Likelihood Publication and Preservation

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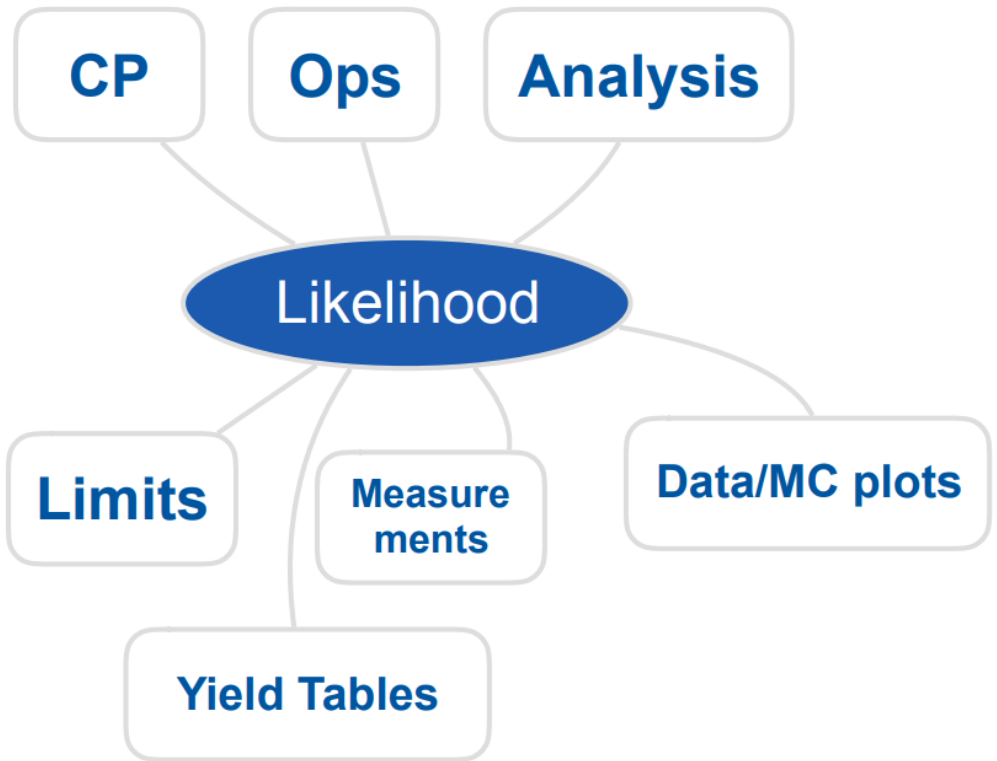
ATLAS EXPERIMENT

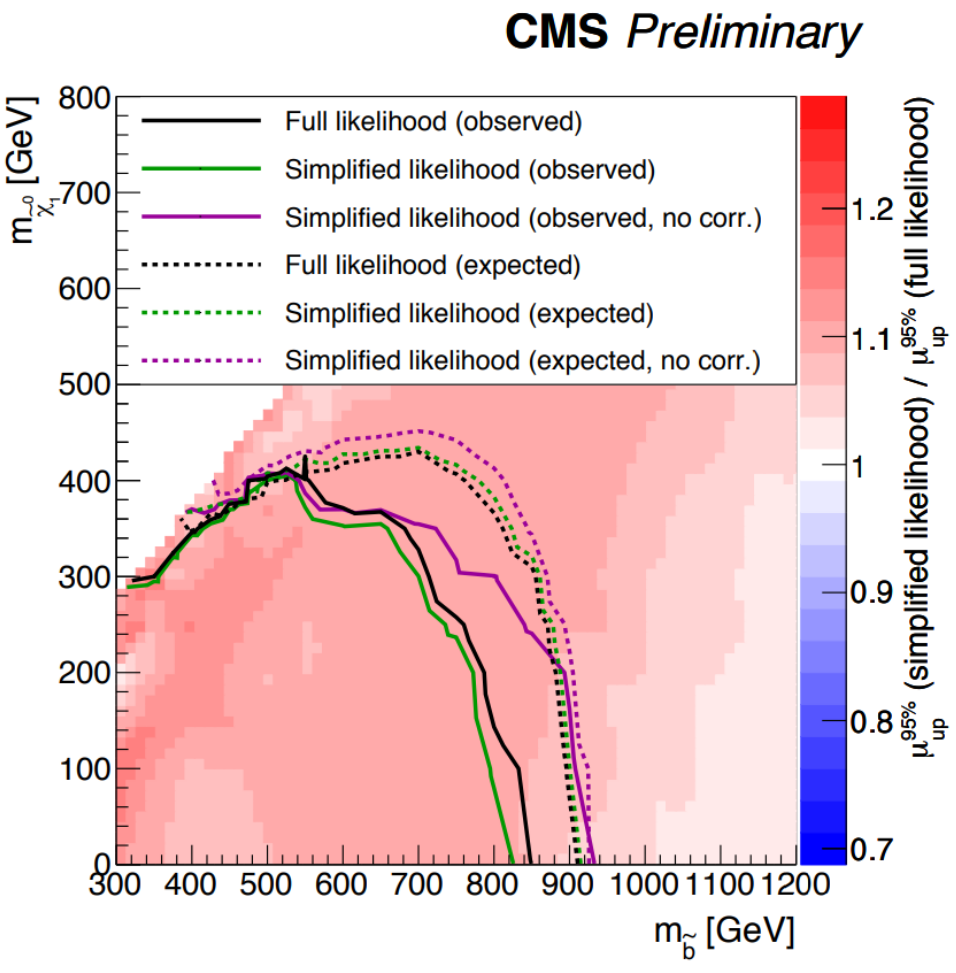
iris hep

Why is the likelihood important?

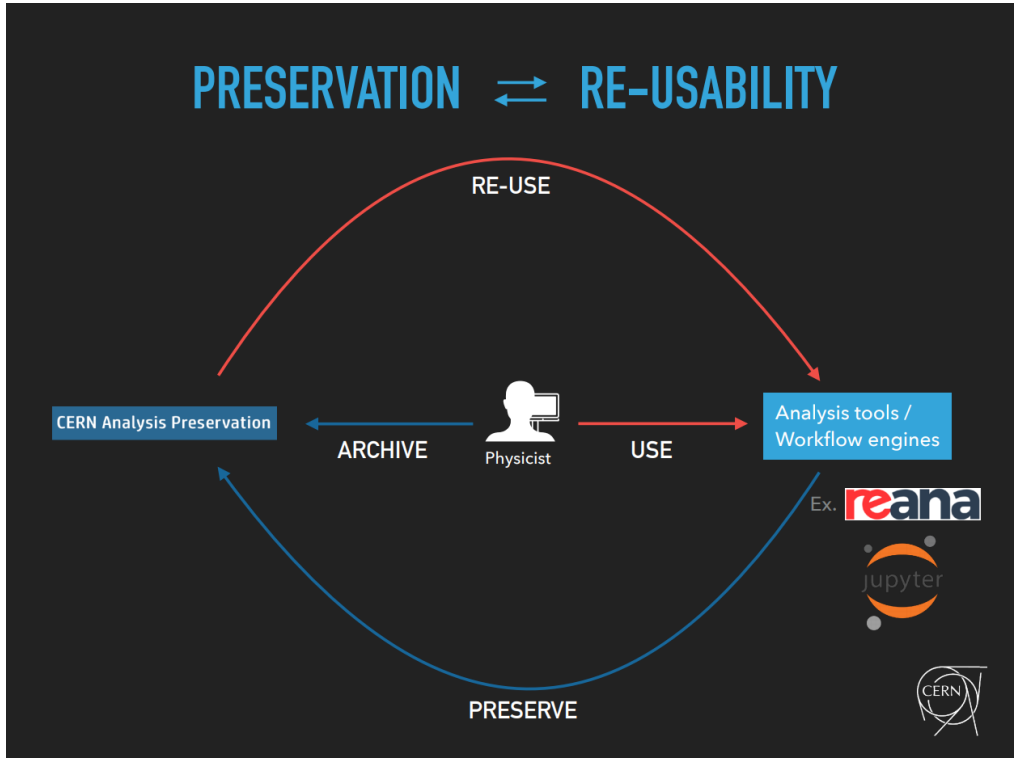
- High information-density summary of analysis
- Almost everything we do in the analysis ultimately affects the likelihood and is encapsulated in it
  - Trigger
  - Detector
  - Combined Performance / Physics Object Groups
  - Systematic Uncertainties
  - Event Selection
- Unique representation of the analysis to reuse and preserve



Partial likelihoods have been published/preserved



(CMS, 2017)



CERN Analysis Preservation implements FAIR data

(CERN, CHEP 2019)

Full likelihood serialization...

...making good on 19 year old agreement to publish likelihoods

Massimo Corradi

It seems to me that there is a general consensus that what is really meaningful for an experiment is *likelihood*, and almost everybody would agree on the prescription that experiments should give their likelihood function for these kinds of results. Does everybody agree on this statement, to publish likelihoods?

Louis Lyons

Any disagreement ? Carried unanimously. That's actually quite an achievement for this Workshop.

(1st Workshop on Confidence Limits, CERN, 2000)

This hadn't been done in HEP until 2019

- In an "open world" of statistics this is a difficult problem to solve
- What to preserve and how? All of ROOT?
- Idea: Focus on a single more tractable binned model first

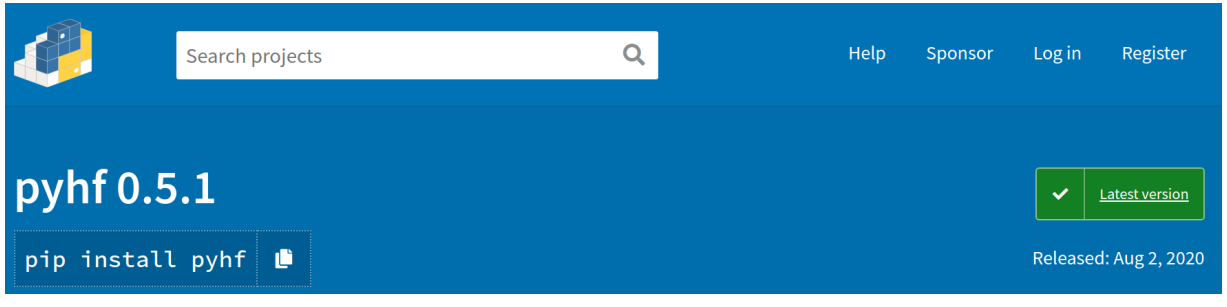
Enter HistFactory and `pyhf`

$$f\left(\text{data}|\text{parameters}\right) = f\left(\vec{n}, \vec{a}|\vec{\eta}, \vec{\chi}\right) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}_c} \text{Pois}\left(n_{cb}|\nu_{cb}\left(\vec{\eta}, \vec{\chi}\right)\right) \prod_{\chi \in \vec{\chi}} c_\chi\left(a_\chi|\chi\right)$$

Use: Multiple disjoint channels (or regions) of binned distributions with multiple samples contributing to each with additional (possibly shared) systematics between sample estimates

HistFactory is used ubiquitously in binned analyses
Focus on this flexible p.d.f. template rather than "open world" of models
This is a mathematical representation! Nowhere is any software spec defined

`pyhf`: HistFactory in pure Python hardware accelerated with autodiff



pyhf differentiable likelihoods

Lukas Heinrich

CERN

Matthew Feickert

Illinois

Giordon Stark

UCSC SCIPP

JSON spec fully describes the HistFactory model

- Human & machine readable **declarative** statistical models
- Industry standard
  - Will be with us forever
- Parsable by every language
  - Highly portable
  - Bidirectional translation with ROOT
- Versionable and easily preserved
  - JSON Schema describing HistFactory specification
  - Attractive for analysis preservation
  - Highly compressible

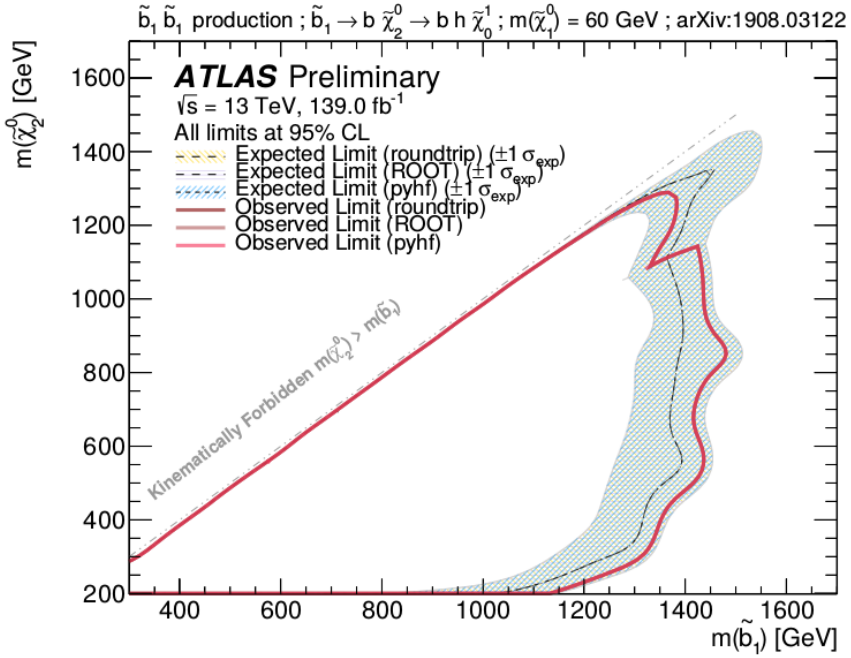
```
{
    "channels": [ # List of regions
        { "name": "singlechannel",
          "samples": [ # List of samples in region
            { "name": "signal",
              "data": [20.0, 10.0],
              # List of rate factors and/or systematic uncertainties
              "modifiers": [ { "name": "mu", "type": "normfactor", "data": null} ]
            },
            { "name": "background",
              "data": [50.0, 63.0],
              "modifiers": [ {"name": "uncorr_bkguncrt", "type": "shapesys", "data": [5.0, 12.0]} ]
            }
          ]
        }
    ],
    "observations": [ # Observed data
        { "name": "singlechannel", "data": [55.0, 62.0] }
    ],
    "measurements": [ # Parameter of interest
        { "name": "Measurement", "config": {"poi": "mu", "parameters": []} }
    ],
    "version": "1.0.0" # Version of spec standard
}
```

JSON defining a single channel, two bin counting experiment with systematics

ATLAS validation and publication of likelihoods

ATLAS Note

Report number	ATL-PHYS-PUB-2019-029
Title	**Reproducing searches for new physics with the ATLAS experiment through publication of full statistical likelihoods**
Corporate Author(s)	The ATLAS collaboration



(ATLAS, 2019)

New open release allows theorists to explore LHC data in a new way

The ATLAS collaboration releases full analysis likelihoods, a first for an LHC experiment

9 JANUARY, 2020 | By Katarina Anthony

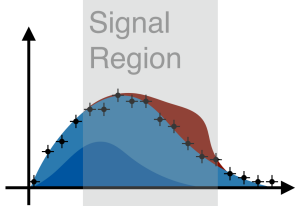
Explore ATLAS open likelihoods on the HEPData platform (Image: CERN)

(CERN, 2020)

JSON Patch for signal model (reinterpretation)

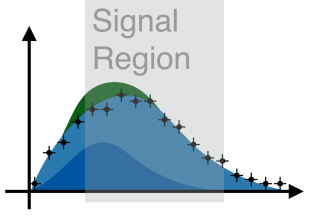
JSON Patch gives ability to **easily mutate model**
Think: test a **new theory** with a **new patch**!
(c.f. Lukas's RECAST talk)

Combined with RECAST gives powerful tool for **reinterpretation studies**



Signal model A

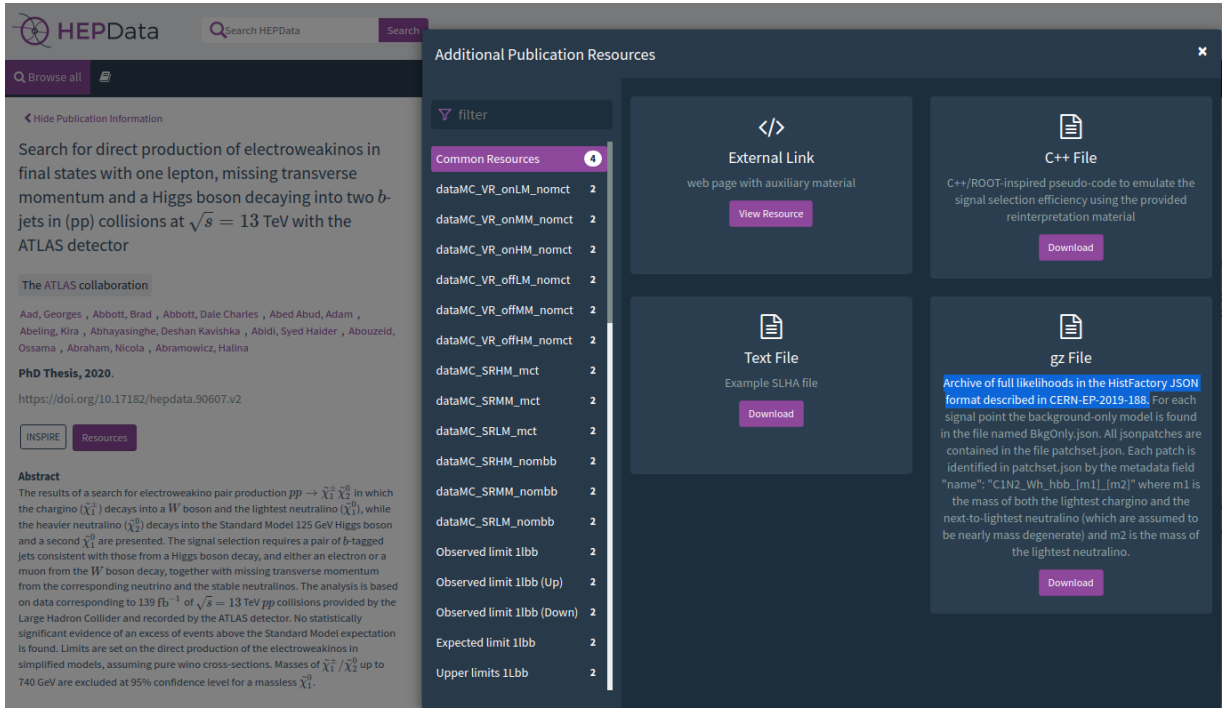
```
# Using CLI
$ pyhf cls example.json | jq .CLs_obs
0.053994246621274014

$ cat new_signal.json
[{
    "op": "replace",
    "path": "/channels/0/samples/0/data",
    "value": [10.0, 6.0]
}]

$ pyhf cls example.json --patch new_signal.json | jq .CLs_obs
0.3536906623262466
```



Signal model B

Likelihoods preserved on HEPData

- Background-only model JSON stored
- Hundreds of signal model JSON Patches stored together as a "patch set" file
- Together are able to publish and fully preserve the full likelihood (with own DOI! DOI 10.17182/hepdata.90607.v2/r2)




```
$ tree archive-likelihoods-hepdata
archive-likelihoods-hepdata
├── BkgOnly.json
├── patchset.json
└── README.md

0 directories, 3 file
```

...can be used from HEPData

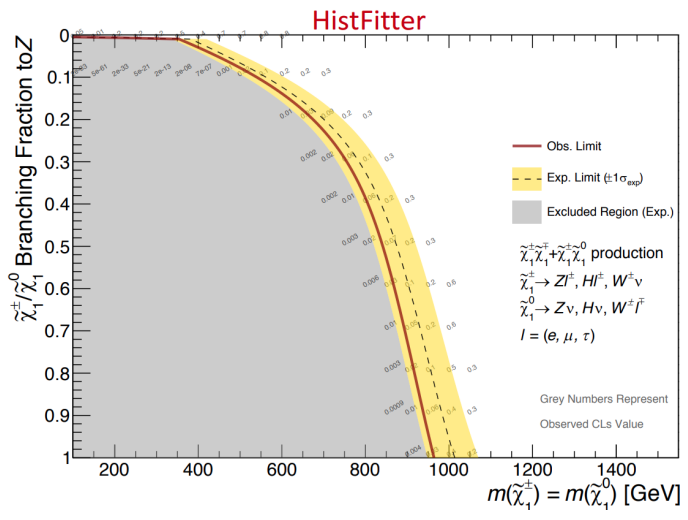
- Background-only model JSON stored
- Hundreds of signal model JSON Patches stored together as a "patch set" file
- Together are able to publish and fully preserve the full likelihood (with own DOI! DOI 10.17182/hepdata.90607.v2/r2)

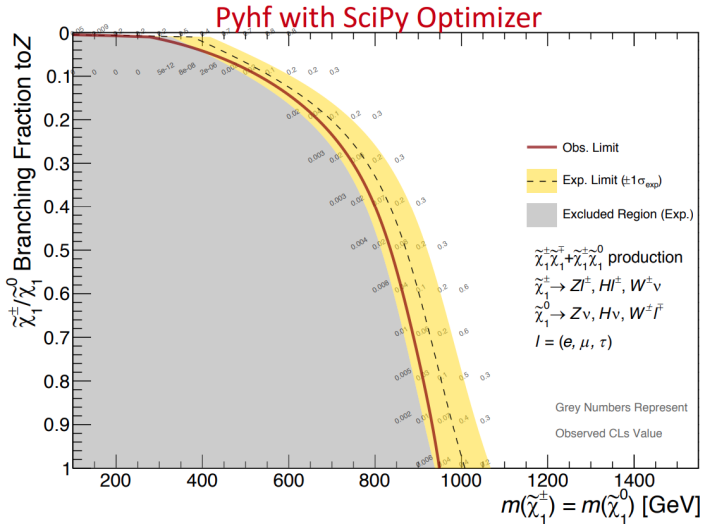
```
# signal patchset for the SUSY EWK 1Lbb analysis
$ curl -sL https://www.hepdata.net/record/resource/1267798?view=true | tar -xzv
$ cd 1Lbb-likelihoods-hepdata

# verify patchset is valid
$ pyhf patchset verify BkgOnly.json patchset.json
All good.

# signal model: m1 = 900, m2 = 300 (chain CLI API output)
$ cat BkgOnly.json | \
  pyhf cls --patch <(pyhf patchset extract --name C1N2_Wh_hbb_900_300 patchset.json) | \
  jq .CLs_obs
0.5004154596172573

# new signal model: m1 = 900, m2 = 400 (use serialized CLI API output)
$ pyhf patchset extract --name C1N2_Wh_hbb_900_400 --output-file C1N2_Wh_hbb_900_400_patch.json patchset.json
$ pyhf cls --patch C1N2_Wh_hbb_900_400_patch.json BkgOnly.json | jq .CLs_obs
0.5735044179801038
```

Rapid adoption in ATLAS...

- Four ATLAS analyses with full likelihoods published to HEPData
- ATLAS SUSY will be continuing to publish full Run 2 likelihoods

- direct staus, doi:10.17182/hepdata.89408 (2019)
- sbottom multi-b, doi:10.17182/hepdata.91127 (2019)
- 1Lbb, doi:10.17182/hepdata.92006 (2019)
- 3L eRJR, doi:10.17182/hepdata.90607.v2 (2020)

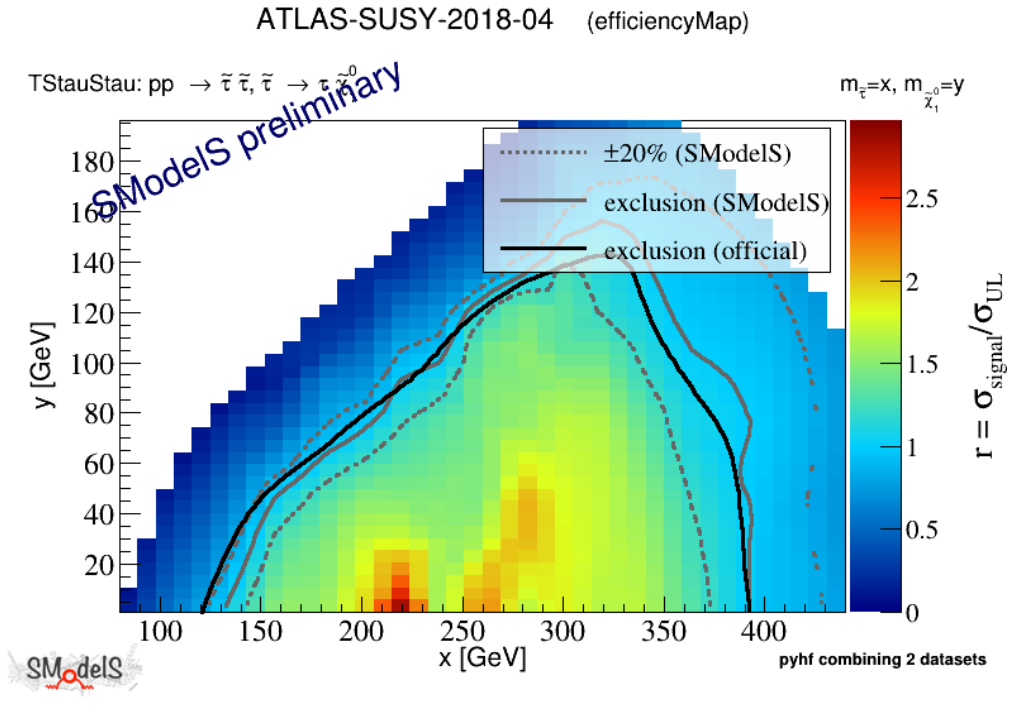




SUSY EWK 3L RPV analysis (ATLAS-CONF-2020-009): Exclusion curves as a function of mass and branching fraction to Z bosons

...and by theory

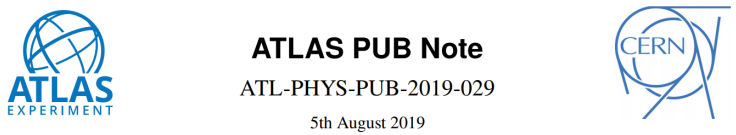
- `pyhf` likelihoods discussed in
  - Les Houches 2019 Physics at TeV Colliders: New Physics Working Group Report
  - Higgs boson potential at colliders: status and perspectives
- SModelS team has implemented a `SModelS/pyhf` interface
  - tool for interpreting simplified-model results from the LHC
  - designed to be used by theorists
- Have produced comparison for *Search for direct stau production in events with two hadronic tau leptons in √s = 13 TeV pp collisions with the ATLAS detector* (ATLAS-SUSY-2018-04) published likelihood
  - Compare simplified likelihood (`SModelS`)
  - to full likelihood (`pyhf`)



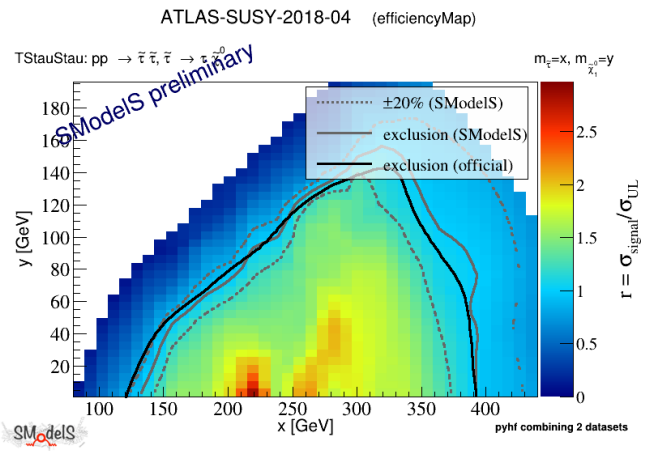
So here is one of our first reasonable validation plots. It's preliminary, the black line is ATLAS-SUSY-2018-04 official exclusion curve. The grey line is SModelS using `pyhf`, running over the published data. — Wolfgang Waltenberger, CMS/SModelS

Summary

- **JSON specification** of `pyhf` likelihoods
  - human/machine readable, versionable, HEPData friendly, orders of magnitude smaller, long term preservation
- **Bidirectional translation** of likelihood specifications
  - ROOT workspaces ↔ `pyhf` JSON
- Publication for the first time of the **full likelihood** of a search for new physics
  - Continued publications from **ATLAS SUSY full Run 2 results**
- **Open publication** on HEPData, reuse and **reinterpretation** with SModelS and RECAST



(ATLAS, 2019)



(SModelS of ATLAS-SUSY-2018-04)

Backup

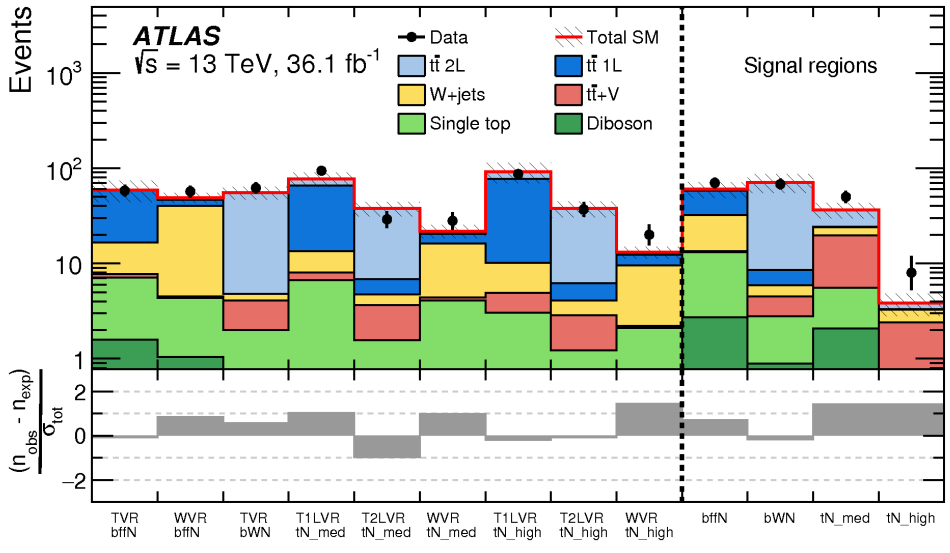
HistFactory Template

$$f\left(\text{data}|\text{parameters}\right) = f\left(\vec{n},\vec{a}|\vec{\eta},\vec{\chi}\right) = \prod_{c\in\text{channels}}\prod_{b\in\text{bins}_c}\text{Pois}\left(n_{cb}|\nu_{cb}\left(\vec{\eta},\vec{\chi}\right)\right)\prod_{\chi\in\vec{\chi}}c_\chi\left(a_\chi|\chi\right)$$

Use: Multiple disjoint channels (or regions) of binned distributions with multiple samples contributing to each with additional (possibly shared) systematics between sample estimates

Main pieces:

- Main Poisson p.d.f. for simultaneous measurement of multiple channels
- Event rates ν_{cb} (nominal rate ν^0_{scb} with rate modifiers)
- Constraint p.d.f. (+ data) for "auxiliary measurements"
  - encode systematic uncertainties (e.g. normalization, shape)
- $\vec{n}$: events, $\vec{a}$: auxiliary data, $\vec{\eta}$: unconstrained pars, $\vec{\chi}$: constrained pars



Example: **Each bin** is separate (1-bin) channel, each **histogram** (color) is a sample and share a **normalization systematic** uncertainty

HistFactory Template

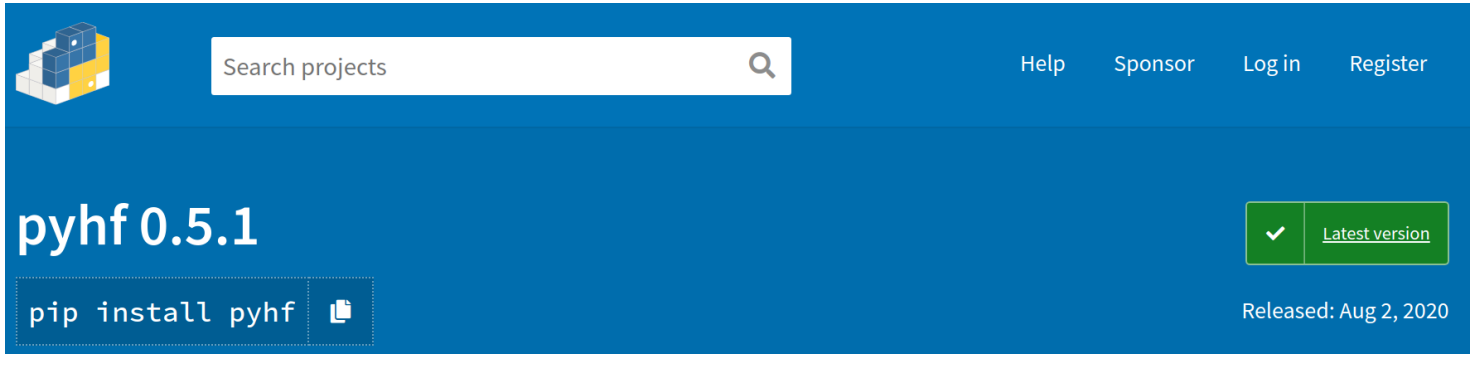
$$f\left(\vec{n}, \vec{a} | \vec{\eta}, \vec{\chi}\right) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}_c} \text{Pois}\left(n_{cb} | \nu_{cb}\left(\vec{\eta}, \vec{\chi}\right)\right) \prod_{\chi \in \vec{\chi}} c_\chi\left(a_\chi | \chi\right)$$

Mathematical grammar for a simultaneous fit with

- multiple "channels" (analysis regions, (stacks of) histograms)
- each region can have multiple bins
- coupled to a set of constraint terms

This is a mathematical representation! Nowhere is any software spec defined
Until now (2018), the only implementation of HistFactory has been in `ROOT`

`pyhf`: HistFactory in pure Python



What is `pyhf`?

Please checkout the many resources we have starting with the website and the SciPy 2020 talk!

References

1. F. James, Y. Perrin, L. Lyons, *Workshop on confidence limits: Proceedings*, 2000.
2. ROOT collaboration, K. Cranmer, G. Lewis, L. Moneta, A. Shibata and W. Verkerke, *HistFactory: A tool for creating statistical models for use with RooFit and RooStats*, 2012.
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4. A. Read, *Modified frequentist analysis of search results (the CL_s method)*, 2000.
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6. ATLAS collaboration, *Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, b-jets and missing transverse momentum*, 2019
7. ATLAS collaboration, *Reproducing searches for new physics with the ATLAS experiment through publication of full statistical likelihoods*, 2019
8. ATLAS collaboration, *Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, b-jets and missing transverse momentum: HEPData entry*, 2019

The end.