CONTUR: a tutorial

by
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Using material provided by the →CONTUR team

UCL/SJTU Workshop 1-2 March 2022

→video tutorial @ RiF workshop 2021

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

Getting started


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

[...]

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

pull docker image
(we're going to generate events as well, so use `contur-herwig:2.2.0-py3` instead of `contur:2.2.0-py3`

(download and) extract tutorial files

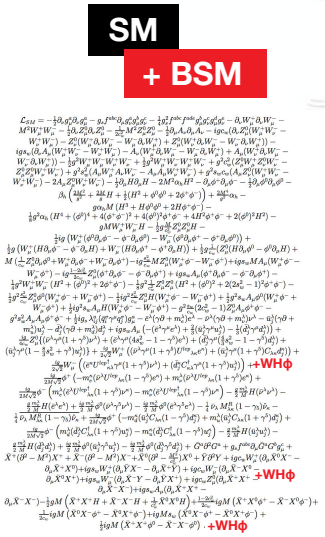
run docker image, binding directories

ready to go!

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



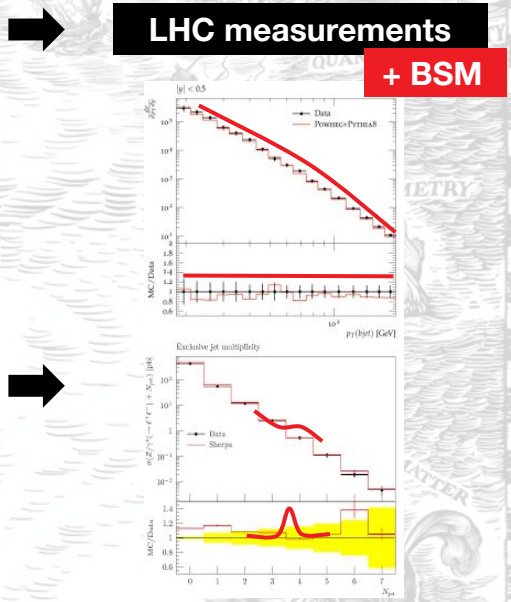


Illustration by Chris Wormell from "A Map of the Invisible"

CONTUR method

Sampling model parameters
contur-batch

↓

Calculate observables
event generators, Rivet, ...

↓

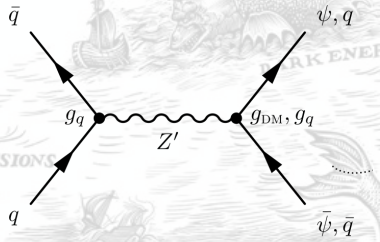
Evaluating the likelihood for a model
contur

↓

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

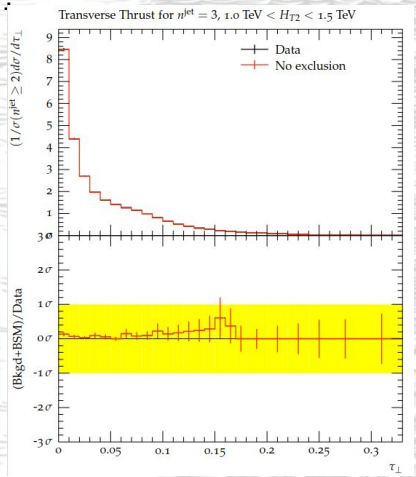


Illustration by Chris Wormell from "A Map of the Invisible"

CONTUR method

Sampling model parameters
contur-batch

↓

Calculate observables
event generators, Rivet, ...

↓

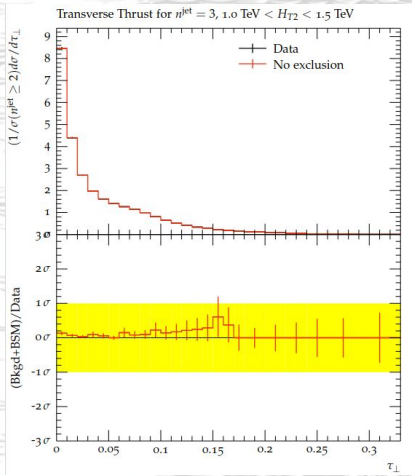
Evaluating the likelihood for a model
contur

↓

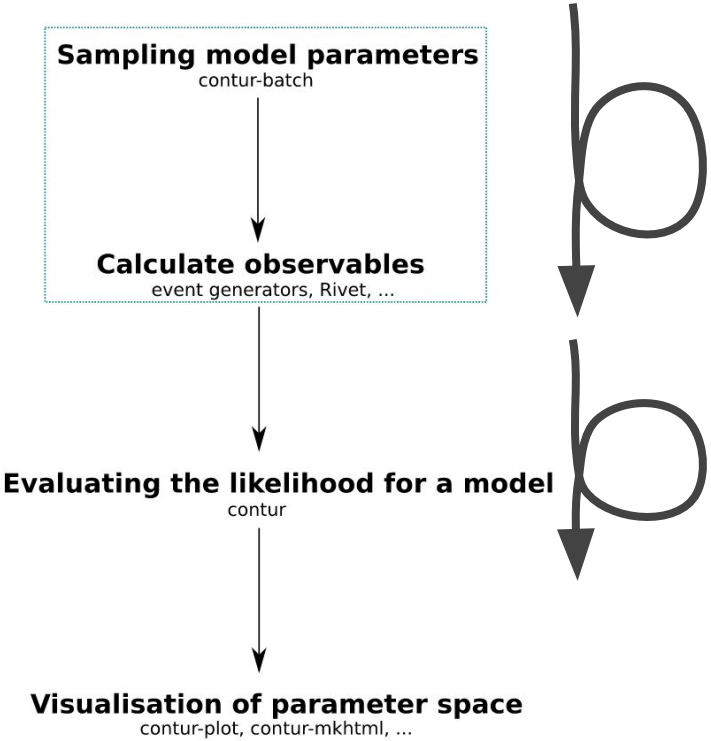
Visualisation of parameter space
contur-plot, contur-mkhtml, ...

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

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



CONTUR method



Repeat for each point in parameter space

- book-keeping and steering machinery provided by CONTUR

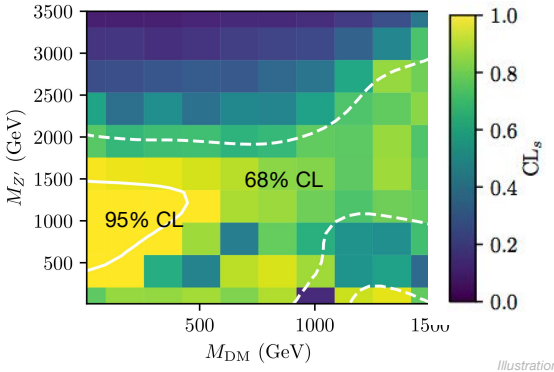


Illustration by Chris Wormell from "A Map of the Invisible"

Outline of tutorial

1. Using UFOs

2. Single parameter point: Calculating observables

3. Single parameter point: Evaluating likelihood

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

already prepared

4. Running a scan with CONTUR

1. Choosing a model


```
# 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
```

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

1. Using UFOs

copy “RunInfo” which tells CONTUR/ RIVET which analyses to use

choose and copy model UFO

convert UFO to HERWIG-readable format

```
# cp -r $CONTUR_ROOT/data/share RunInfo
# cd RunInfo/
# cp -r $CONTUR_ROOT/data/Models/DM/DMsimp_s_spin1 .
# ufo2herwig DMsimp_s_spin1/
============================================================
LENGTH 1
finished generating model:    FRModel
model directory:        DM_vector_mediator_UFO/
generated:              122 vertices
============================================================
library:                FRModel.so
input file:             LHC-FRModel.in
model file:             FRModel.model
============================================================
To complete the installation, compile by typing "make".
An example input file is provided as LHC-FRModel.in,
you'll need to change the required particles in there.

DONE!
============================================================
# make
g++ -std=c++11 -fPIC -I/herwig/include -I/herwig/include -I/herwig/include -Wall -Wextra -pedantic -O2 -DBOOST_UBLAS_NDEBUG -c
FRModel.cc -o FRModel.o
[...]
```

compile UFO

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

2. A look at herwig.in


```
read FRModel.model
set /Herwig/FRModel/Particles/Y1:NominalMass {mY1}*GeV
set /Herwig/FRModel/Particles/Xm:NominalMass {mXm}*GeV
set /Herwig/FRModel/FRModel:gYXm {gYXm}
set /Herwig/FRModel/FRModel:gYq  {gYq}

cd /Herwig/NewPhysics
insert HPConstructor:Outgoing 0 /Herwig/FRModel/Particles/Y1
insert HPConstructor:Outgoing 0 /Herwig/FRModel/Particles/Xm
insert ResConstructor:Intermediates 0 /Herwig/FRModel/Particles/Y1

~
```

example command files for HERWIG for simplified DM + vector mediator model. (Beam information included in Contur

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

Outgoing particles and resonant particles defined.

2. Single parameter point: Calculating observables

Head to this page and follow the instruction on running single parameter point

https://gitlab.com/hepcedar/contur#herwig-and-rivet-combined-run-on-a-single-single-set-of-rivet-analyses

Contur-batch commands will not work in the page but you could do $ contur-batch -n 1000 --seed 101 -s to generate the grid without submitting.

* information about measurements can be found →here

3. Single parameter point: Evaluating likelihood


```
# contur Rivet.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

information about CONTUR run

some measurements have to be excluded*

* →on the importance of model-independent measurements

3. Single parameter point: Evaluating likelihood

(continued)

```
[...]
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 Rivet.yoda
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)

[...]
```

loading histograms and theory inputs

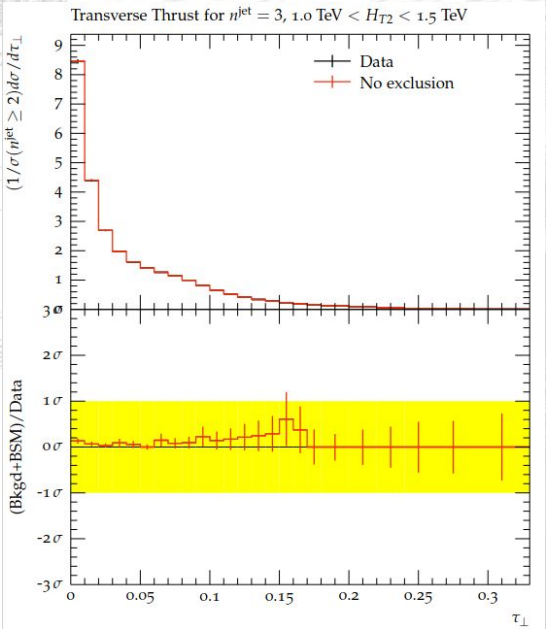
exclusion of ≈98%!

make plots using a wrapper for `rivet-mkhtml`

(this will take some time)

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

Hadronic event shapes in multijet final states
(→ATLAS_2020_I1808726)



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

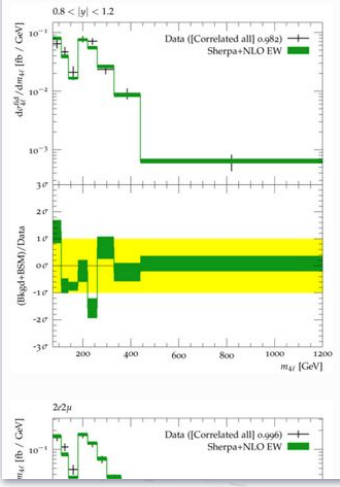
Pool: **ATLAS_13_4L** *four leptons*

- 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

3. Using theory predictions

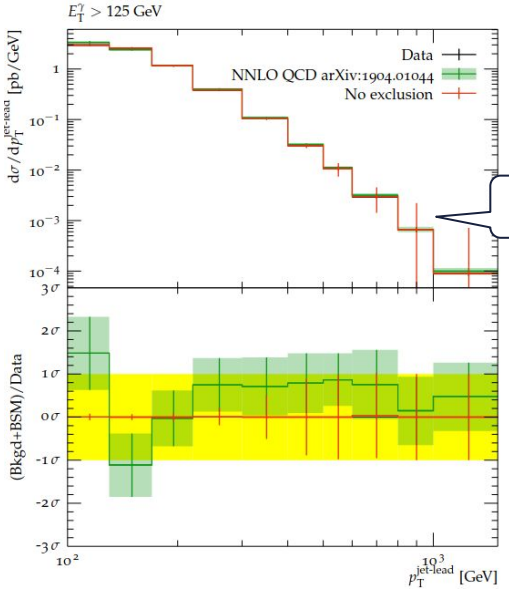
how to enable using theory predictions in practice?

```
# mv contur-plots contur-plots_noTheory; rm -r ANALYSIS
# rivet -a ATLAS_2017_I1645627 LHC-FRModel.hepmc
# contur --ana-match ATLAS_2017_I1645627 Rivet.yoda
[...]
INFO - Combined exclusion for these plots is 3.91 %
# contur --ana-match ATLAS_2017_I1645627 Rivet.yoda --theory
[...]
INFO - Combined exclusion for these plots is 4.41 %
# contur-mkhtml Rivet.yoda
[...]
```

store and remove previous results

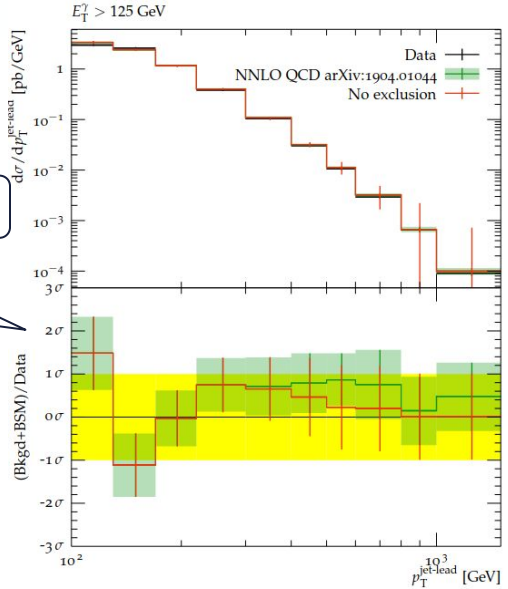
≈3.9% exclusion in default mode

exclusion changes when provided theory predictions are used



without theory: Bkgd=Data

with theory: Bkgd=SM



Isolated photon + jets at 13 TeV
(→ATLAS_2017_I1645627)

4. A look at param_files.dat


```
cat param_file.dat
[Run]
generator = "/path/to/Herwig-7.2.1/bin/activate"
contur = "/path/to/contur/setupContur.sh"

[Parameters]
[[mXm]]
mode   = LIN
start  = 10.0
stop   = 1500.0
number = 10

[[mY1]]
mode   = LIN
start  = 10.0
stop   = 3500.0
number = 10

[[gYXm]]
mode  = CONST
value = 1.0

[[gYq]]
mode  = CONST
value = 0.25
```

tell CONTUR which generator etc. to use and where to find them

tell CONTUR to vary dark matter mass from 10 to 1500 GeV in 10 equidistant steps

mediator mass is second scan parameter

tell CONTUR to treat couplings as constant

with this setup, signal grid generated with

```
# 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

```
# 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
```

(this will take some time)

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)

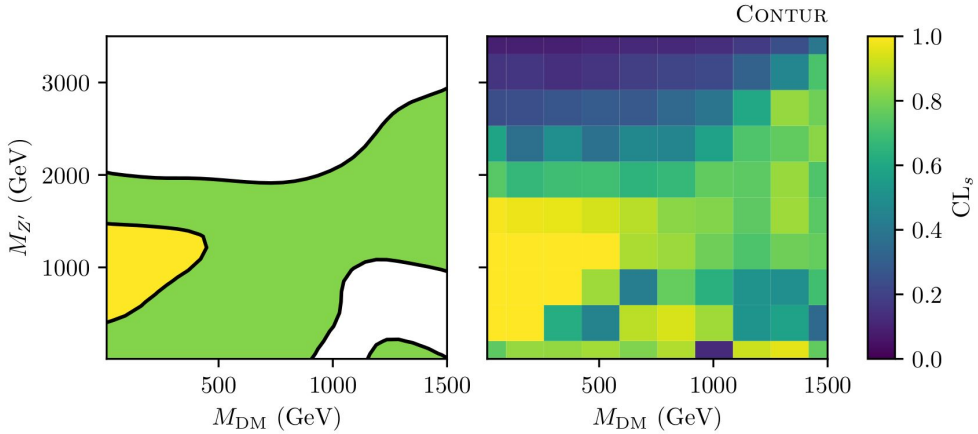
report exclusion for grid point and go to next one

summarise run and give output

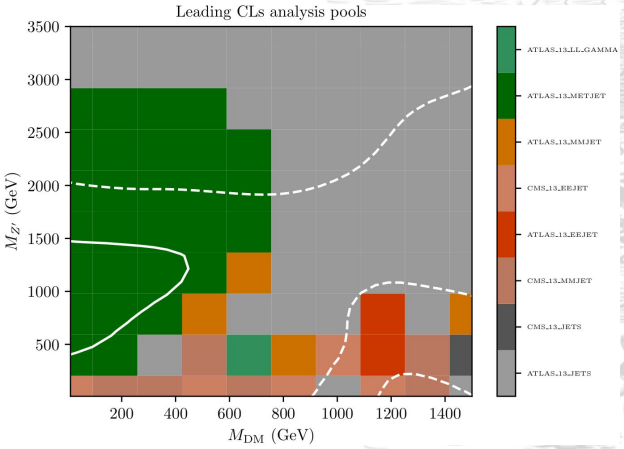
4. Plotting with CONTUR

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

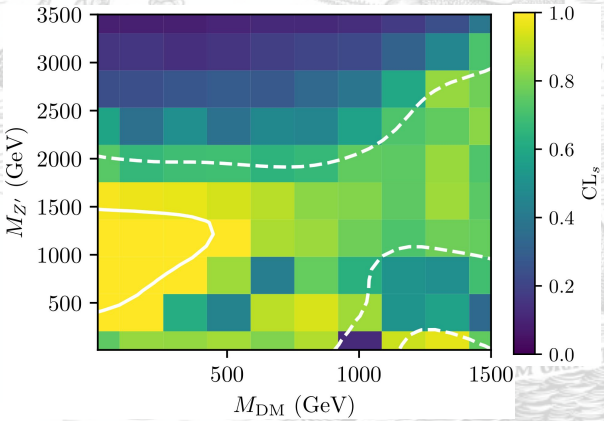


conturPlots/dominantPools0.pdf

4. Plotting with CONTUR

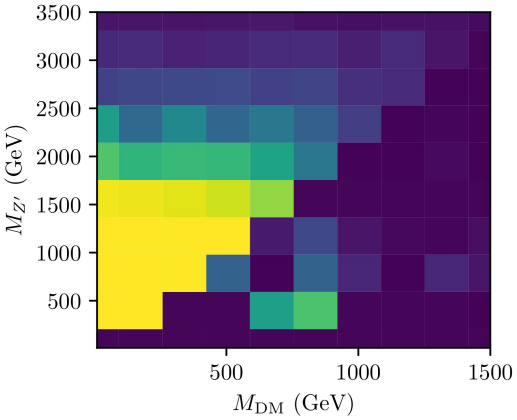
to plot the exclusion for each pool separately

```
# 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
```

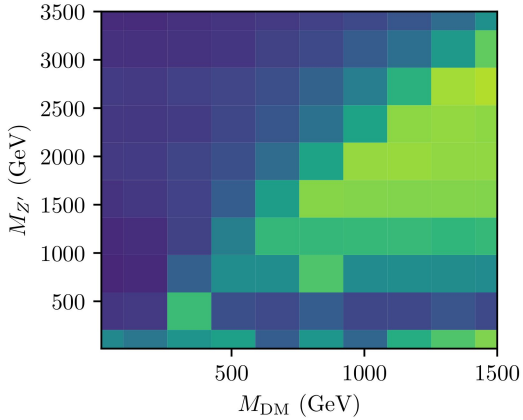


total exclusion

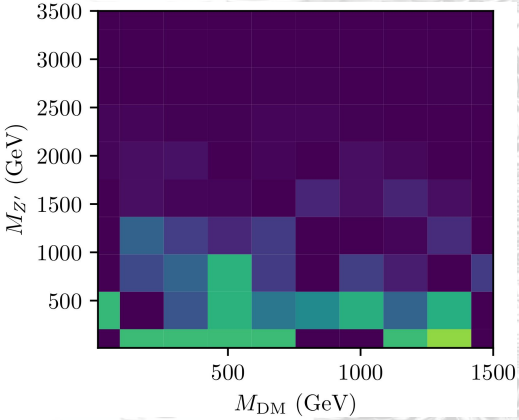
and find your plots at ANALYSIS/conturPlot/pools



ATLAS_13_METJETMesh.pdf



ATLAS_13_JETSMesh.pdf



CMS_13_MMJETMesh.pdf

Bonus: Plotting cross sections

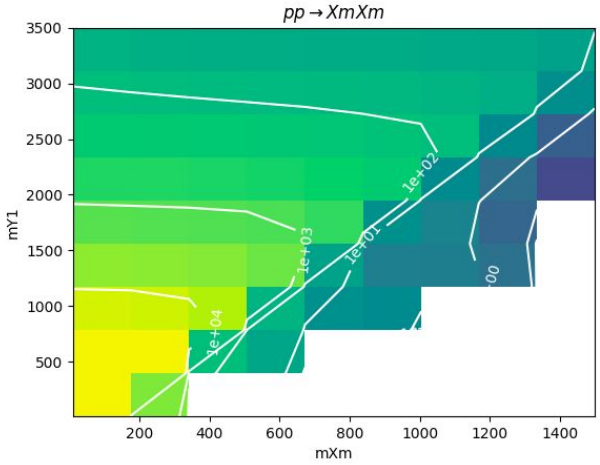
to plot the cross sections for the different processes do

```
# 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)
[...]
```

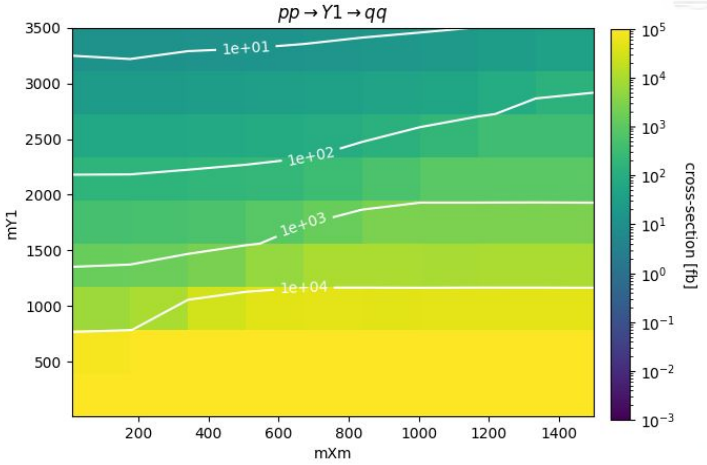
all the grid points we used

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)

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

For more information check out the →CONTUR webpages
or send us an →e-mail