

Likelihood preservation and statistical reproduction of searches for new physics

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on behalf of the ATLAS collaboration

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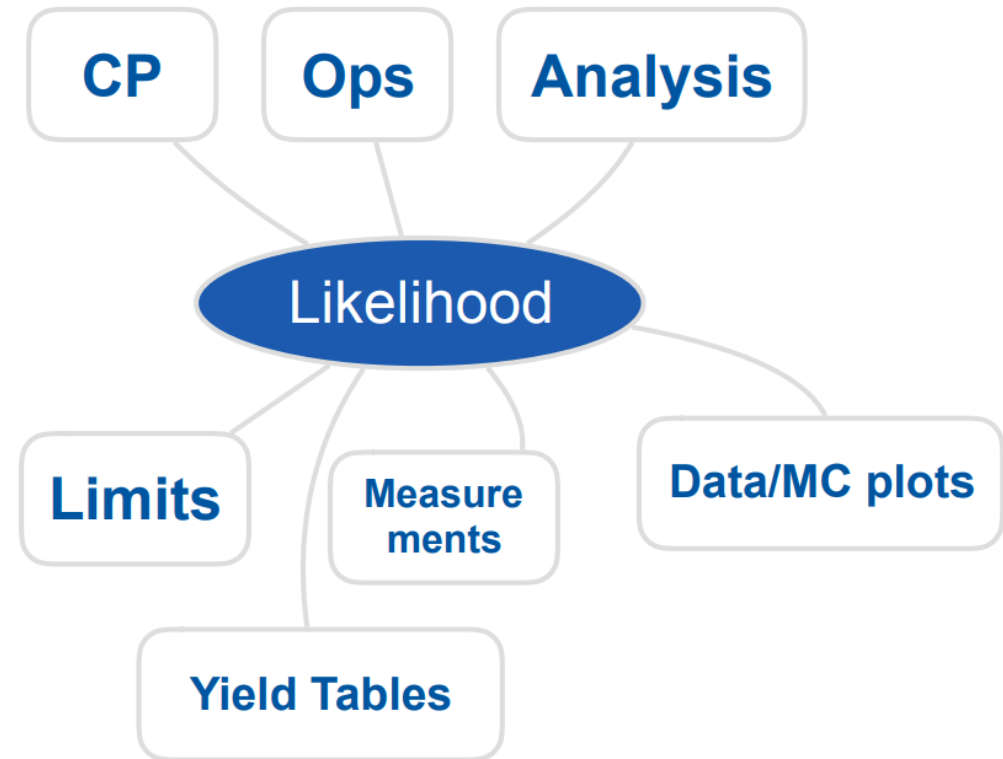
CHEP 2019

November 7th, 2019



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.](#)

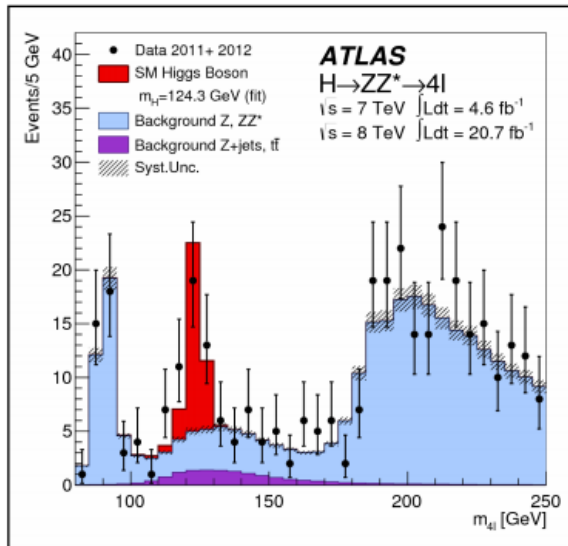
[\(1st Workshop on Confidence Limits, CERN, 2000\)](#)

This hadn't been done in HEP until now

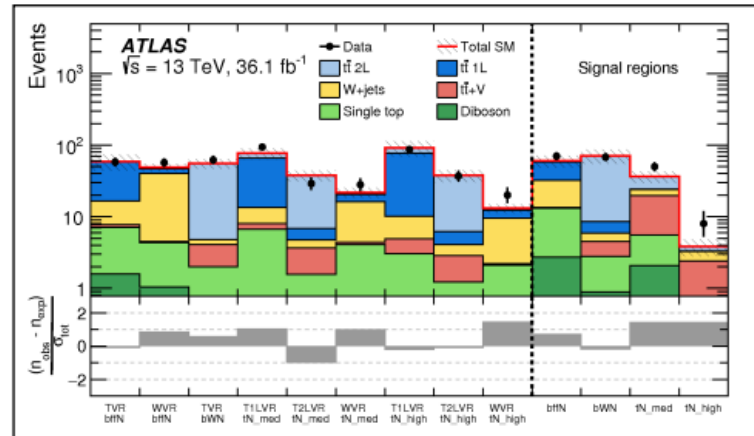
- In an "open world" of statistics this is a difficult problem to solve
- What to preserve and how? All of ROOT?
- Idea: Focus on a single more tractable binned model first

Enter HistFactory

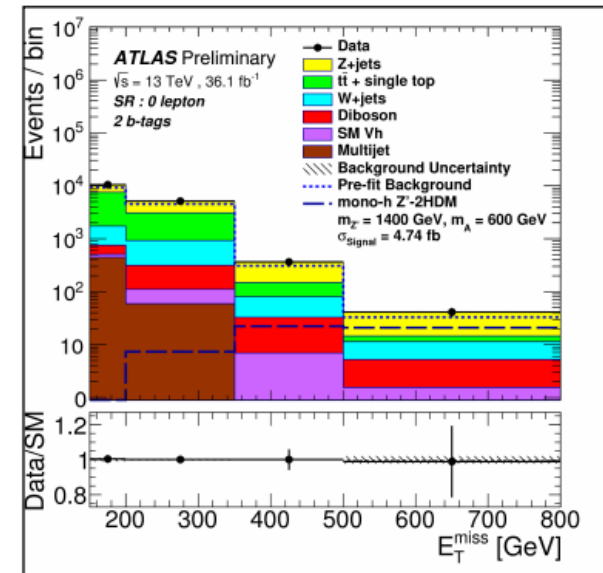
- A flexible p.d.f. template to build statistical models from binned distributions and data
- Developed by Cranmer, Lewis, Moneta, Shibata, and Verkerke ([CERN-OPEN-2012-016](#))
- Widely used by the HEP community for standard model measurements and BSM searches



SM



SUSY



Exotics

HistFactory Template

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

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

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} from nominal rate ν_{scb}^0 and rate modifiers κ and Δ
- 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

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

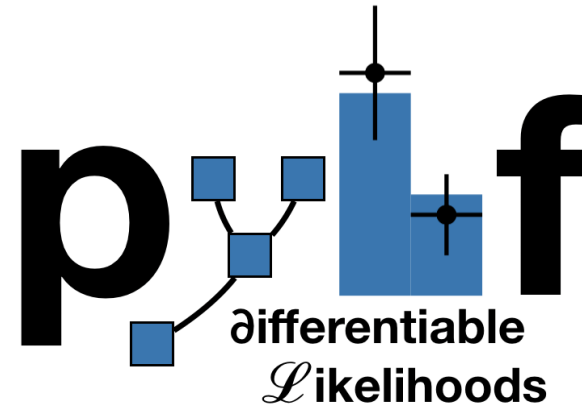
This is a mathematical representation! Nowhere is any software spec defined

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](https://doi.org/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](https://doi.org/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": [
    0.0004090387453250841,
    0.0032606968023913925,
    0.02255257597653917,
    0.11898700005707148,
    0.39844667251932997
  ],
  "CLs_obs": 0.053994246621274014
}
```

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]
}]
```

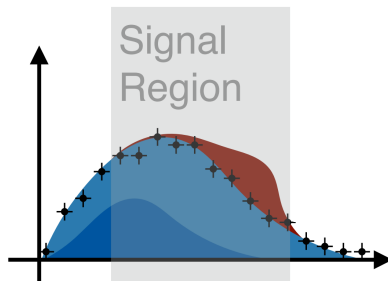
New Signal (JSON Patch file)

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

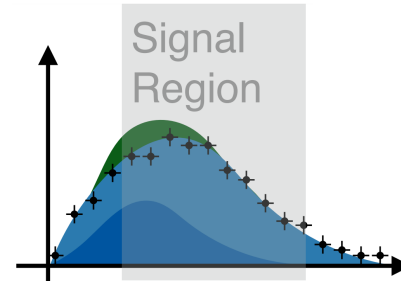
Reinterpretation

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](https://doi.org/10.17182/hepdata.89408.v1/r2))

HEPData Search HEPData

Q Browse all

Hide Publication Information

Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, b -jets and missing transverse momentum

The ATLAS collaboration

Aad, Georges , Abbott, Brad , Abbott, Dale Charles , Abidinov, Ovsat , Abed Abud, Adam , Abeling, Kira , Abhayasinghe, Deshan Kavishka , Abidi, Syed Haider , Abouzeid, Ossama , Abraham, Nicola

No Journal Information, 2019

<https://doi.org/10.17182/hepdata.89408>

INSPIRE Resources

Abstract

$\tilde{b}_1 \rightarrow b + \tilde{\chi}_2^0$. Each $\tilde{\chi}_2^0$ is assumed to subsequently decay with 100% branching ratio into a Higgs boson (h) like the one in the Standard Model and the lightest neutralino: $\tilde{\chi}_2^0 \rightarrow h + \tilde{\chi}_1^0$. The $\tilde{\chi}_1^0$ is assumed to be the lightest supersymmetric particle (LSP) and is stable. Two signal mass configurations are targeted: the first has a constant LSP mass of 60 GeV; and the second has a constant mass difference between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ of 130 GeV. The final states considered contain no charged leptons, three or more b -jets, and large missing transverse momentum. No significant excess of events over the Standard Model background expectation is observed in any of the signal regions considered. Limits at the 95% confidence level are placed in the supersymmetric models considered, and bottom-squarks with mass up to 1.5 TeV are excluded.

Additional Publication Resources

filter

Common Resources 4

Missing Transverse Energy 2

Effective Mass 2

Object Based Missing Transverse Energy significance 2

MaxMin alternative algorithm average $m_{h_{\text{cand}}}$ 2

Leading jet pT 2

MaxMin algorithm $m_{h_{\text{cand}}}$ 2

Efficiency_SRA_M_m60 2

Acceptance_SRC_28 2

Acceptance_SRC_26 2

Acceptance_SRC_24 2

Acceptance_SRA_M_dm130 2

Acceptance_SRB 2

Acceptance_SRA_L_dm130 2

External Link
Web page with auxiliary material
View Resource

C++ File
Truth code to compute acceptance for all signal regions using the SimpleAnalysis framework
Download

gz File
Archive of full likelihoods in the HistFactory JSON format described in ATL-PHYS-PUB-2019-029. Provided are 3 statistical models labeled RegionA, RegionB and RegionC respectively each in their own sub-directory. For each model the background-only model is found in the file named 'BkgOnly.json'. For each model a set of patches for various signal points is provided.
Download

gz File
slha files for the 3 baseline signal points used in the analysis for regions A,B,C
Download

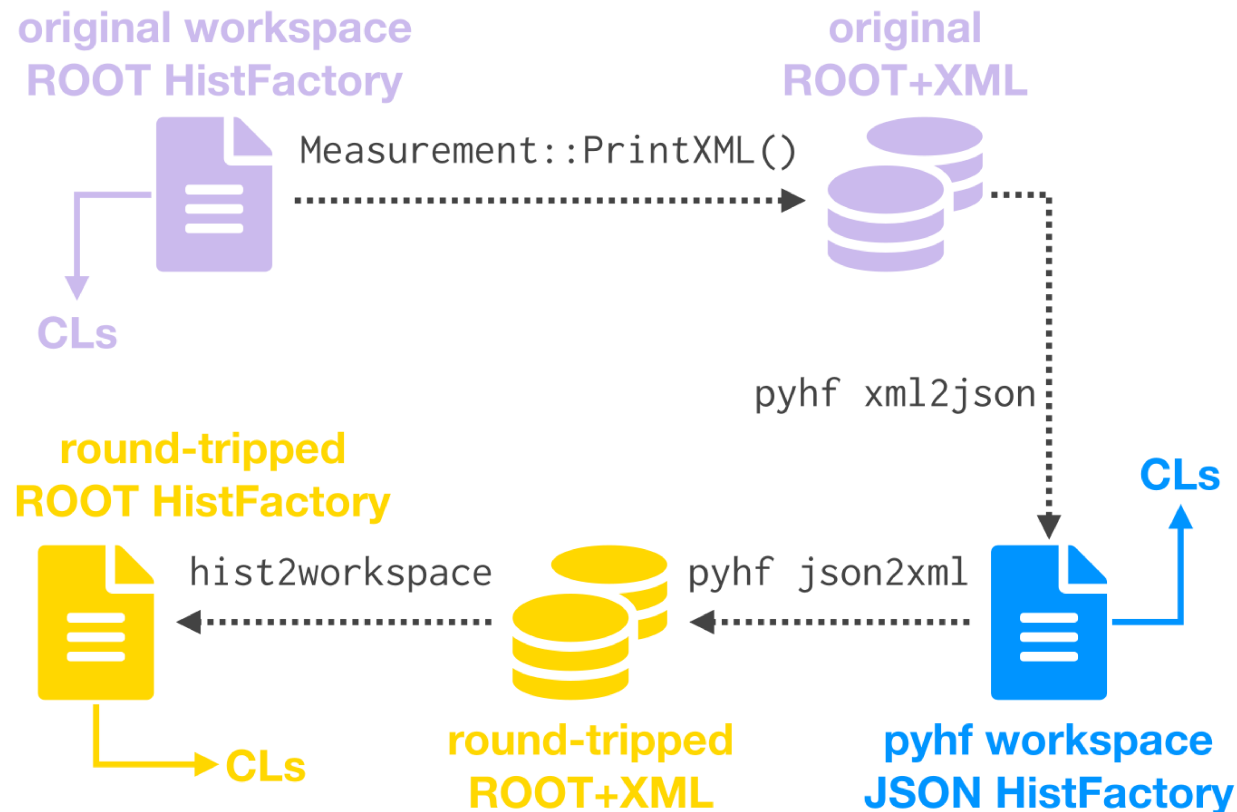
...can be streamed from HEPData

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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
```

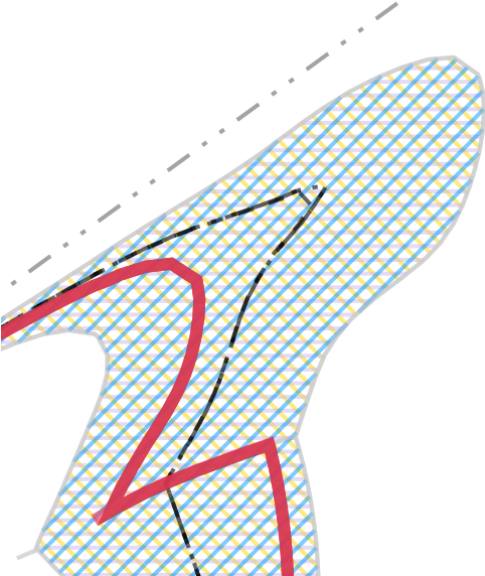
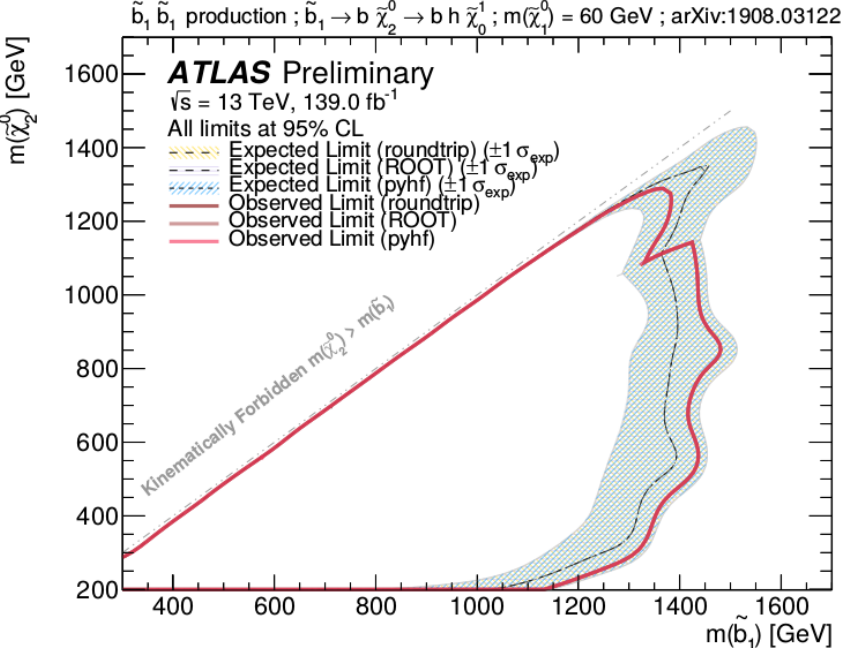
Likelihood serialization and reproduction

- 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



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
 - 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

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)



ATLAS PUB Note

ATL-PHYS-PUB-2019-029

5th August 2019

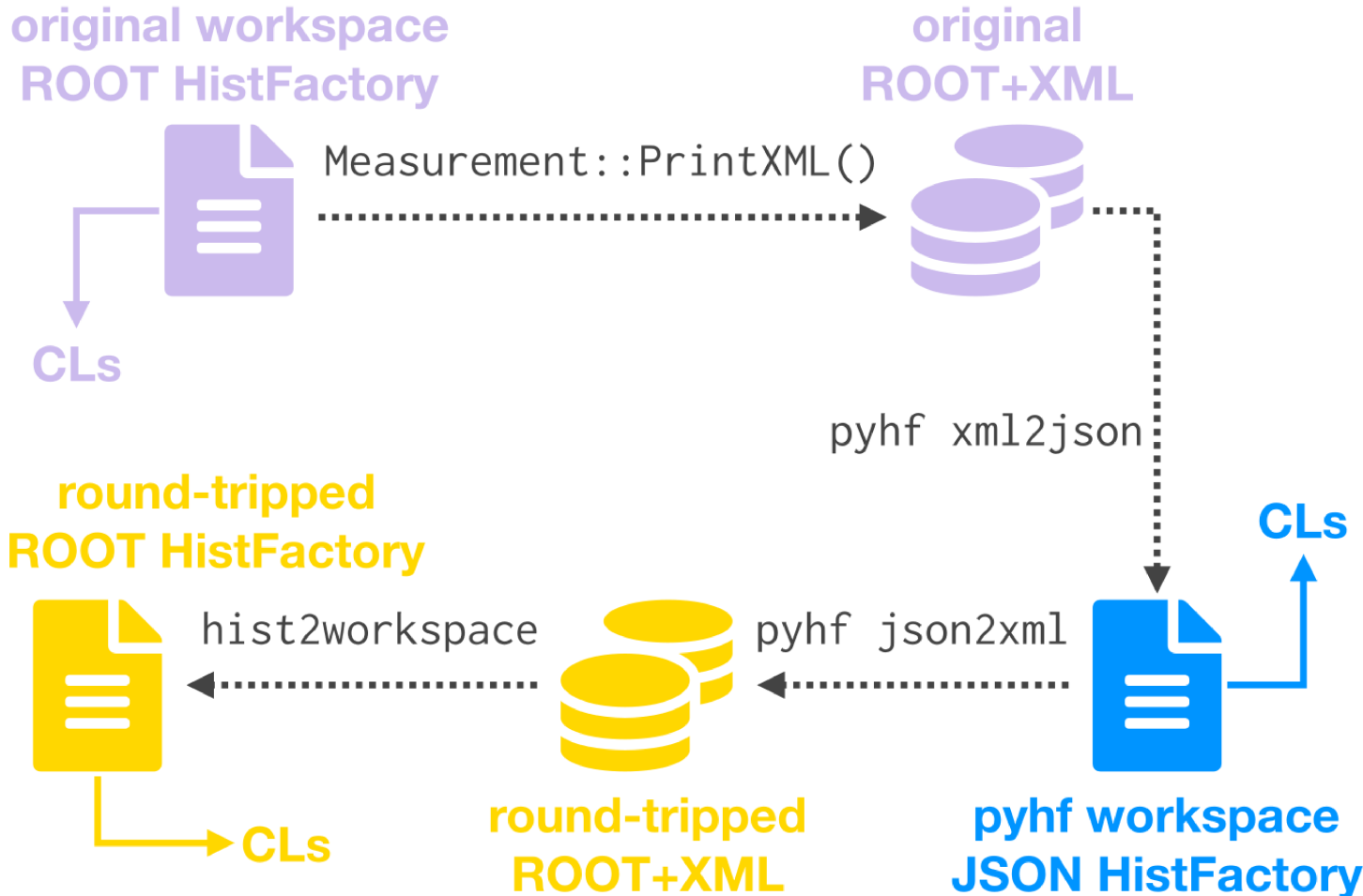


Reproducing searches for new physics with the ATLAS experiment through publication of full statistical likelihoods

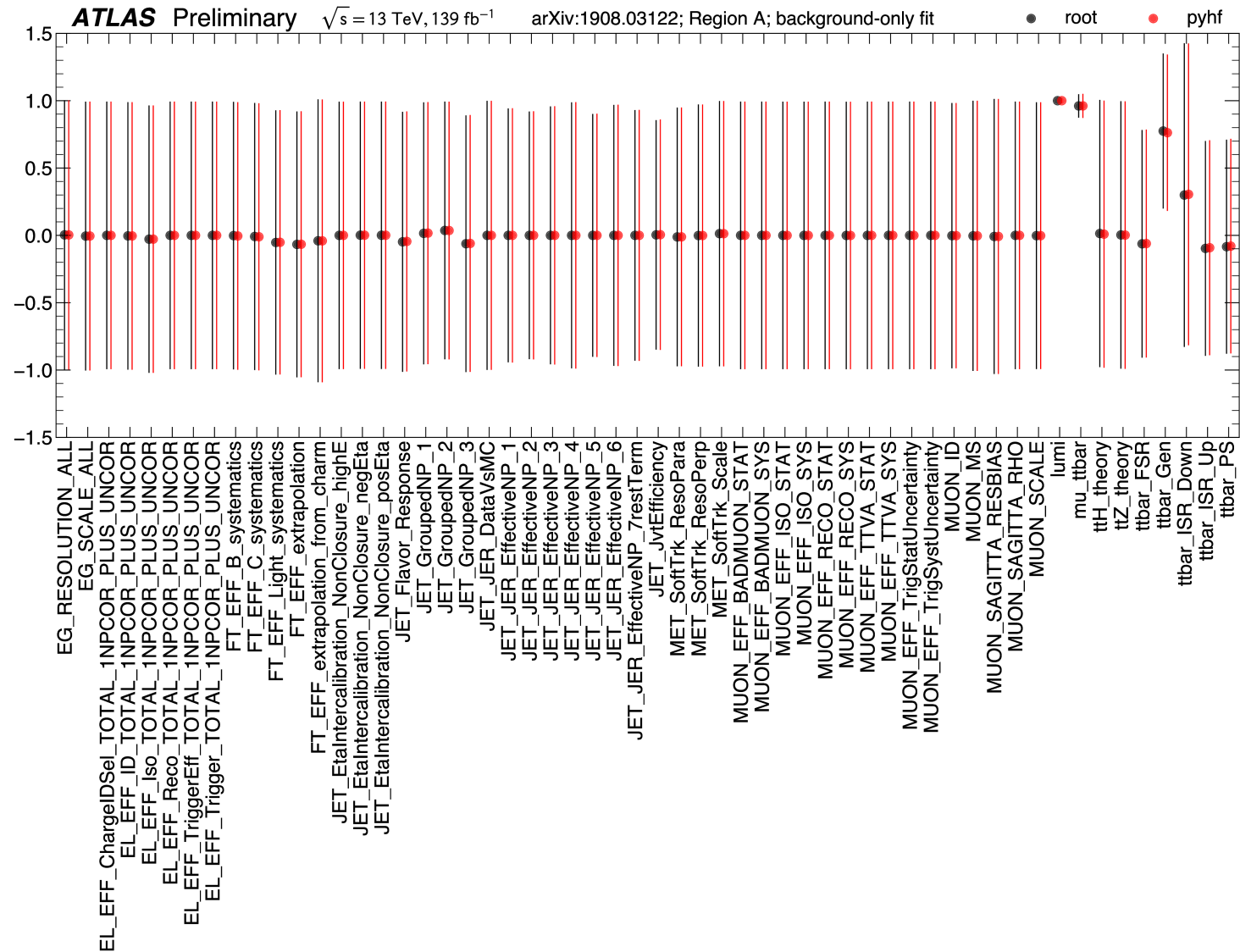
The ATLAS Collaboration

(ATLAS, 2019)

ROOT + XML to JSON and back



Best-fit parameter values



JSON Patch files for new signal models

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0.053994246621274014
```

```
$ cat new_signal.json  
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  }  
]
```

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

Likelihoods can be streamed from HEPData

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    tar -O -xzv RegionA/patch.sbottom_1300_205_60.json) | \
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  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
```

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

