# Likelihood preservation and statistical reproduction of searches for new physics

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on behalf of the ATLAS collaboration

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CHEP 2019

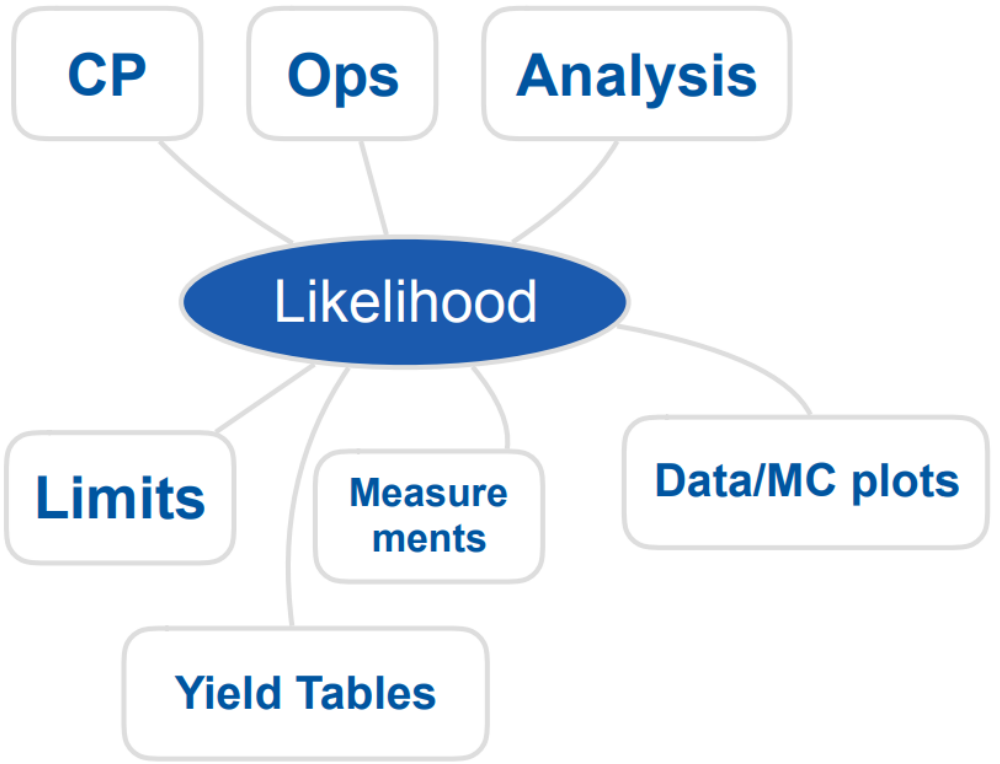
November 7th, 2019

ILLINOIS

ATLAS EXPERIMENT

# 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
  - Systematic Uncertainties
  - Event Selection
- Unique representation of the analysis to preserve



# 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.

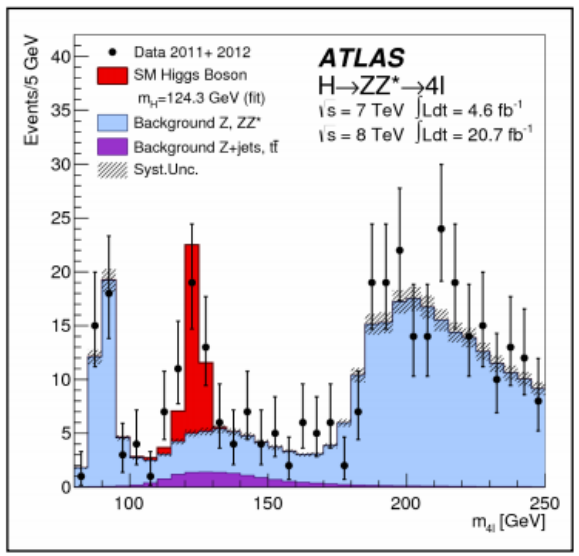
(1st Workshop on Confidence Limits, CERN, 2000)

**This hadn't been done in HEP until now**

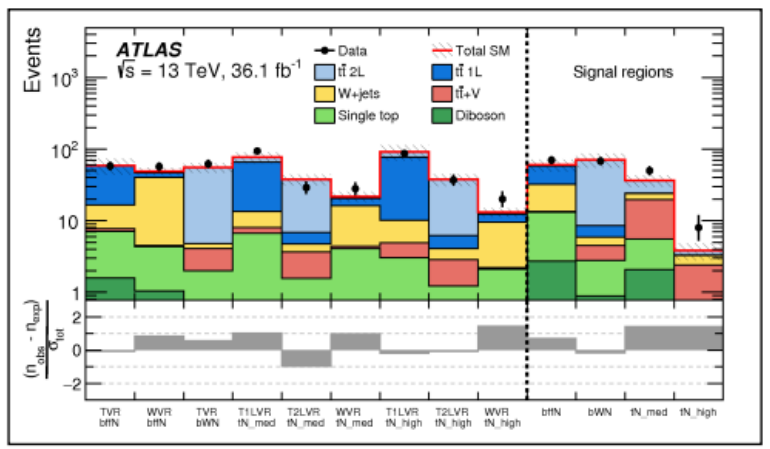
- In an "open world" of statistics this is a difficult problem to solve
- What to preserve and how? All of ROOT?
- Idea: Focus on a single more tractable binned model first

# Enter HistFactory

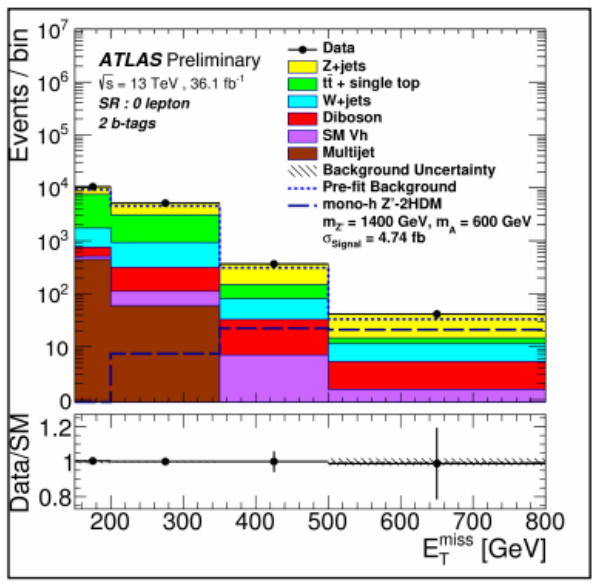
- A flexible p.d.f. template to build statistical models from binned distributions and data
- Developed by Cranmer, Lewis, Moneta, Shibata, and Verkerke (CERN-OPEN-2012-016)
- Widely used by the HEP community for standard model measurements and BSM searches




SM




SUSY




Exotics

# HistFactory Template

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

$$\nu_{cb}(\vec{\eta},\vec{\chi}) = \sum_{s\in\text{samples}}\underbrace{\left(\sum_{\kappa\in\vec{\kappa}}\kappa_{scb}(\vec{\eta},\vec{\chi})\right)}_{\text{multiplicative}}\left(\nu^0_{scb}(\vec{\eta},\vec{\chi}) + \underbrace{\sum_{\Delta\in\vec{\Delta}}\Delta_{scb}(\vec{\eta},\vec{\chi})}_{\text{additive}}\right)$$

**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 $\nu_{cb}$ from nominal rate $\nu^0_{scb}$ and rate modifiers $\kappa$ and $\Delta$
- Constraint p.d.f. (+ data) for "auxiliary measurements"
  - encoding systematic uncertainties (normalization, shape, etc)
- $\vec{n}$: events, $\vec{a}$: auxiliary data, $\vec{\eta}$: unconstrained pars, $\vec{\chi}$: constrained pars

# HistFactory Template

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

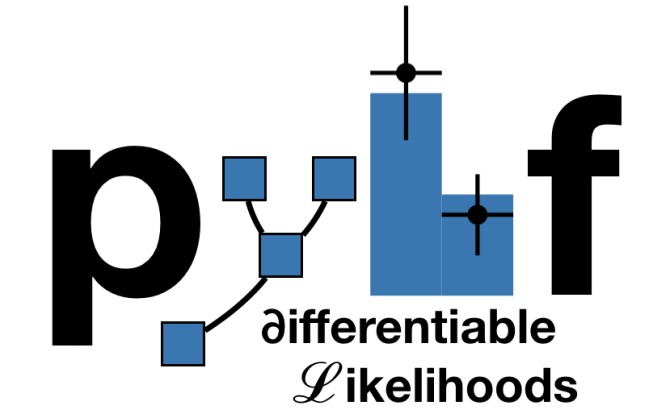
**This is a mathematical representation!** Nowhere is any software spec defined

Until now, the only implementation of HistFactory has been in RooStats+RooFit

- Preservation: Likelihood stored in the binary ROOT format
  - Challenge for long-term preservation (i.e. HEPData)
  - Why is a histogram needed for an array of numbers?
- To start using HistFactory p.d.f.s first have to learn ROOT, RooFit, RooStats
  - Problem for our theory colleagues (generally don't want to)
- Difficult to use for reinterpretation

# `pyhf`: HistFactory in pure Python

- First non-ROOT implementation of the HistFactory p.d.f. template
  - DOI 10.5281/zenodo.1169739
- pure-Python library as second implementation of HistFactory
  - `pip install pyhf`
  - No dependence on ROOT!




- Has a JSON spec that fully describes the HistFactory model
  - JSON: Industry standard, parsable by every language, human & machine readable, versionable and easily preserved (HEPData is JSON)
- Open source tool for all of HEP
  - Originated from a DIANA/HEP project fellowship and now an IRIS-HEP supported project
  - Used for reinterpretation in phenomenology paper (DOI: 10.1007/JHEP04(2019)144)
  - Used internally in ATLAS for pMSSM SUSY large scale reinterpretation

# Example pyhf JSON spec

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

```
{
    "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
}
```

# Live demo time!

**Just click the button!**

# $CL_s$ Example using `pyhf` CLI

```
$ pyhf cls example.json
{
    "CLs_exp": [
        0.00040903874532508 41,
        0.00326069680239139 25,
        0.02255257597653917,
        0.11898700005707148,
        0.39844667251932997
    ],
    "CLs_obs": 0.05399424662127401 4
}
```

# JSON Patch for new signal models

```
{
    "channels": [
        { "name": "singlechannel",
          "samples": [
            { "name": "signal",
              "data": [20.0, 10.0],
              "modifiers": [ { "name": "mu", "type": "normfactor", "data": null} ]
            },
# Rest of the model
}
```

Original model

```
[{
    "op": "replace",
    "path": "/channels/0/samples/0/data",
    "value": [10.0, 6.0]
}]
```

New Signal (JSON Patch file)

```
{
    "channels": [
        { "name": "singlechannel",
          "samples": [
            { "name": "signal",
              "data": [10.0, 6.0],
              "modifiers": [ { "name": "mu", "type": "normfactor", "data": null} ]
            },
# Rest of the model
}
```

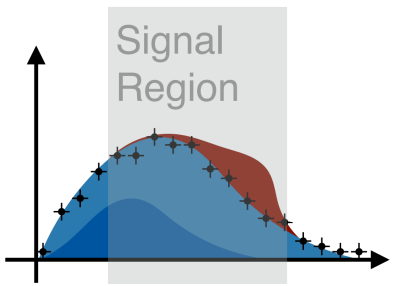
Reinterpretation

# JSON Patch for new signal models

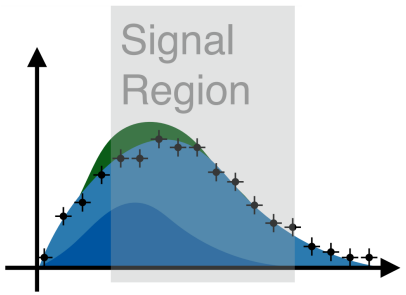
```
$ pyhf cls example.json | jq .CLs_obs
0.053994246621274014

$ 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
```



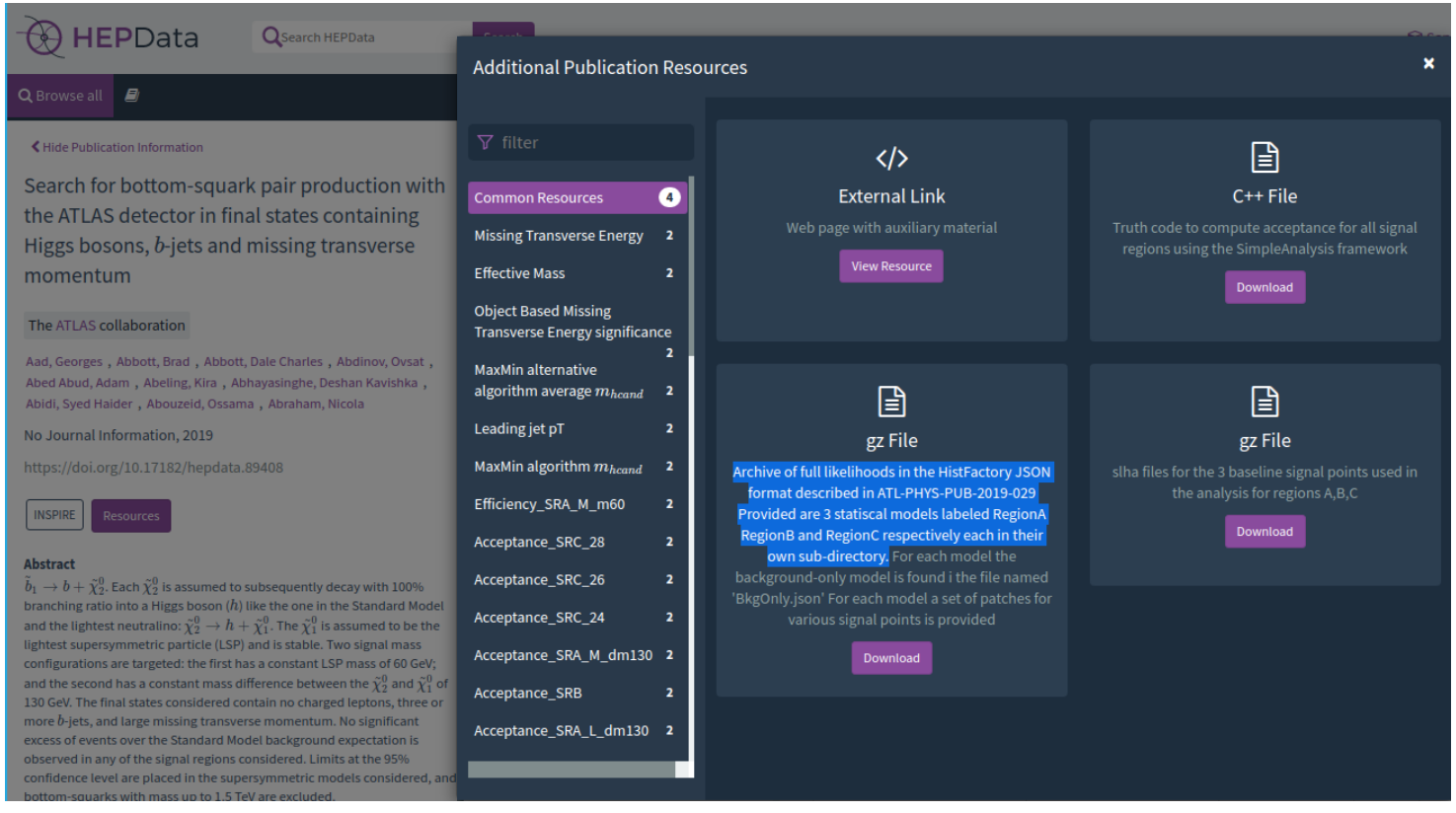

Original analysis (model A)




Recast analysis (model B)

# Likelihoods preserved on HEPData

- Background-only model JSON stored
- Signal models stored as JSON Patch files
- Together are able to fully preserve the full model (with own DOI! DOI 10.17182/hepdata.89408.v1/r2 )



# ...can be streamed from HEPData

- Background-only model JSON stored
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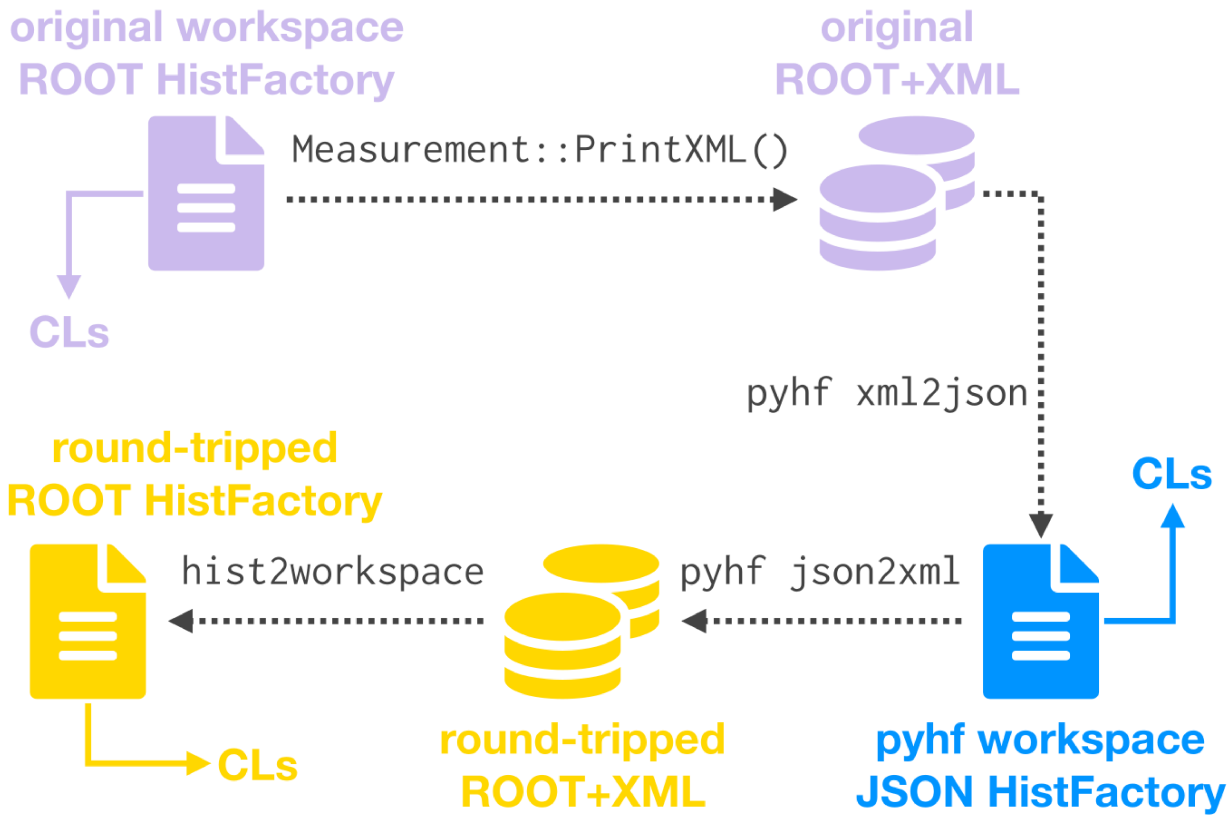
```
# One signal model
$ curl -sL https://doi.org/10.17182/hepdata.89408.v1/r2 | \
  tar -O -xzv RegionA/BkgOnly.json | \
  pyhf cls --patch <(curl -sL https://doi.org/10.17182/hepdata.89408.v1/r2 | \
    tar -O -xzv RegionA/patch.sbottom_1300_205_60.json) | \
  jq .CLs_obs
0.2444363799054463

# A different signal model
$ curl -sL https://doi.org/10.17182/hepdata.89408.v1/r2 | \
  tar -O -xzv RegionA/BkgOnly.json | \
  pyhf cls --patch <(curl -sL https://doi.org/10.17182/hepdata.89408.v1/r2 | \
    tar -O -xzv RegionA/patch.sbottom_1300_230_100.json) | \
  jq .CLs_obs
0.040766026035752724
```

# Likelihood serialization and reproduction

- ATLAS PUB note on the JSON schema for serialization and reproduction of results (ATL-PHYS-PUB-2019-029)
  - Contours: original ROOT+XML, pyhf JSON, JSON converted back to ROOT+XML



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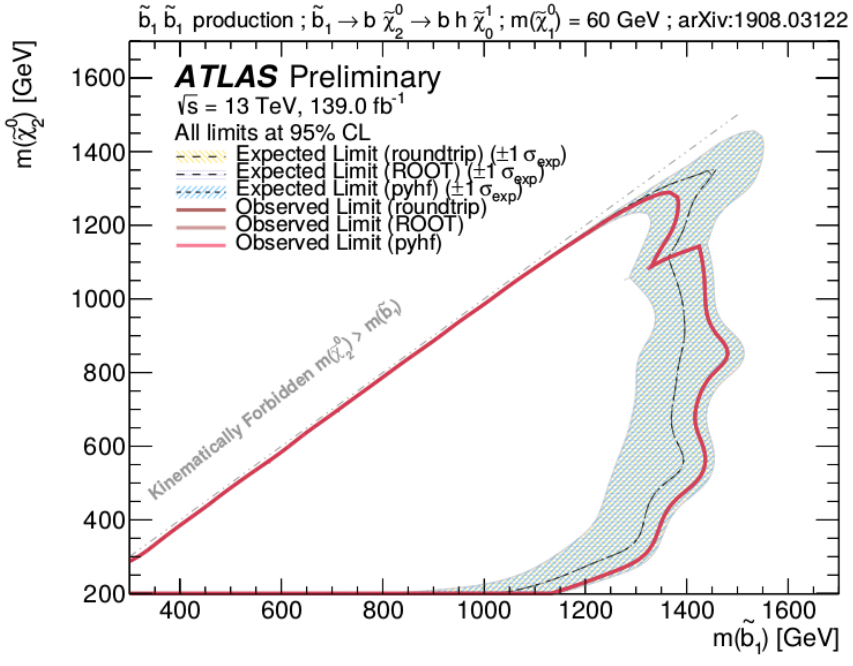
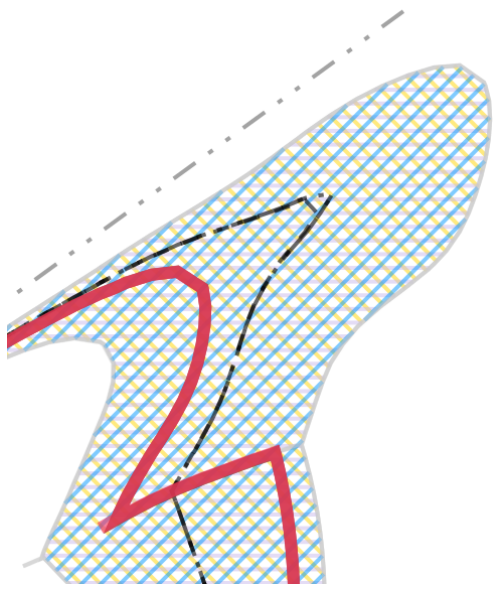
  - Contours: original ROOT+XML, pyhf JSON, JSON converted back to ROOT+XML
    - Overlay of contours nice visualization of near perfect agreement
  - Serialized likelihood and reproduced results of ATLAS Run-2 search for sbottom quarks (CERN-EP-2019-142) and published to HEPData
  - Shown to reproduce results but faster! **ROOT:** 10+ hours **pyhf:** < 30 minutes



# Summary

Through pyhf are able to provide:

- **JSON specification** of likelihoods
  - human/machine readable, versionable, HEPData friendly, orders of magnitude smaller
- **Bidirectional translation** of likelihood specifications
  - ROOT workspaces ↔ JSON
- Independent **pure-Python implementation** of HistFactory + hypothesis testing
- Publication for the first time of the **full likelihood** of a search for new physics

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ATLAS EXPERIMENT

**ATLAS PUB Note**

ATL-PHYS-PUB-2019-029

5th August 2019

CERN

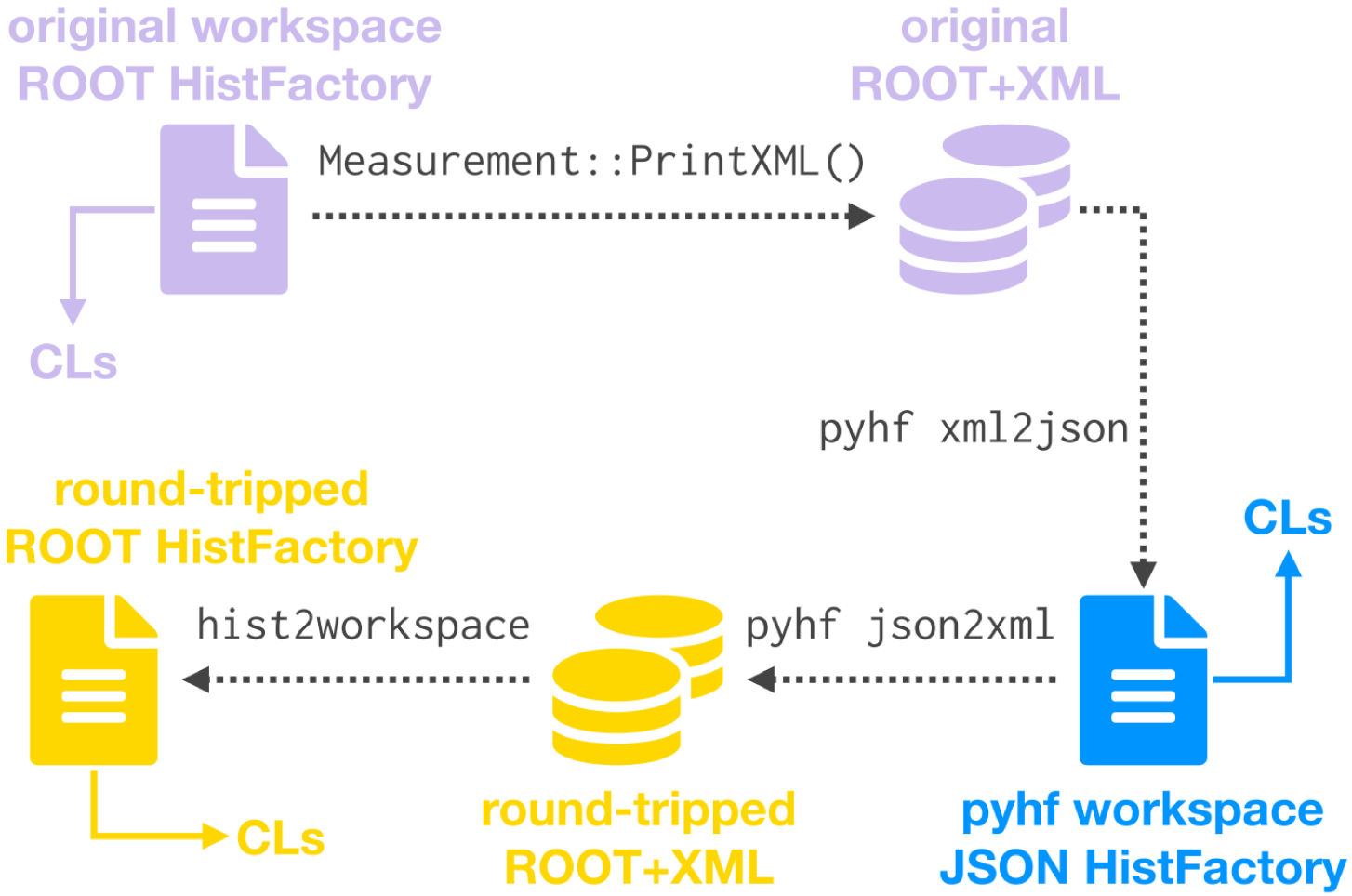
**Reproducing searches for new physics with the ATLAS experiment through publication of full statistical likelihoods**

The ATLAS Collaboration

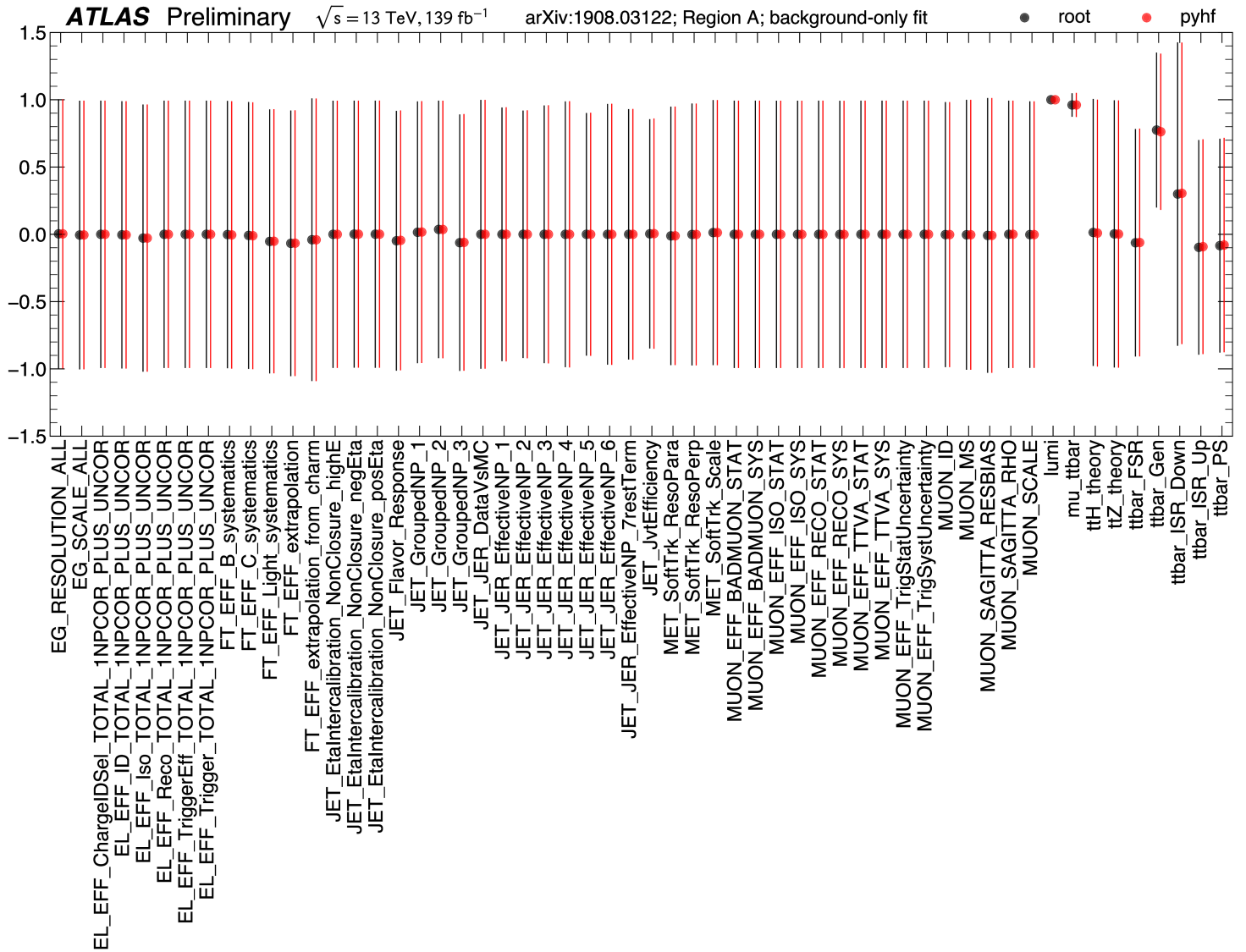
(ATLAS, 2019)

# Backup

# ROOT + XML to JSON and back



# Best-fit parameter values



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# 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.
3. L. Heinrich, H. Schulz, J. Turner and Y. Zhou, *Constraining $A_4$ Leptonic Flavour Model Parameters at Colliders and Beyond*, 2018.
4. 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
5. ATLAS collaboration, *Reproducing searches for new physics with the ATLAS experiment through publication of full statistical likelihoods*, 2019
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: HEPData entry*, 2019

The end.