Beyond the Standard Model : phenomenology and LHC constraints of exotic dark matter

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LPSC Grenoble & LAPTh Annecy

Mid-thesis presentation, March 25, 2021

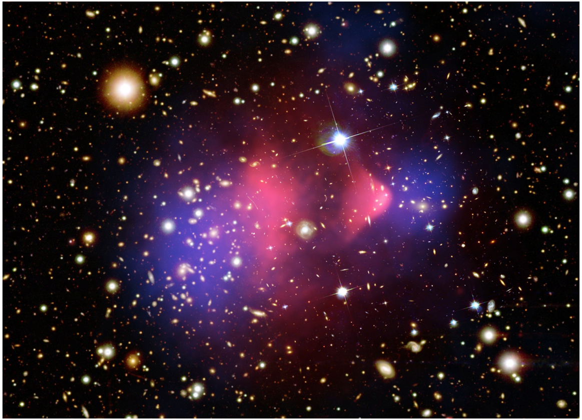
Supervised by Sabine Kraml and Genevieve Belanger

Outline

G.A., Araz, Fuks, Kraml, Waltenberger, Les Houches 2019 proceedings, contribution 15 [arXiv]
G.A., Kraml, Waltenberger, CPC 264 (2021) 107909 [arXiv]
G.A., Heisig, Khosa, Kraml, Kulkarni, Lessa, Neuhuber,
Reyes-González, Waltenberger, Wongel, TOOLS 2020 proceedings [arXiv]

Evidences for dark matter (DM)

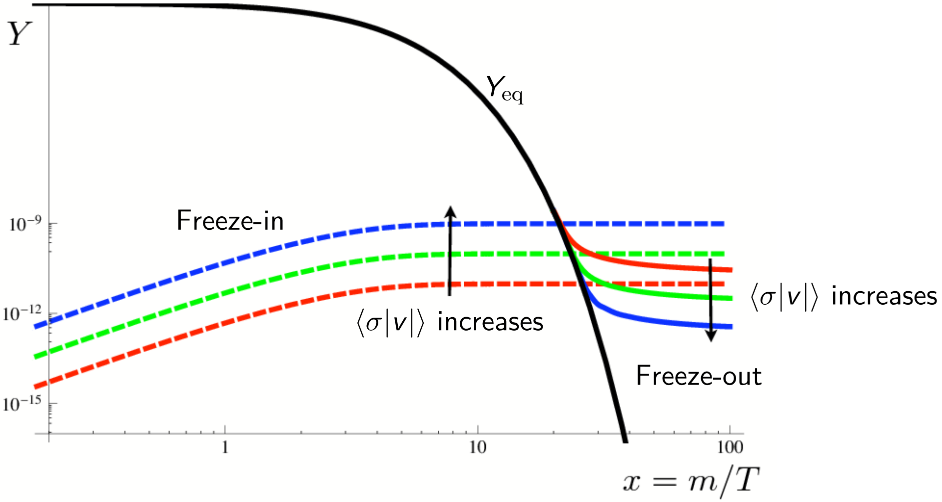
- Many evidences hinting for a missing mass
  - Galaxy rotation curves
  - Galaxy clusters
  - Gravitational lensing
  - And others
- Must be massive, weakly interacting, dark



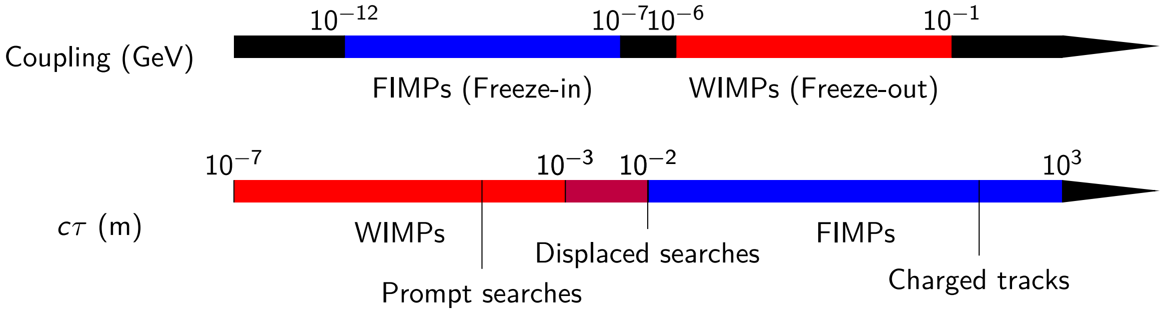
The DM theory landscape

Nature 562, 5156 (2018)

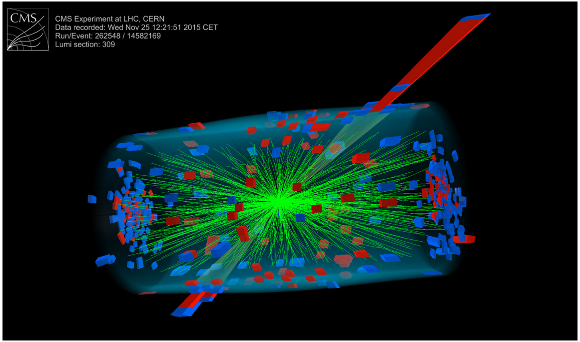
Dark matter production in the universe

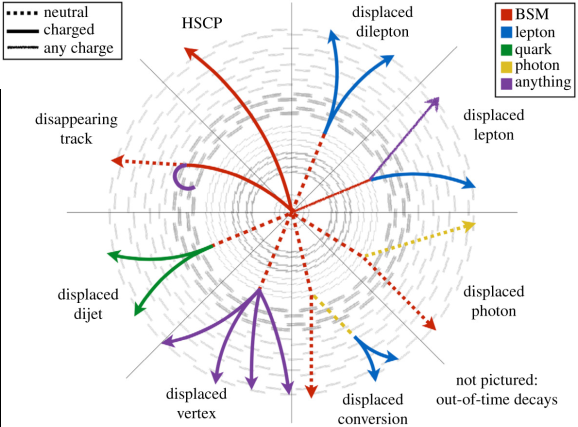


WIMPs, FIMPs and beyond



At the LHC : Missing energy and long lived signatures





How to use LHC results?

- Monte Carlo event generation + detector simulation (MadGraph + MadAnalysis)
  - simulate the whole collision, detector effects and selection cutflow
  - captures differences in kinematical distributions
  - more generally applicable
  - very CPU-time consuming

- Using simplified model results (SModelS)
  - uses the efficiencies provided by experimentalists
  - assumes the cut acceptances are approx. the same as in the simplified models
  - much faster
  - suitable for large scans

G.A., Araz, Fuks, Kraml, Waltenberger, Les Houches 2019 proceedings, contribution 15 [arXiv]
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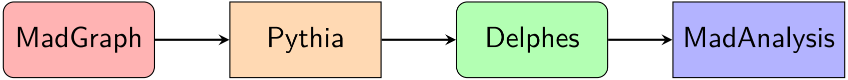
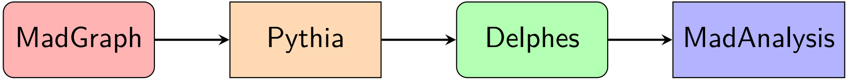
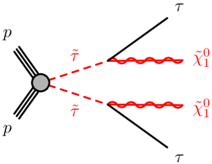
Recasting workflow



ATLAS-SUSY-2018-04

Recasting workflow





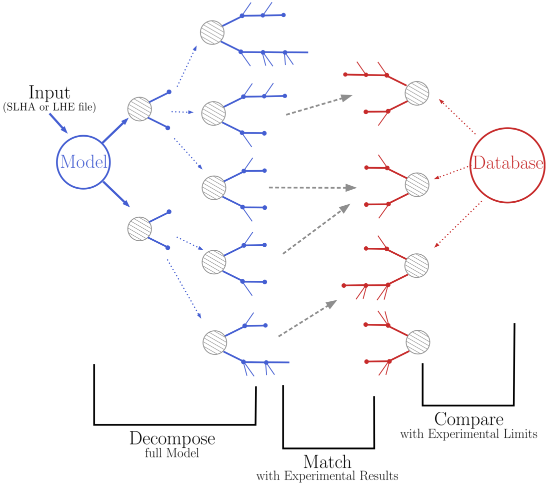
SR – lowMass	**SR – highMass**
2 tight τ (OS)	2 medium τ (OS)
–	≥ 1 tight τ
$\Delta R(\tau_1, \tau_2) < 3.2$	$E_T^{miss} > 150$ GeV
$75 < E_T^{miss} < 150$ GeV	$\Delta R(\tau_1, \tau_2) < 3.2$
$m_{T2} > 70$ GeV	$m_{T2} > 70$ GeV

ATLAS-SUSY-2018-04

Re-using simplified model results : SModelS

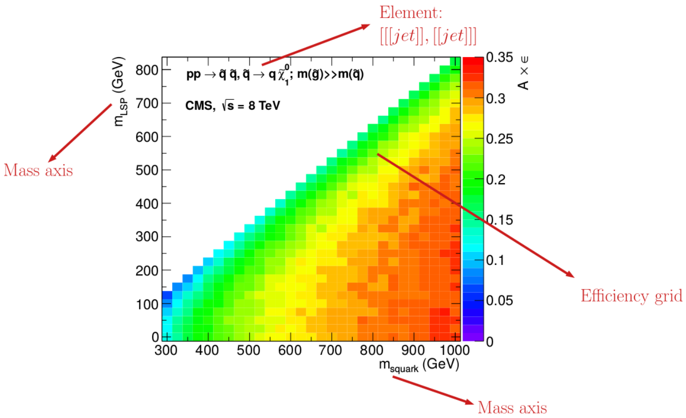
- Based on a general procedure to decompose BSM collider signatures featuring a $\mathbb{Z}_2$-like symmetry into simplified-model topologies
- Large database of simplified-model results (currently $\sim$100 ATLAS ans CMS searches)
- New generic treatment of width-dependent results with a variety of LLP analyses

See online SModelS documentation at
smodels.readthedocs.io



SModelS database

- Upper limit (UL)
  - Constrains $\sigma \times \prod_j BR_j$
  - Only binary decision
- Efficiency map (EM)
  - Allows to sum contributions from several topologies
  - Can compute a likelihood (confidence level)



Combining signal regions (SRs)

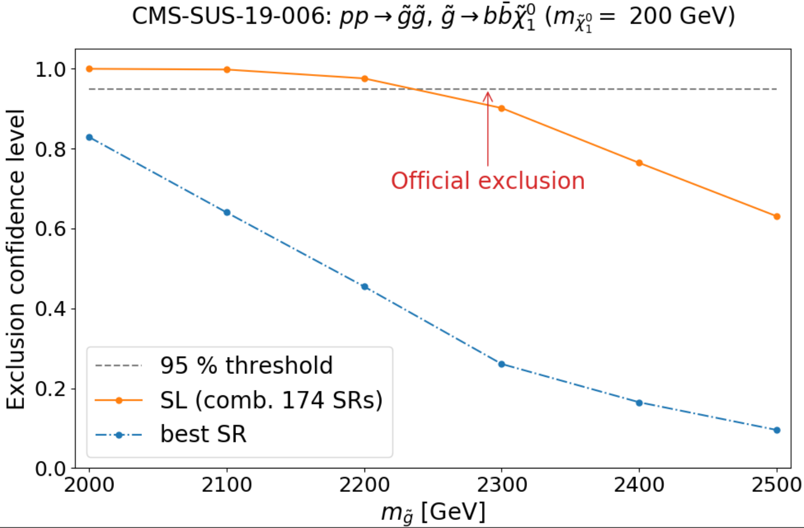
- For a proper statistical evaluation
  - need to compute a likelihood
  - without specific likelihood information : can only compute for each signal region (SR)

$$\mathcal{L}(\mu, \theta | D) = \frac{(\mu s + b + \theta)^{n_{obs}} e^{-(\mu s + b + \theta)}}{n_{obs}!} exp\left(-\frac{\theta^2}{2\delta^2}\right)$$

$\Rightarrow$ use the “most sensitive” SR

- **Simplified likelihoods** : global background uncertainty [CMS-NOTE-2017-001]
  - summarized into a covariance matrix
  - one Gaussian error for each SR
- **Full likelihoods** : full statistical descriptions of analyses [ATL-PHYS-PUB-2019-029]
  - encapsulate the detailed information about the analysis (detailed systematic uncertainties)
  - reproduces exactly the experimental analysis and allows for a more precise reinterpretation

Simplified likelihood in MadAnalysis



Les Houches 2019 proceedings, contribution 15 [arXiv]

- CMS-SUS-16-039
- CMS-SUS-17-001
- CMS-SUS-19-006
- CMS-SUS-16-048

Full ATLAS likelihoods

- Serialization of `HistFactory` workspaces under the JSON format
- Provides observed signals, expected backgrounds and systematic uncertainties as in the experimental analysis
- Can be used in `RooFit` or `pyhf` (a pure-python implementation of `HistFactory`)

ATL-PHYS-PUB-2019-029

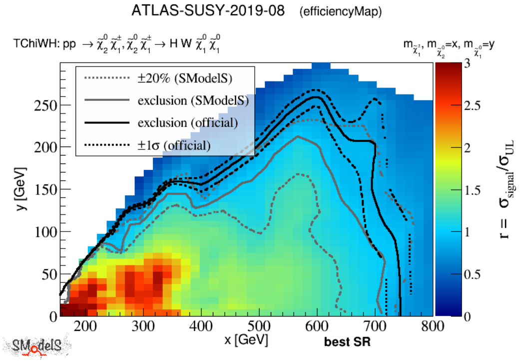

```
{
  "channels": [
    {▭
    {▭
    {
      "name": "SR1cut_cuts",
      "samples": [▭
    },
    {
      "name": "SR2cut_cuts",
      "samples": [
        {
          "data": [
            2.570836067199707
          ],
          "modifiers": [▭
          "name": "Boson_Staus"
        },
        {
          "data": [
            0.044047050178050995
          ],
          "modifiers": [▭
          "name": "Z_Staus"
        },
```


Signal regions

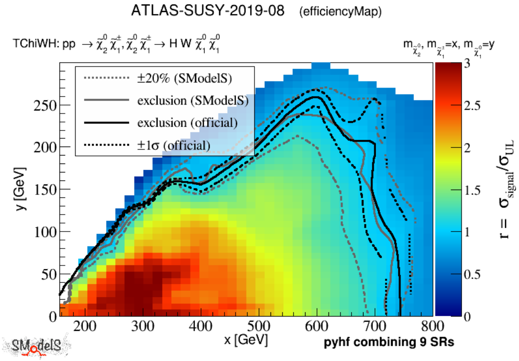
Background contributions

Implementation of a SModelS interface to pyhf

CPC 264 (2021) 107909 [arXiv] and TOOLS2020 proceedings [arXiv]



Standard "best SR" procedure



pyhf likelihoods

$\Rightarrow$ ATLAS-SUSY-2018-04, ATLAS-SUSY-2018-31 and more to come

Cited in CERN seminar by Kyle Cranmer

USAGE IN PHENO RECASTING TOOLS

G. Alguero, **J. Araz**, B. Fuks, SK, W. Waltenberger
Contr. 15, LH 2019 BSM WG report, arXiv:2002.12220

Usage in MadAnalysis 5

MA5-pyhf interface established within the LH PhysTeV 2019 workshop

- the relevant JSON files must be located in the same analysis folder as the recast code (done automatically at the time of the PAD installation).
- The `analysis.info` file must include new <pyhf> elements specifying the names of the JSON files together with the corresponding channels (ensembles of SRs) and the regions they include, as defined in the JSON files.

```
<pyhf id="RegionA">
  <name>atlas_susy_2018_031_SRA.json</name>
    <regions>
      <channel name="SR_meff">SRA_L SRA_M SRA_H</channel>
      <channel name="VRtt_meff"> </channel>
      <channel name="CRtt_meff"> </channel>
    </regions>
</pyhf>
```

S. Kraml - Feedback on use of public likelihoods - 24 Sep 2020

Gaël Alguero, SK, Wolfgang Waltenberger,
arXiv:2009.01809

SModelS-pyhf interface

- Available from SModelS v1.2.4 onward (released Sep. 3rd, 2020)
- The interfacing of pyhf to SModelS consists of two parts:
  - addition of an independent module `tools/pyhfInterface.py`
  - changes brought to `experiment/datasetObj.py`
- Can be turned on/off by setting

  `combineSR = True/False`

  in the `parameters.ini` file *)

`PyhfData` class:
Storing and handling of the information related to the JSON files and input signal predictions.
Collects information in the workspaces such as the number of SRs, and the paths to the SR `samples` where the BSM predictions are to be written.
The VRs and CRs are assumed not to contribute and removed from the workspaces.

`PyhfUpperLimitComputer` class:
For inferring the upper limits given the `PyhfData` information

*) The same flag also turns on the SR combination in the simplified likelihood approach for CMS efficiency map results, for which a covariance matrix is available.

S. Kraml - Feedback on use of public likelihoods - 24 Sep 2020 13

EP-IT Data science seminars

PHYSTAT seminar: Likelihood publishing, RECAST, and simulation-based inference

by Kyle Stuart Cranmer (New York University (US))

Wednesday 14 Oct 2020, 14:00 → 15:00 Europe/Zurich

CERN

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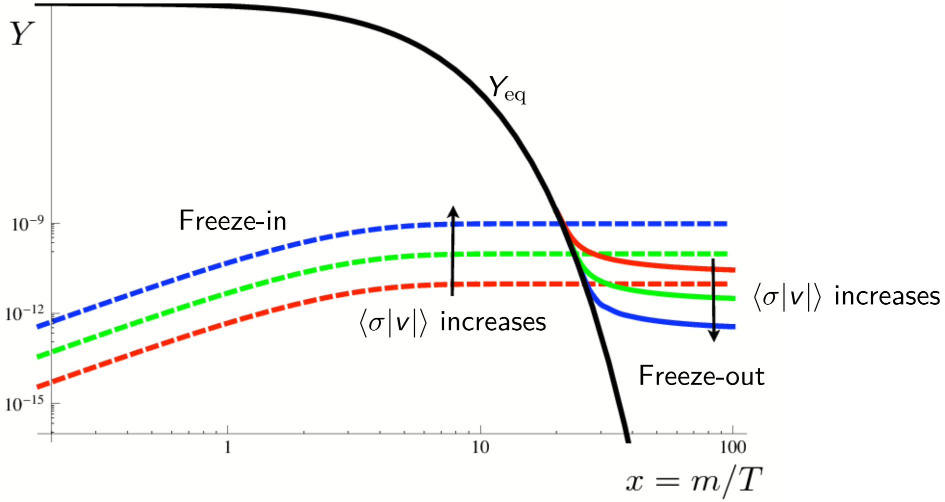
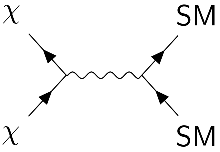
Outline

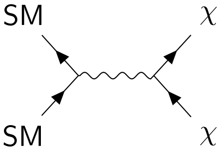
“In between” freeze-out and freeze-in

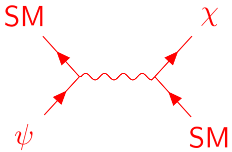


Coscattering

- Standard freeze-out equation
  $\dot{n}_\chi + 3Hn_\chi = -\langle\sigma|v|\rangle\left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$
- Freeze-in
- coscattering
  $\dot{n}_\psi + 3Hn_\psi = -\langle\sigma|v|\rangle\left(n_\psi^2 - n_{\psi,\mathrm{eq}}^2\right) - \Gamma_{\psi\to\chi}\left(n_\chi - n_\psi \frac{n_\chi^{\mathrm{eq}}}{n_\psi^{\mathrm{eq}}}\right)$
  $\dot{n}_\chi + 3Hn_\chi = \Gamma_{\psi\to\chi}\left(n_\chi - n_\psi \frac{n_\chi^{\mathrm{eq}}}{n_\psi^{\mathrm{eq}}}\right)$







χ : dark matter
ψ : heavier odd particle

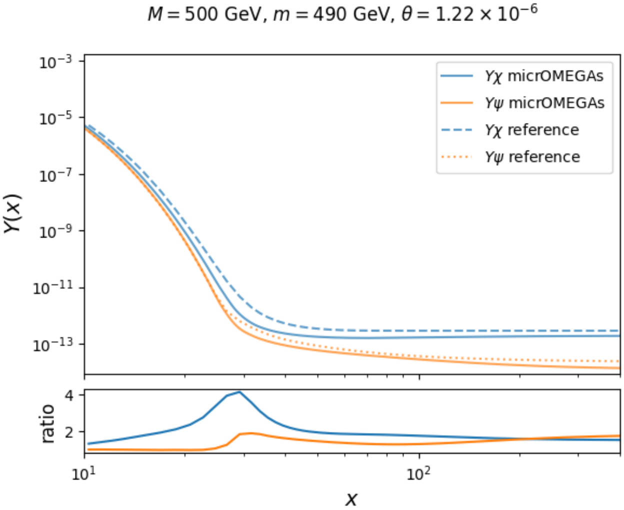
R.T.D'agnolo et al., Phys. Rev. Lett. 119, 061102 (2017) [arXiv]
M.Garny et al., Phys. Rev. D 96, 103521 (2017) [arXiv]

Work in progress in micrOMEGAs

- Testing coscattering with a Singlet-Triplet model
  - Standard Model $+\chi^0 + \{\psi^0, \psi^\pm\}$
- with a compressed spectrum
  - small mass splitting
  - small couplings

F.Brümmer, JHEP 2001 (2020) 113

[arXiv]



Scotogenic model

Ernest Ma, Phys.Rev.D73:077301,2006 [arXiv]

- Standard Model extended with
  - an inert Higgs doublet
  - and right-handed neutrinos

$$\begin{pmatrix} H_1^\pm \\ H_1^0 \end{pmatrix}, \begin{pmatrix} H_2^\pm \\ H_2^0 \end{pmatrix}, \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

  - odd under a $\mathbb{Z}_2$-symmetry

Field	Generations	$\mathrm{SU(3)_c}$	$\mathrm{SU(2)_L}$	$\mathrm{U(1)_Y}$	$\mathbb{Z}_2$
ℓ_L	3	**1**	**2**	$-1/2$	$+$
e_R	3	**1**	**1**	-1	$+$
H_1	1	**1**	**2**	$1/2$	$+$
H_2	1	**1**	**2**	$1/2$	$-$
N	3	**1**	**1**	0	$-$

$$H_1 \xrightarrow{\mathbb{Z}_2} H_1$$

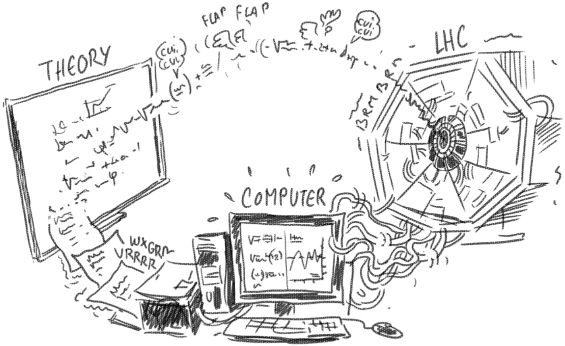
$$H_2 \xrightarrow{\mathbb{Z}_2} -H_2$$

- radiative neutrino masses
- provides different DM candidates
  - different production mechanisms (freeze-in, freeze-out, ...)
  - probe with the appropriate LHC signatures (prompt, long-lived, ...)

Conclusions

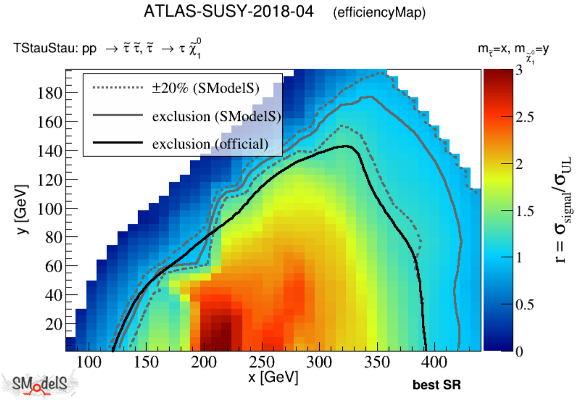
- simplified likelihoods implemented in MadAnalysis5
  - ability to use CMS covariance matrices
  - database extended with all usable covariance matrices
- SModelS/pyhf interface from SModelS v1.2.4 onwards
  - ability to use full likelihoods from ATLAS
  - added EMs + JSON files for three 139 fb^{-1} analyses
- more accurate reinterpretations, more reliable statistical evaluation e.g. for fits
- work in progress
  - coscattering in micrOMEGAs
  - scotogenic model

Thanks for your attention !

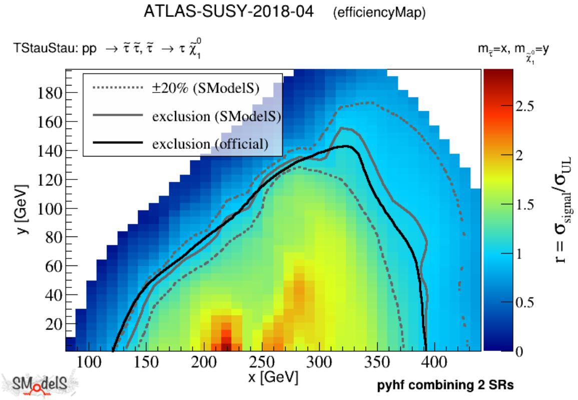


SModelS-pyhf interface

arXiv:2009.01809 (pyhf interface)



Standard "best SR" procedure



pyhf likelihoods

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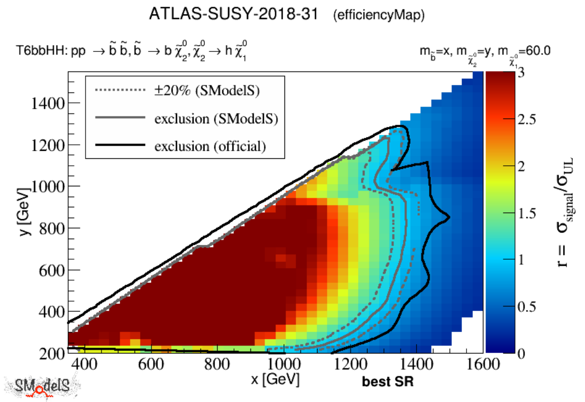

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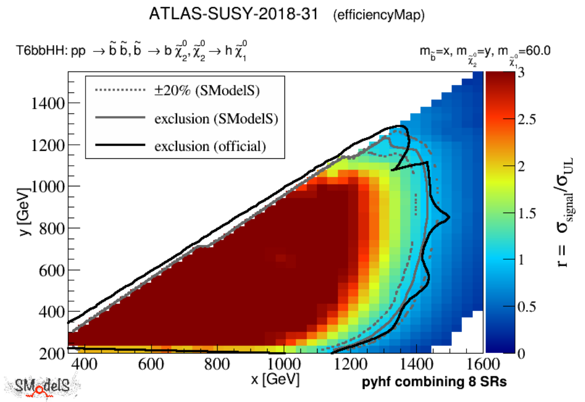


pyhf likelihoods

ATLAS likelihoods

$$p(n, a|\eta, \chi) = \underbrace{\prod_{c \in channels} \prod_{b \in bins} \text{Pois}\Big(n_{cb}|\nu_{cb}(\eta, \chi)\Big)}_{\text{Measurements}} \underbrace{\prod_{\chi} c_{\chi}(a_{\chi}|\chi)}_{\text{Constraints}} \tag{1}$$

relates the observed events and auxiliary data (n, a)
to the free and constrained parameters (η, χ)

$$\nu_{cb}(\eta, \chi) = \sum_{s \in samples} \nu_{scb}(\eta, \chi) = \sum_{s \in samples} \underbrace{\prod_{\kappa} \kappa_{scb}(\eta, \chi)}_{\text{Mujtiplicative modifiers}} \left(\nu^{0}_{scb}(\eta, \chi) + \underbrace{\sum_{\Delta} \Delta_{scb}(\eta, \chi)}_{\text{Additive modifiers}}\right) \tag{2}$$

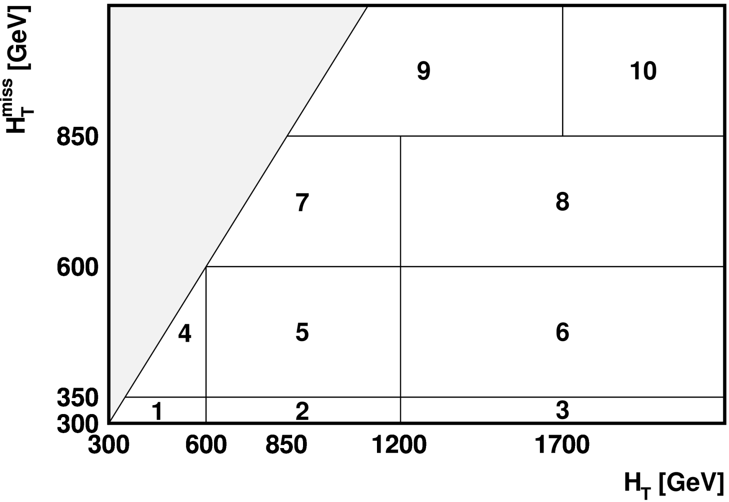
ATL-PHYS-PUB-2019-029

Simplified likelihood

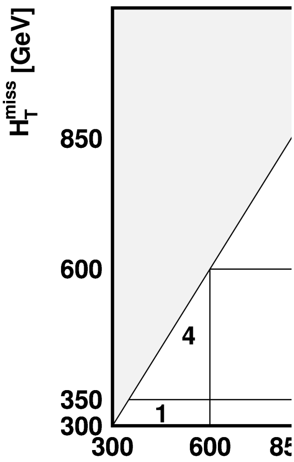
$$\mathcal{L}(\mu, \theta | D) = \prod_{i=1}^{N} \frac{(\mu s_i + b_i + \theta_i)^{n^i_{obs}} e^{-(\mu s_i + b_i + \theta_i)}}{n^i_{obs}!} \; exp\left(-\frac{1}{2}\vec{\theta}^T V^{-1} \vec{\theta}\right)$$

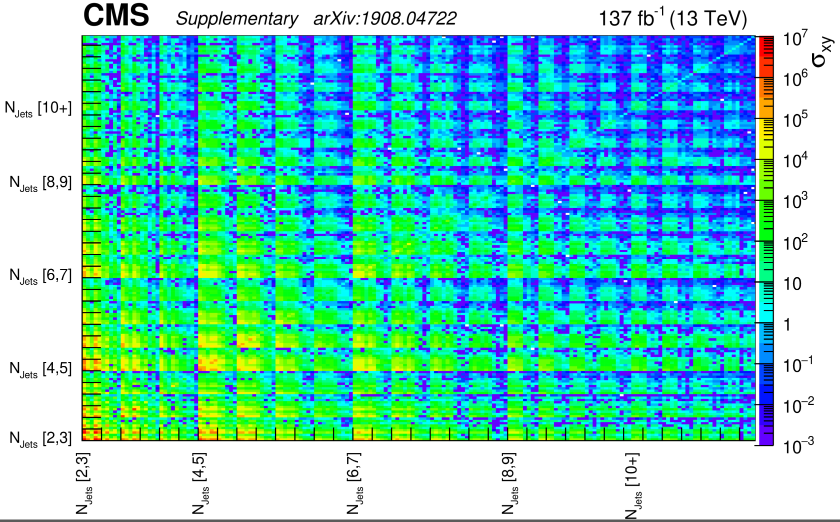
with a product over all N SRs where V is the covariance matrix

CMS-SUS-19-006 covariance matrix

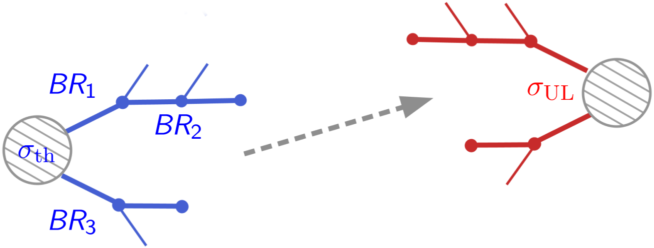


CMS-SUS-19-006 covariance matrix



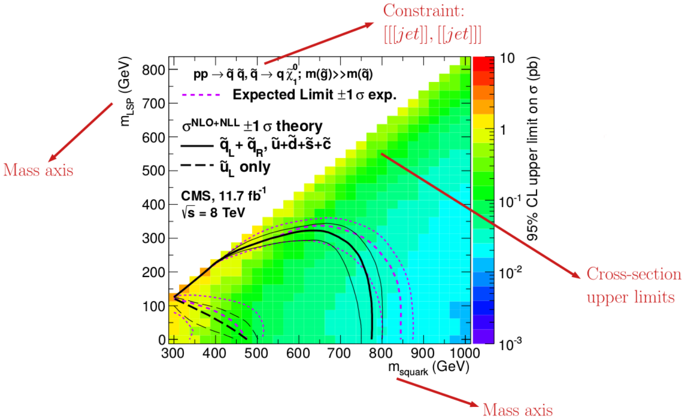


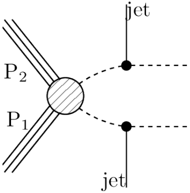
Matching in SModelS



$\sigma_{\rm th} \times BR_1 \times BR_2 \times BR_3$ to compare with $\sigma_{\rm UL}$

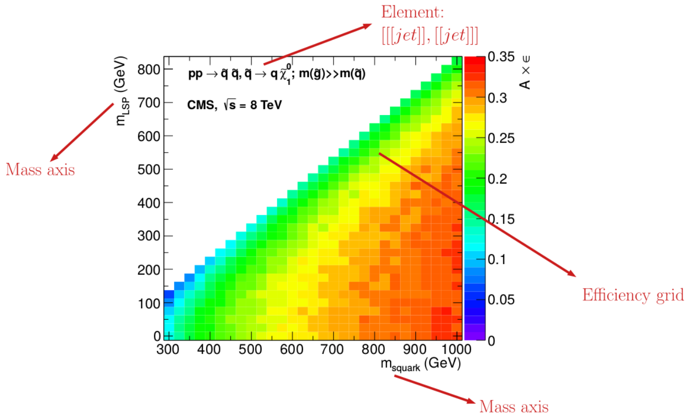
Upper limit map (UL) in SModelS



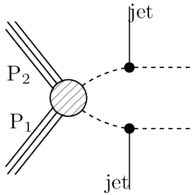


- Constrains $\sigma \times \prod_j BR_j$ per topology
- Only binary decision : excluded or not

Efficiency map (EM) in SModelS



one EM/topology for each signal region



- Constrains $\sum_i A_i \epsilon_i \times \sigma_i \times \prod_j BR_j$ per signal region
- Can sum contributions from several topologies
- Can compute a likelihood (exclusion confidence level)

Efficieny map

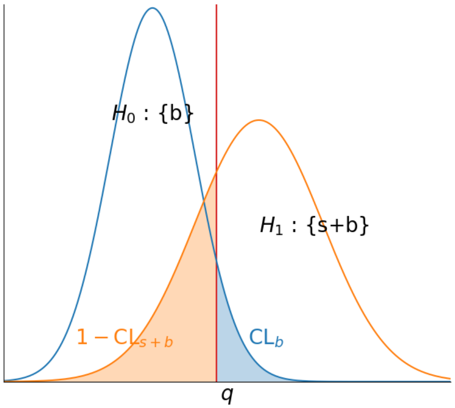
Hypothesis test

- Testing hypothesis H_0 : {only background} against H_1 : {background + new signal}
- Definition of a log likelihood ratio

$$q = -2\log\left(\frac{\mathcal{L}(\mathrm{data}|H_1)}{\mathcal{L}(\mathrm{data}|H_0)}\right)$$

- Computing a robust p-value ratio

$$\mathrm{CL}_s = \frac{\mathrm{CL}_{s+b}}{\mathrm{CL}_b}$$



Acceptance and efficiency

$$N = A\epsilon\sigma\mathcal{L}$$

- A and ϵ : acceptance and efficiency
- σ and $\mathcal{L}$: cross section and integrated luminosity