Map of the Invisible"

Introduction

CONTUR - “Constraints On New Theories Using →[RIVET](#)”

- reinterpretation tool that helps to constrain BSM models using existing LHC measurements
- useful links:
  - CONTUR manual [→SciPost Phys. Core 4, 013 (2021)]
  - →CONTUR webpage
  - →CONTUR code
- general idea:
  - SM is finely balanced and well measured
  - ➔ cannot simply add BSM model without it showing up in SM distributions
  - ➔ CONTUR: check hundreds of such measurements simultaneously

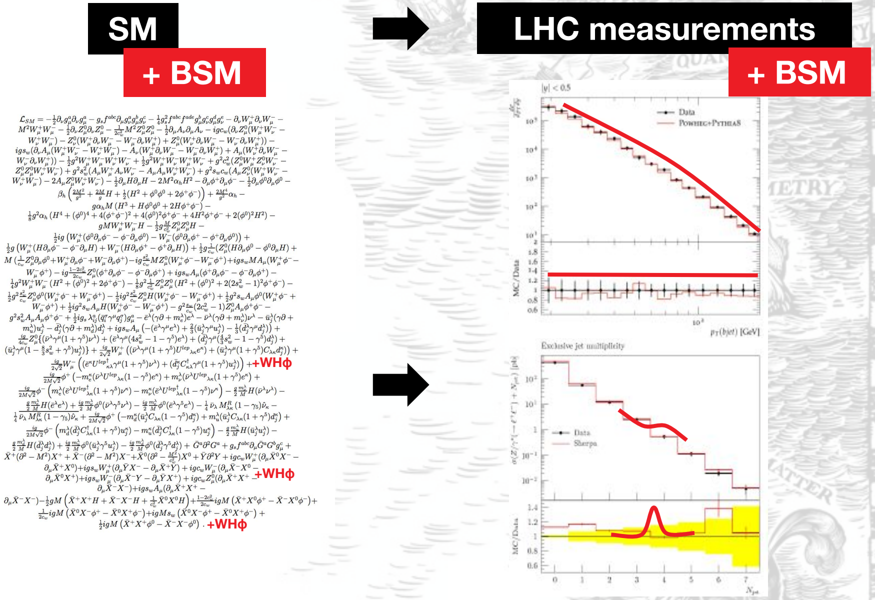


Illustration by Chris Wormell from “A Map of the Invisible”

CONTUR method

Sampling model parameters
contur-batch

↓

Calculate observables
event generators, Rivet, ...

↓

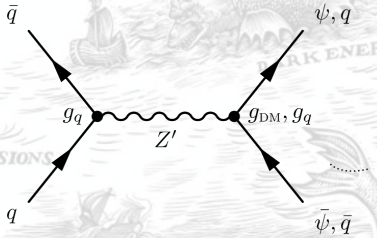
Evaluating the likelihood for a model
contur

↓

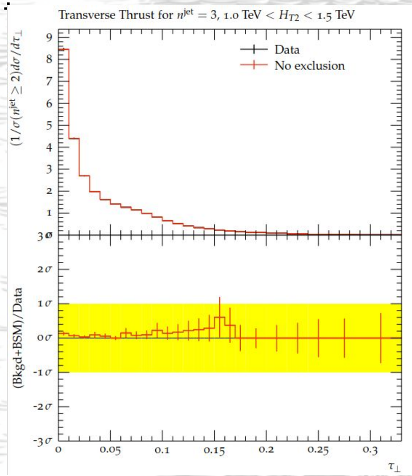
Visualisation of parameter space
contur-plot, contur-mkhtml, ...

- many BSM models encoded in →Universal Feynrules Output (**UFO**) format

➔ switching between models easy



1. Event generation
2. Effect on existing measurements?
   - many (~150) LHC measurements available as **RIVET routine** (runnable plugin that preserves analysis logic)
   - →RIVET optimised for speed, can evaluate impact in hundreds of routines with negligible runtime compared to event generation



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CONTUR method

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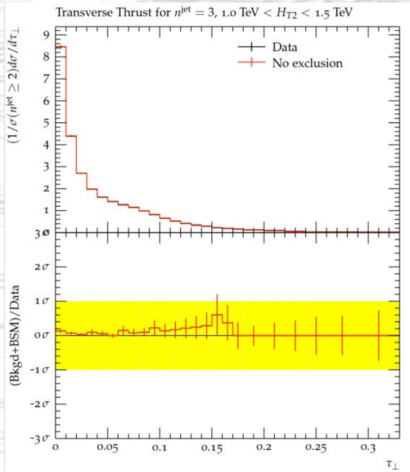
↓

Visualisation of parameter space
contur-plot, contur-mkhtml, ...

- group RIVET routines into orthogonal pools
- use CL_s method to determine confidence level of excluding **signal(+bkg)** considering **data** and uncertainties

$$L(\mu) = \frac{(\mu s + b)^n}{n!} e^{-(\mu s + b)}$$



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CONTUR method

Sampling model parameters
contur-batch

↓

Calculate observables
event generators, Rivet, ...

↓

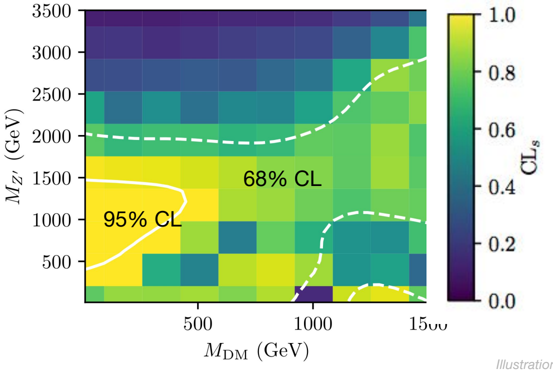
Evaluating the likelihood for a model
contur

↓

Visualisation of parameter space
contur-plot, contur-mkhtml, ...

Repeat for each point in parameter space

- book-keeping and steering machinery provided by CONTUR



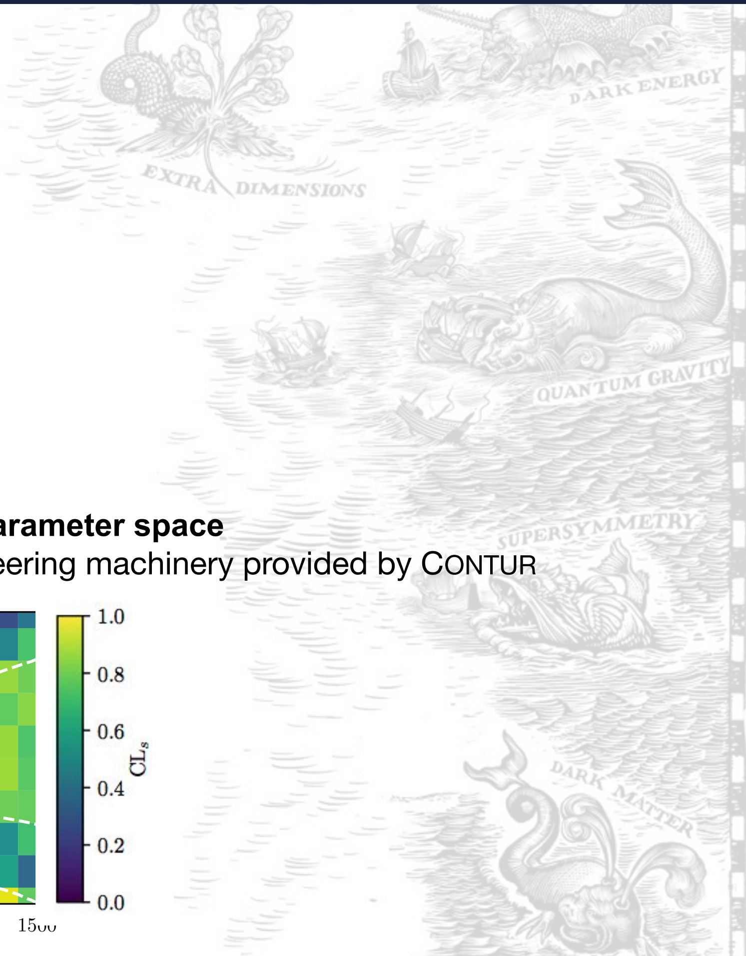
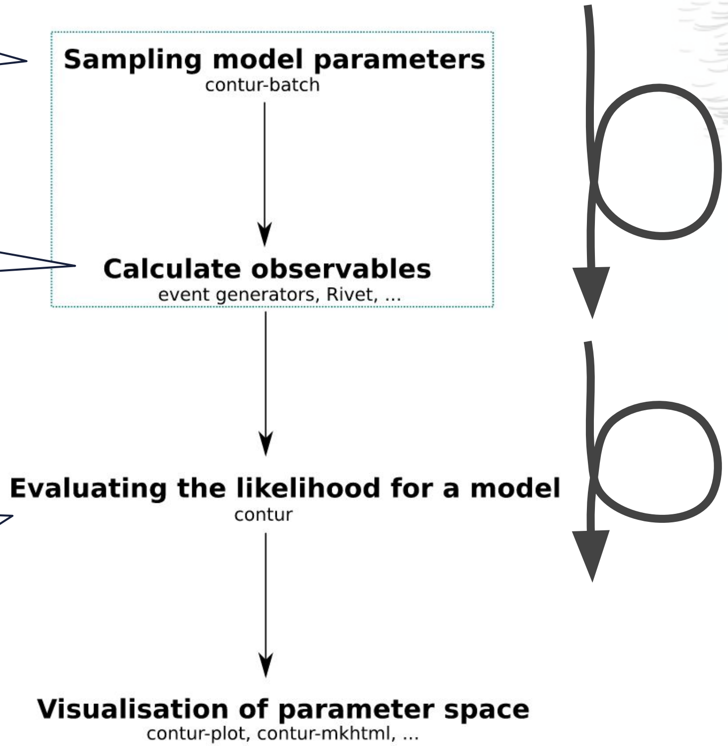


Illustration by Chris Wormell from "A Map of the Invisible"

Outline of tutorial



1. Using UFOs

2. Single parameter point: Calculating observables

3. Single parameter point: Evaluating likelihood

already prepared

4. Running a scan with CONTUR

Illustration by Chris Wormell from "A Map of the Invisible"

0. Getting started


```
$ docker pull hepstore/contur-herwig:latest

[...]

$ unzip contur_tutorial.zip -d contur_tutorial
$ cd contur_tutorial
$ docker run -it -v ${PWD}:/contur_tutorial hepstore/contur-herwig:latest
---------------------------------------
Contur environment successfully enabled
---------------------------------------
root@34d102de55ac:/contur#
```

pull docker image
(we're going to generate events as well, so make sure to use `contur-herwig` instead of only `contur`

(download and) extract tutorial files

run docker image, binding directories

ready to go!

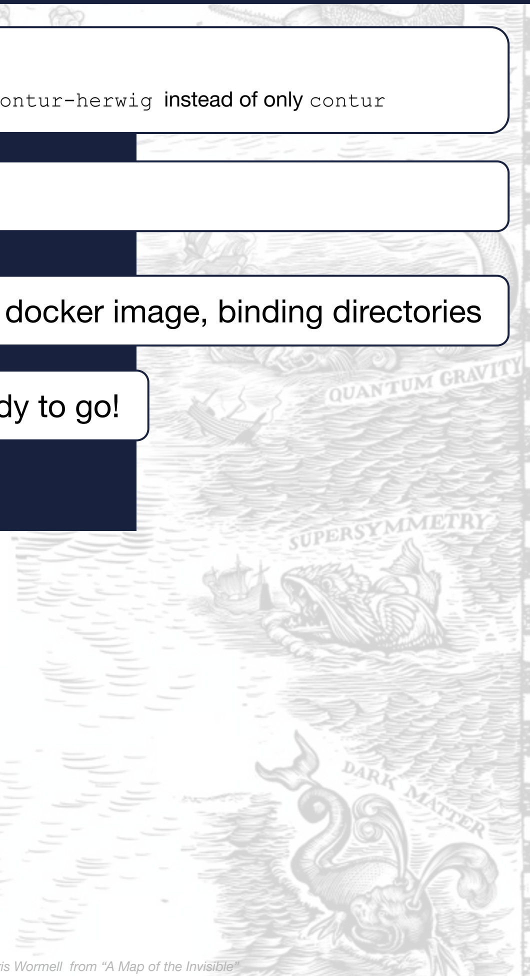


Illustration by Chris Wormell from "A Map of the Invisible"

1. Having a look at available BSM models


```
# apt install tree
Reading package lists... Done
[...]
Setting up tree (1.8.0-1) ...
# tree $CONTUR_ROOT/data/Models/ -d
/contur/data/Models/
|-- 2HDM
|    |-- Gildener-Weinberg
|    |    `-- G-W
|    |-- InertDoublet
|    |    `-- InertDoublet_UFO
|    `-- KL-LH2017
|         `-- 2HDM_K1_UFO_final
|-- ALP
|    `-- ALP
|-- B-L
|    `-- B-L-3
|-- DE
|    `-- Standard_Model_cosmo_UFO
|-- DM
|    |-- DMSimp_t
|    |-- DM_vector_mediator_HF_UFO
|    |-- DM_vector_mediator_UFO
|    |-- DMsimp_s_spin1
|    |-- DMspin2
|    |    `-- DMspin2
|    |-- InertDoublet_UFO
|    `-- Pseudoscalar_2HDM
|-- FNU_Zprime
|    `-- zPrime_UFO_LO_mod
[...]
```

```
(continued)
|-- Gambit
|    |-- slha_files__mN2_mN3__3sigma__20x20
|    |-- slha_files__mN4_mN3__3sigma__20x20
|    `-- slha_grid_plot_mC1_mN1__3sigma__40x40
|-- HeavyDarkMesons
|    |-- Gaugephilic_SU2L
|    |-- Gaugephobic_SU2L
|    `-- Gaugephobic_SU2R
|-- HeavyN
|    `-- SM_HeavyN_NLO
|-- Neutral_Scalar
|    |-- Neutral_scalar_CPeven_UFO
|    `-- Neutral_scalar_CPodd_UFO
|-- NeutrinoEFT
|    `-- Neutrino_EFT_maj_UFO
|-- PBZpWp
|-- TFHM
|    |-- Zprime_MDM_UFO
|    |-- Zprime_MUM_UFO
|    `-- Zprime_TFHM_Mix_UFO
|-- TopColour
|    `-- SMWZP_UFO
`-- VLQ
        |-- ATLAS
        `-- VLQ_UFO

49 directories
```

There are many BSM models available in Contur.

In this model we will work with an s-channel mediated DM model (DMsim_s_spin1)

In principle you can also use models directly from →FeynRules model database but many models there still using py2

Illustration by Chris Wormell from "A Map of the Invisible"

2. Single parameter point: Calculating observables

1. Once you are in the Docker image, from the “contur-tutorial” directory you should find the provided “myscan00” folder. We will use this folder later in the tutorial to create 2D parameter scans.
2. First, let’s make a new directory called “run-area” and navigate into it. The run-area is where you are running everything from now on:

```
contur_tutorial $ mkdir run-area
contur_tutorial $ cd run-area
```

3. Then copy the RunInfo folder, which contains information about which Rivet analyses are used when running Contur later on:

```
run-area $ cp -r  $CONTUR_ROOT/data/share RunInfo
```

4. Then cd into RunInfo and copy the example DMsimp_s_spin1 model into here:

```
run-area $ cd RunInfo
RunInfo  $ cp -r $CONTUR_ROOT/data/Models/DM/DMsimp_s_spin1 .
```

* information about measurements can be found →here

CONTINUE ……

2. Single parameter point: Calculating observables

5. Build the UFO model using Herwig ‘ufo2herwig’ command:

```
RunInfo $ ufo2herwig DMsimp_s_spin1
RunInfo $ make
```

This step allows Herwig to include this particular DM model in the event generation.

6. Most models in the Contur models database provide a herwig.in file. This contains instructions for Herwig. Let’s take a look at how this works on the next slide…

* information about measurements can be found →here

Illustration by Chris Wormell from “A Map of the Invisible”

A look at herwig.in

```
# Read in the Feynrules model
read FRModel.model

# set the masses which we don't want to change
set /Herwig/FRModel/Particles/Xc:NominalMass 4000.*GeV
set /Herwig/FRModel/Particles/Xc~:NominalMass 4000.*GeV
set /Herwig/FRModel/Particles/Xr:NominalMass 4000.*GeV

# templating for the masses we do want to change
set /Herwig/FRModel/Particles/Xd:NominalMass {mXd}*GeV
set /Herwig/FRModel/Particles/Xd~:NominalMass {mXd}*GeV
set /Herwig/FRModel/Particles/Y1:NominalMass {mY1}*GeV

# templating for the couplings we want to change
set /Herwig/FRModel/FRModel:gVXd {gVXd}
~ (replaced with ~ as it is too long to fit in one page)
~
~

cd /Herwig/NewPhysics
# set the outgoing particles for the inclusive process
insert HPConstructor:Outgoing 0 /Herwig/FRModel/Particles/Xd
insert HPConstructor:Outgoing 0 /Herwig/FRModel/Particles/Xd~
insert HPConstructor:Outgoing 0 /Herwig/FRModel/Particles/Y1

# set the intermediate particles for the resonant process
insert ResConstructor:Intermediates 0 /Herwig/FRModel/Particles/Y1
```

example command files for HERWIG for simplified DM model. (Beam information included in Contur)

Create grid point values, replace parameter value -> {parameter value}

Outgoing particles and resonant particles defined.

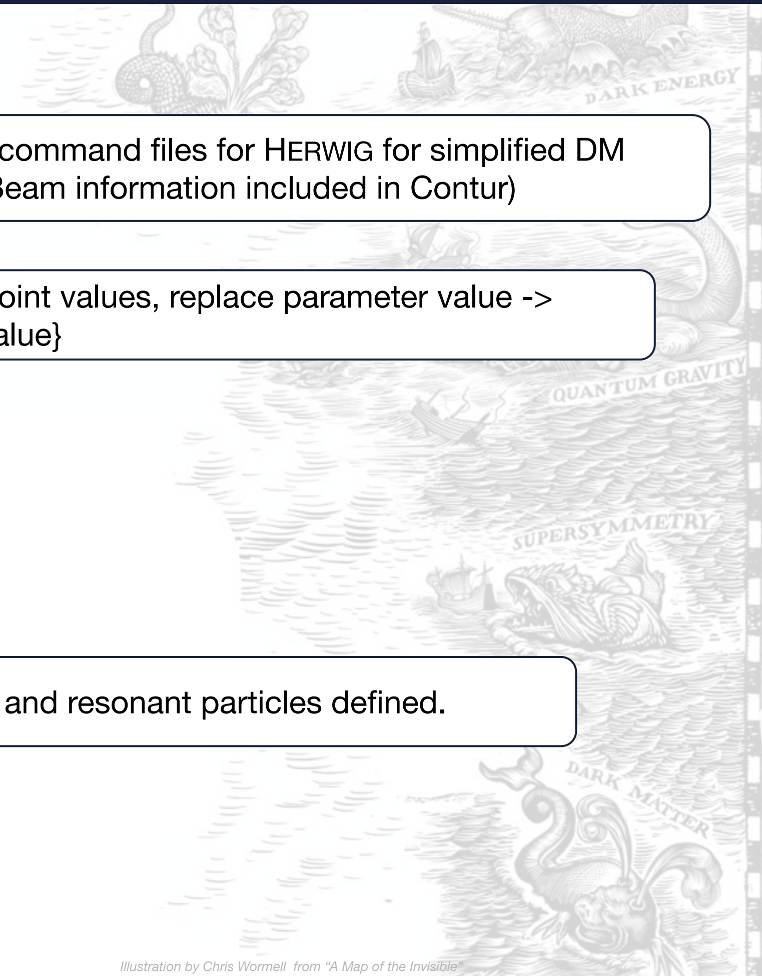


Illustration by Chris Wormell from "A Map of the Invisible"

2. Single parameter point: Calculating observables

6. Copy the template herwig.in file from our DM model to the top level of run-area:

```
RunInfo  $ cd ..   (you should navigate to your run-area for this step)
run-area $ cp RunInfo/DMsimp_s_spin1/herwig.in .
run-area $ cp RunInfo/DMsimp_s_spin1/param_file.dat .
```

The param_file.dat (example in slide 19) specifies the parameters and the corresponding scan range.

7. Build the full herwig input file for a single point:

```
$ contur-batch --single -o myscanSingle
```

This should create a directory called myscanSingle/13TeV/0000 which will contain a herwig.in file with the full instructions for a run, and with BSM model variables substituted from param_file.dat. There will be some other files which would be used if we were generating a full scan, but which you can ignore for now (the full version is provided for this tutorial!)

* information about measurements can be found →here

Illustration by Chris Wormell from "A Map of the Invisible"

2. Single parameter point: Calculating observables

8a. Annoyingly, the particular parameter point generated here has the DM mass equal to the mediator mass. This is not wrong, but it does make the integration step very slow. So we suggest you go into the herwig.in file and edit the line:

*set /Herwig/FRModel/Particles/Y1:NominalMass 10.0*GeV*

To

*set /Herwig/FRModel/Particles/Y1:NominalMass 100.0*GeV*

Which should be quicker.

> *If the `Herwig read` step (step 8) still takes too long, you can `cd contur_tutorial/myScan00/13TeV/0000` and continue from slide 15 using the `herwig-S101-runpoint_0000.yoda` file instead*

8. Build the Herwig run card (herwig.run).

```
$ cd myscanSingle/13TeV/0000
$ Herwig read herwig.in -I ../../../RunInfo -L ../../../RunInfo
```

9. Run the Herwig run card, specifying the number of events to generate. This can take a while so, as a first test, running around 200 events is fine:

```
$ Herwig run herwig.run -N 200
```

This will produce the file herwig.yoda containing the results of the Herwig run. You can extract exclusions from this Yoda file with Contur as described in the next slide.

* information about measurements can be found →here

3. Single parameter point: Evaluating likelihood


```
# contur herwig.yoda
Writing log to contur.log
INFO - Running Contur version 2.1.0
INFO - See https://hepcedar.gitlab.io/contur-webpage/
INFO - Running Contur version 2.1.0
INFO - See https://hepcedar.gitlab.io/contur-webpage/
INFO - Run Information
Contur is running in /contur_tutorial
on analysis objects in ['Rivet.yoda']
Excluding Higgs to WW measurements
Excluding secret b-veto measurements
Excluding ATLAS WZ SM measurement
Building all available data correlations, combining bins where possible
Building default background model from data, ignoring (optional) SM theory predictions

INFO - Found 2524 analysisobjects in Rivet.yoda
INFO - Found 1249 potentially valid histograms in Rivet.yoda, with cross section 16.04672 pb
INFO - Loading reference and theory data from all yoda files in $RIVET_DATA_PATH matching paths in input yoda
Processing reference/theory YODAs: 0it [00:00, ?it/s]

[...]
```

do statistical analysis with CONTUR
Have a look at `contur --help` to learn about all the available options

information about CONTUR run

some measurements have to be excluded*

* →on the importance of model-independent measurements

Illustration by Chris Wormell from "A Map of the Invisible"

3. Single parameter point: Evaluating likelihood

(continued)

loading histograms and theory inputs

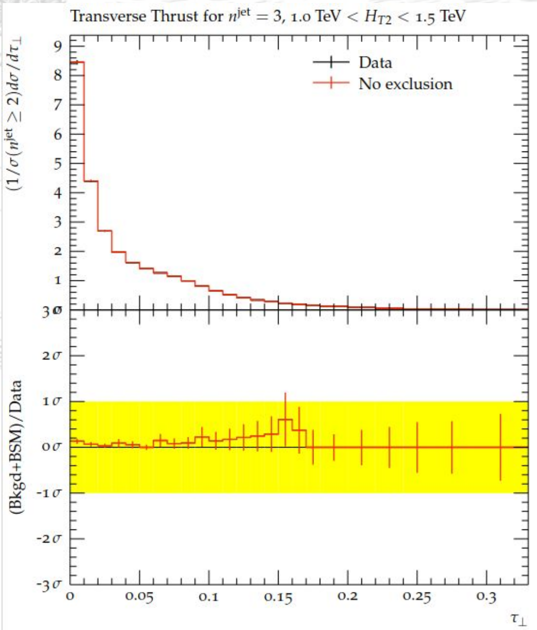
```
[...]
INFO - Done loading static data
100%|████████████████████████████████████████████████████████████
█████████████| 1249/1249 [00:07<00:00, 177.27it/s]
INFO - Added yodafile with reported exclusion of: 0.9830562298818333
INFO - Run Information
Contur is running in /contur_tutorial
on analysis objects in ['Rivet.yoda']
Excluding Higgs to WW measurements
Excluding secret b-veto measurements
Excluding ATLAS WZ SM measurement
Building all available data correlations, combining bins where possible
Building default background model from data, ignoring (optional) SM theory predictions

Parameter values not known for this run.
INFO - Combined exclusion for these plots is 98.31 %

# contur-mkhtml
Making 14 plots
Plotting contur-plots/ATLAS_13_MMJET/ATLAS_2020_I1788444/d08-x01-y01.dat (14/14 remaining)
Plotting contur-plots/ATLAS_13_MMJET/ATLAS_2020_I1788444/d10-x01-y01.dat (13/14 remaining)
Plotting contur-plots/ATLAS_13_MMJET/ATLAS_2020_I1788444/d04-x01-y01.dat (12/14 remaining)
Plotting contur-plots/ATLAS_13_MMJET/ATLAS_2020_I1788444/d05-x01-y01.dat (11/14 remaining)

[...]
```

exclusion of ≈98%!

make plots using a wrapper for `rivet-mkhtml`

(this will take some time)

Hadronic event shapes in multijet final states
(→ATLAS_2020_I1808726)



opening contur-plots/index.html in a browser of your choice

3. Using theory predictions

- caveat: often SM prediction not given in HEPData

➔ CONTUR uses Bkgd=Data by default
  - ugly hack, but it works, since we claim no significant deviations seen at LHC so far
  - cannot claim discovery, only falsify BSM model
- however: using theory predictions nonetheless supported

→webpage on measurements available to CONTUR

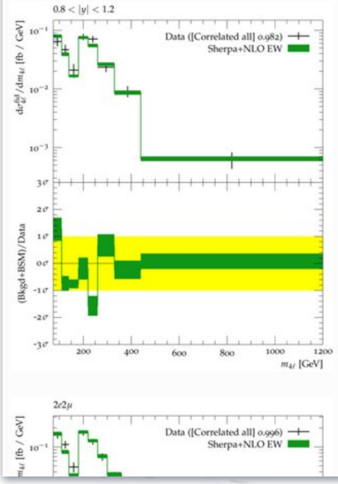
Pool: **ATLAS_13_4L** *four leptons*

- ATLAS_2017_I1625109, Measurement of $ZZ -> 4ell$ production at 13 TeV [14]. No SM theory predictions available for this analysis.
- ATLAS_2019_I1720442, Inclusive 4-lepton lineshape at 13 TeV [25]. SM theory predictions are available here.

Standard Model Predictions for ATLAS_2019_I1720442

Sherpa+NLO EW [25, 100]: See measurement paper for full details. HEPData record at https://doi.org/10.17182/hepdata.84818

Stored in file: ATLAS_2019_I1720442-Theory.yoda



- advanced users may even provide their own theory predictions

Illustration by Chris Wormell from "A Map of the Invisible"

4. A look at param_files.dat


```
#Based off configObj python template

[Parameters]
[[mXd]]
mode = LIN
start = 10.0
stop = 1610.0
number = 18
[[mY1]]
mode = LIN
start = 10.0
stop =  3610.0
number = 16
[[gVq]]
mode = CONST
value = 0.25
[[gVl]]
mode = CONST
value = 0.25
[[gVXd]]
mode = CONST
value = 1.0
[[gAXd]]
mode = CONST
value = 1.0
[[gAq]]
mode = CONST
value = 0.25
```

tell CONTUR to vary dark matter mass from 10 to 1610 GeV in 18 equidistant steps

mediator mass is second scan parameter

tell CONTUR to treat couplings as constant

For this tutorial, the signal grid is already generated and provided for you in the myscan00 directory. It was created with the following command:

```
# contur-batch -p param_file.dat -P -b 13TeV -w 2:00
```

4. Running a CONTUR scan

now run CONTUR in grid mode by calling

(this will take some time)

```
# contur -g myscan00
Writing log to contur.log
INFO - Running Contur version 2.1.0
INFO - See https://hepcedar.gitlab.io/contur-webpage/
INFO - Running Contur version 2.1.0
INFO - See https://hepcedar.gitlab.io/contur-webpage/
INFO - Run Information
Contur is running in /contur_tutorial
on files in myscan00
Excluding Higgs to WW measurements
Excluding secret b-veto measurements
Excluding ATLAS WZ SM measurement
Building all available data correlations, combining bins where possible
Building default background model from data, ignoring (optional) SM theory predictions

INFO - Removing unnecessary files from grid
WARNING - NO YODA FILES FOUND IN DIRECTORY 13TeV
INFO - Found valid yoda file contur_tutorial/myscan00/13TeV/0000/runpoint_0000.yoda.gz
INFO - Sampled at:
gYXm: 1.0
gYq: 0.25
mXm: 10.0
mY1: 10.0
```

information about CONTUR run

information about current grid point

4. Running a CONTUR scan

(continued)

```
INFO - Found 1474 analysisobjects in /contur_tutorial/myscan00/13TeV/0000/runpoint_0000.yoda.gz
INFO - Loading reference and theory data from all yoda files in $RIVET_DATA_PATH matching paths in input yoda
Processing reference/theory YODAs: 0it [00:00, ?it/s]

[...]

Processing reference/theory YODAs: 0it [00:00, ?it/s]
INFO - Done loading static data

[...]

INFO - Added yodafile with reported exclusion of: 0.7537528372111337
INFO - Found valid yoda file contur_tutorial/myscan00/13TeV/0001/runpoint_0001.yoda.gz

[...]
[...]

INFO - Found 100 yoda files
INFO - Merging maps
INFO - Writing output map to : ANALYSIS/contur.map
```

loading histograms (and theory inputs, but only once)

report exclusion for grid point and go to next one

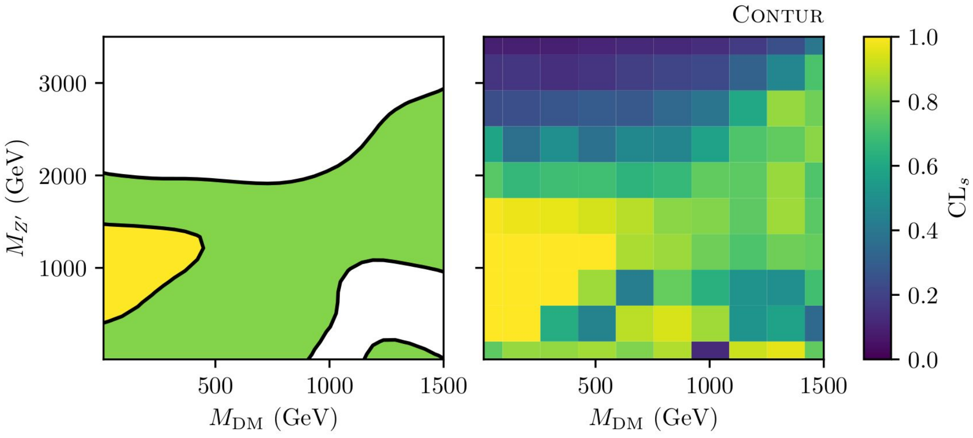
summarise run and give output

Illustration by Chris Wormell from "A Map of the Invisible"

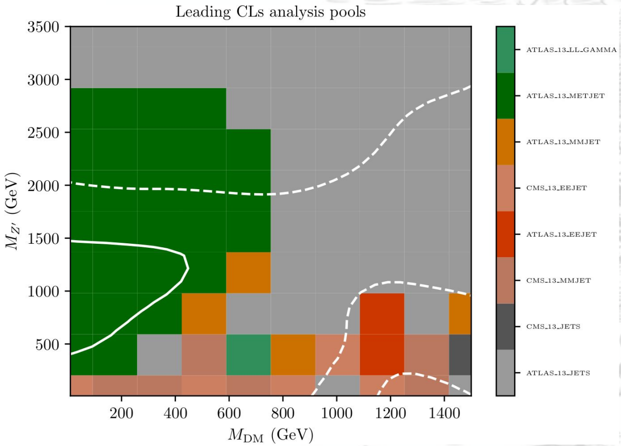
4. Plotting with CONTUR

to plot do

```
# cd ANALYSIS
# contur-plot contur.map mXm mY1
Matplotlib is building the font cache; this may take a moment.
Writing log to contur_plot.log
INFO - Running Contur version2.1.0
INFO - See https://hepcedar.gitlab.io/contur-webpage/
INFO - Starting plotting engine, outputs written to conturPlot
INFO - Plotting combined exclusion limit grid
INFO - plot dominant pools level 0 (1/1)
INFO - Done
```



conturPlots/combinedHybrid.pdf



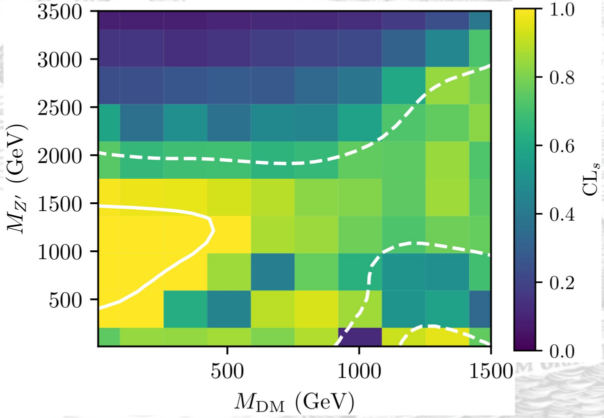
conturPlots/dominantPools0.pdf

Illustration by Chris Wormell from “A Map of the Invisible”

4. Plotting with CONTUR

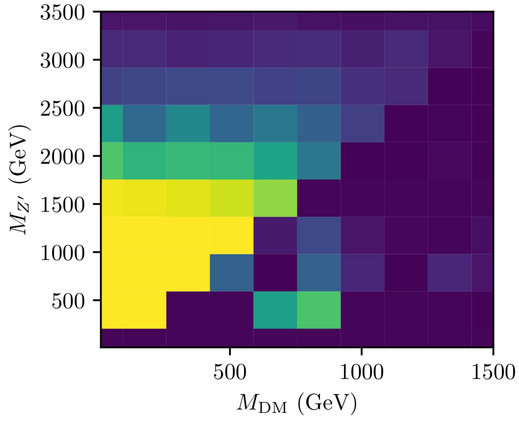
to plot the exclusion for each pool separately

```
# contur-plot contur.map mXm mY1 --pools
Writing log to contur_plot.log
INFO - Running Contur version2.1.0
INFO - See https://hepcedar.gitlab.io/contur-webpage/
INFO - Starting plotting engine, outputs written to conturPlot
INFO - Plotting combined exclusion limit grid
INFO - plot dominant pools level 0 (1/1)
INFO - Requested plotting of individual analysis pools, found 17 pools to plot
INFO - plot ATLAS_13_EEJET (1/17 done)

[...]

Done
```

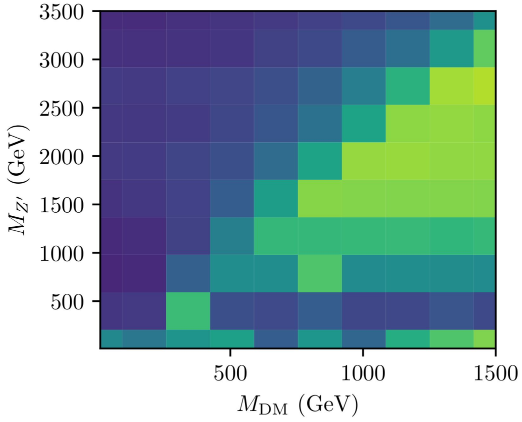


total exclusion

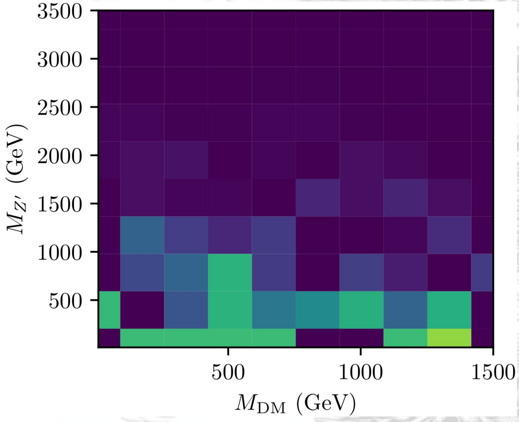
and find your plots at ANALYSIS/conturPlot/pools



ATLAS_13_METJETMesh.pdf



ATLAS_13_JETSMesh.pdf



CMS_13_MMJETMesh.pdf

Bonus: Plotting cross sections

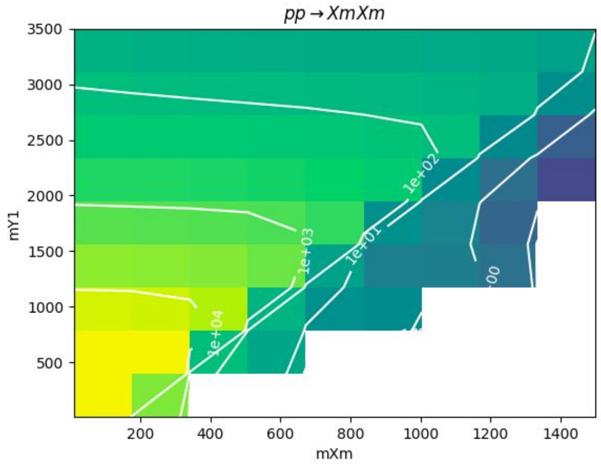
to plot the cross sections for the different processes do

```
# cd /contur_tutorial
# contur-scan-herwig-xs-br --xy mXm,mY1 myscan00/13TeV/
Point 0/100: 0000
Point 10/100: 0010
[...]
xBins:10 [10.0, 175.555556, 341.111111, 506.666667, 672.222222, 837.777778, 1003.333333, 1168.888889, 1334.444444, 1500.0]
yBins:10 [10.0, 397.777778, 785.555556, 1173.333333, 1561.111111, 1948.888889, 2336.666667, 2724.444444, 3112.222222, 3500.0]
max_xs: 150300000.000000 fb
min_xs: 0.030000 fb
1/8 doing p p \rightarrow Y1 q (max = 150300000.000 fb)
[...]
```

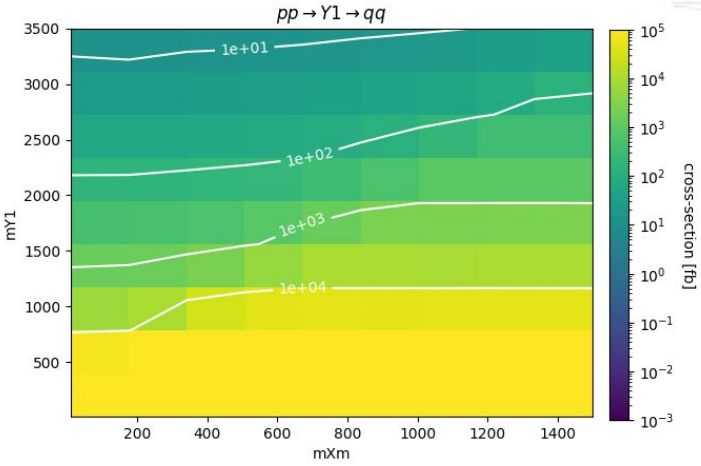
all the grid points we used

minimum and maximum cross section

and find your plots at CONTUR_xs_scans/process_plots*/



p_p_to_Xm_Xm.pdf



p_p_to_Y1_to_q_q.pdf

The End

(of this tutorial)

For more information check out the →[CONTUR webpages]
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Illustration by Chris Wormell from “A Map of the Invisible”