pyhf Intro

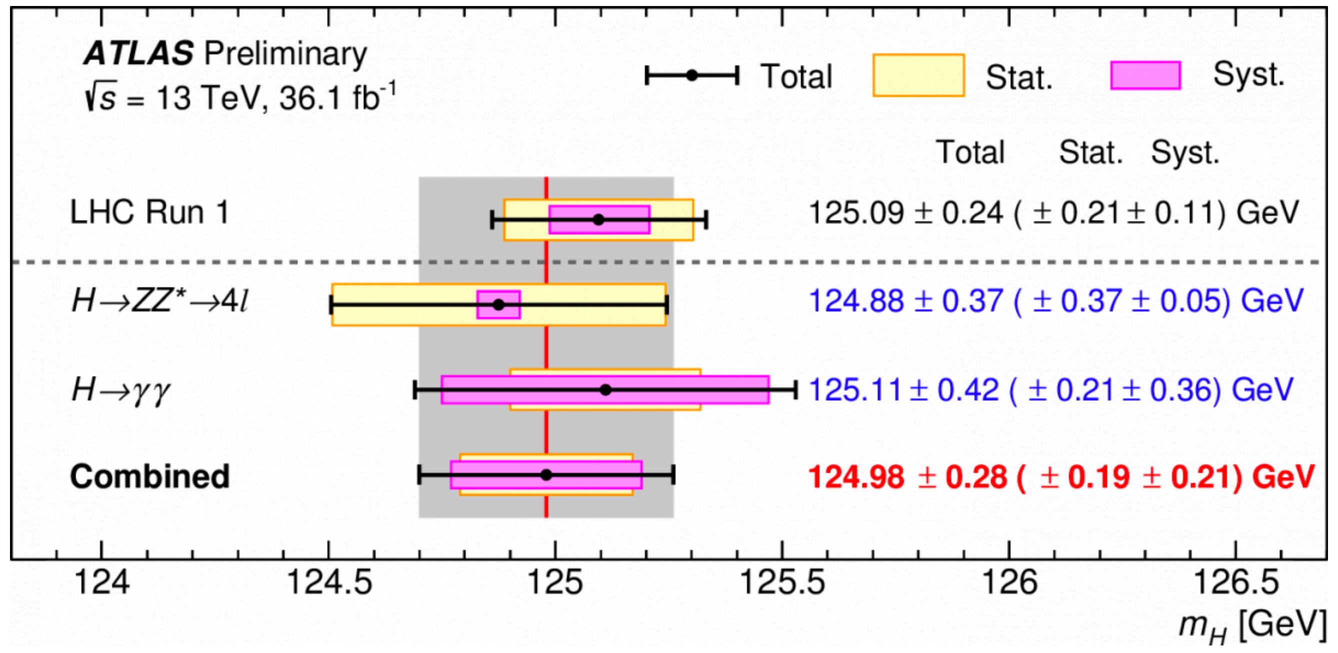
public likelihoods & all that

Lukas Heinrich, CERN

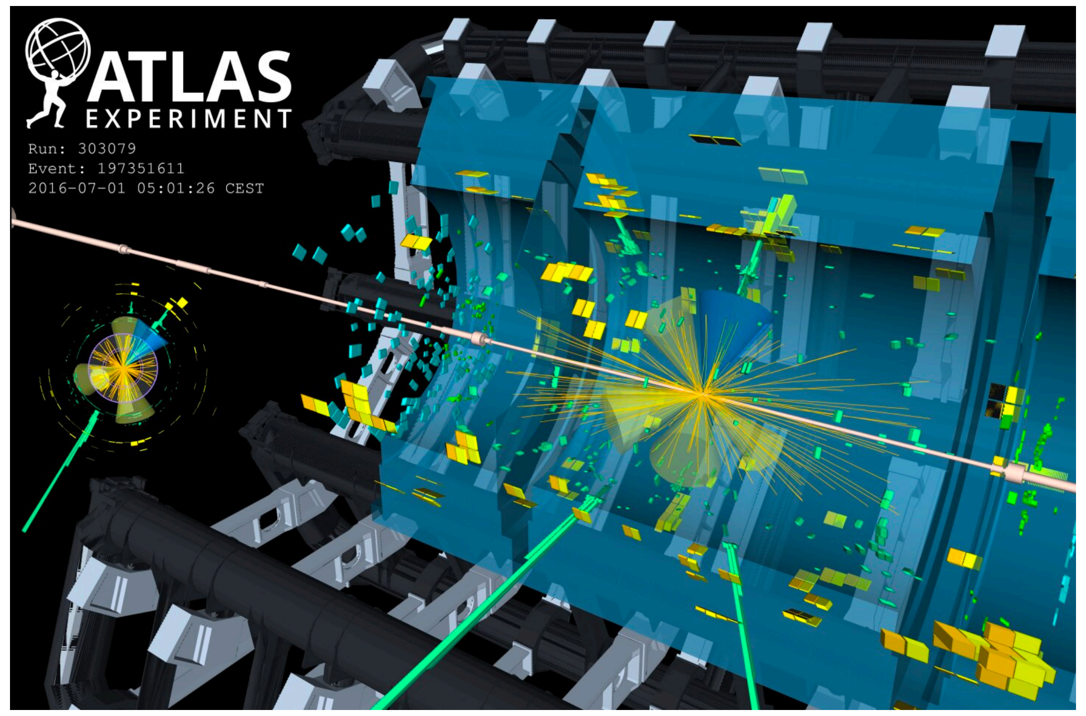
Big Picture Goals

Our job: extract as much information from experimental data as possible

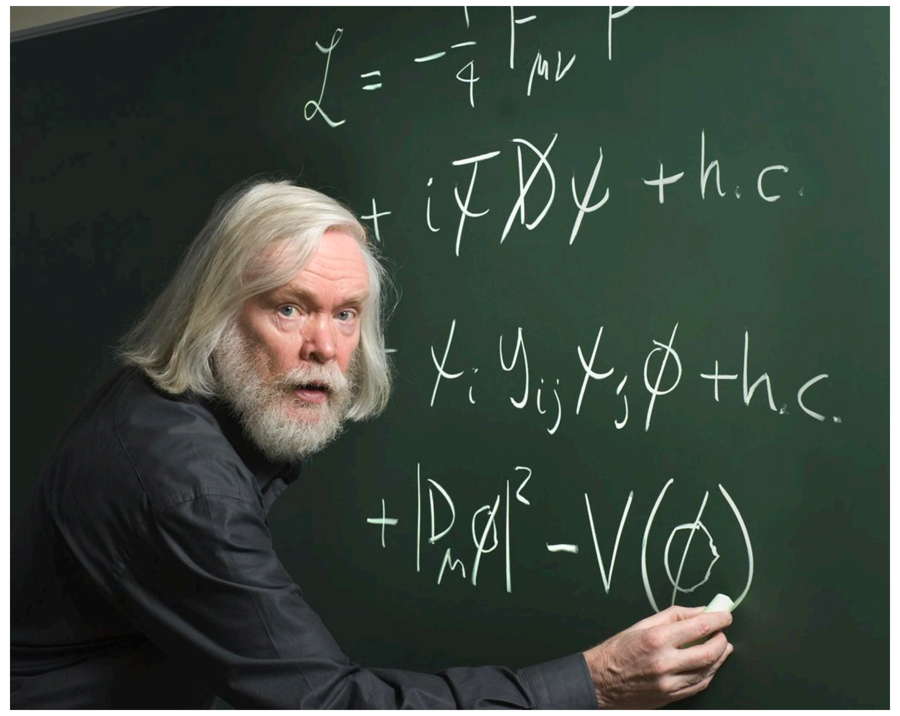
$$p(\text{theory}|\text{data}) = \frac{p(\text{data}|\text{theory})}{p(\text{data})} p(\text{theory})$$



results / insight



experimentalists



theorists

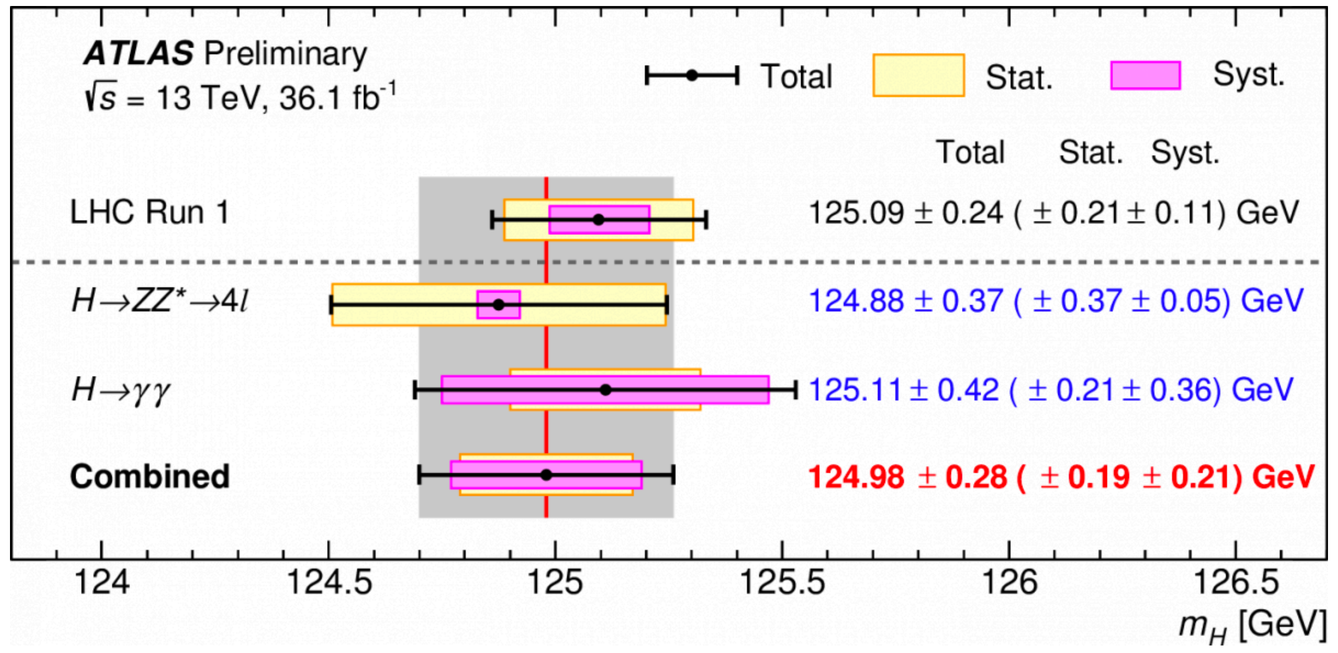
Big Picture Goals

Our job: extract as much information from experimental data as possible

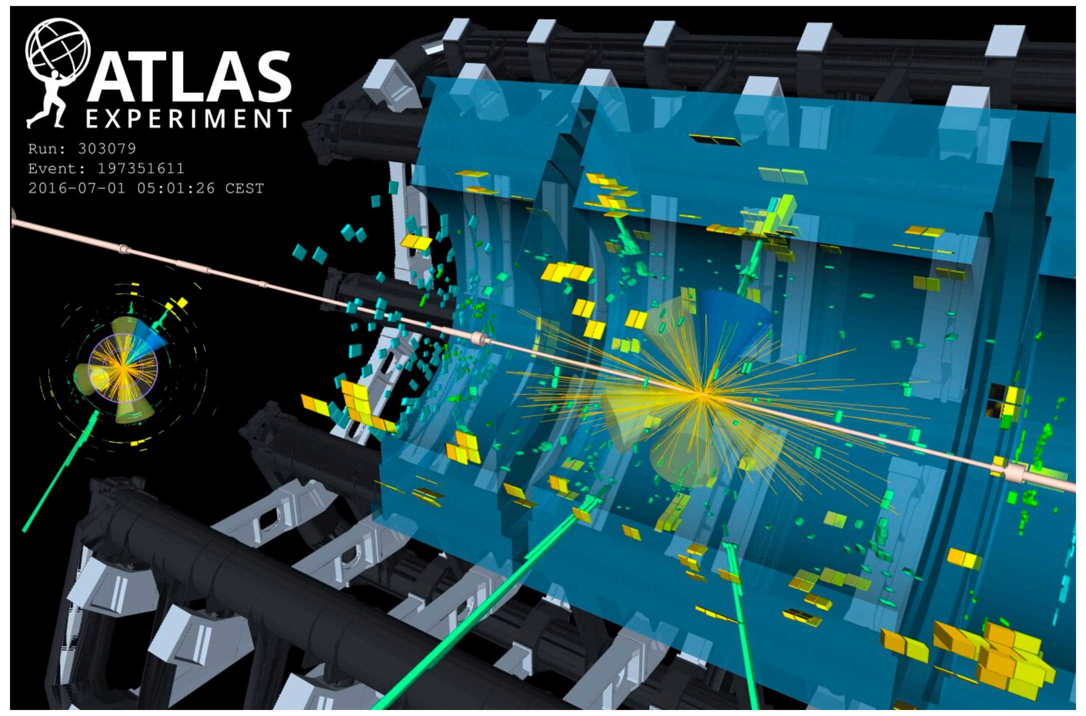
The Likelihood

$$p(\text{theory}|\text{data}) = \frac{p(\text{data}|\text{theory})}{p(\text{data})}\, p(\text{theory})$$

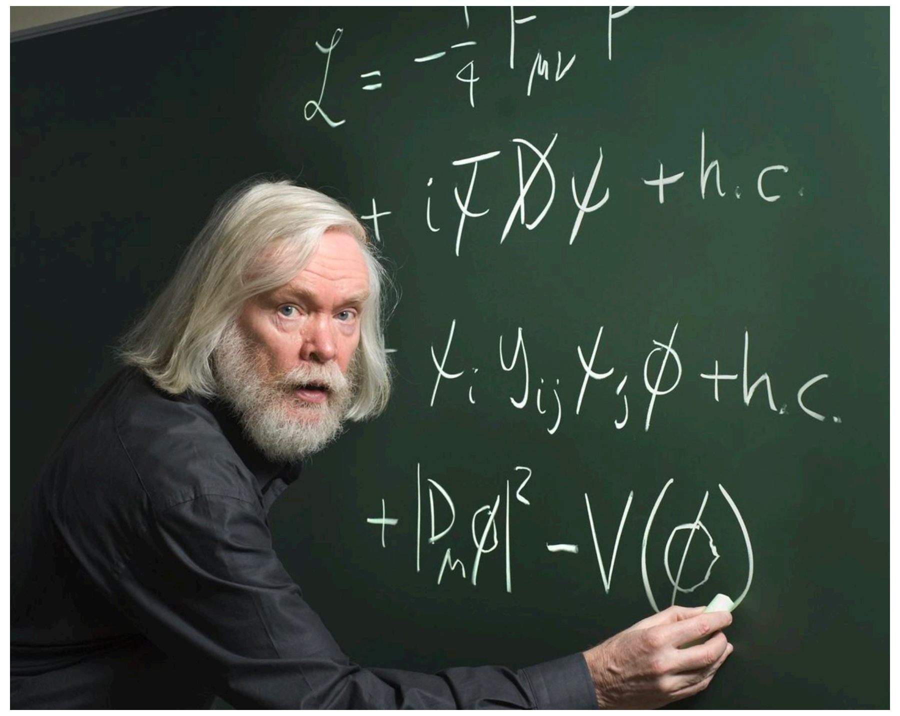
Posterior — Evidence — Prior



results / insight



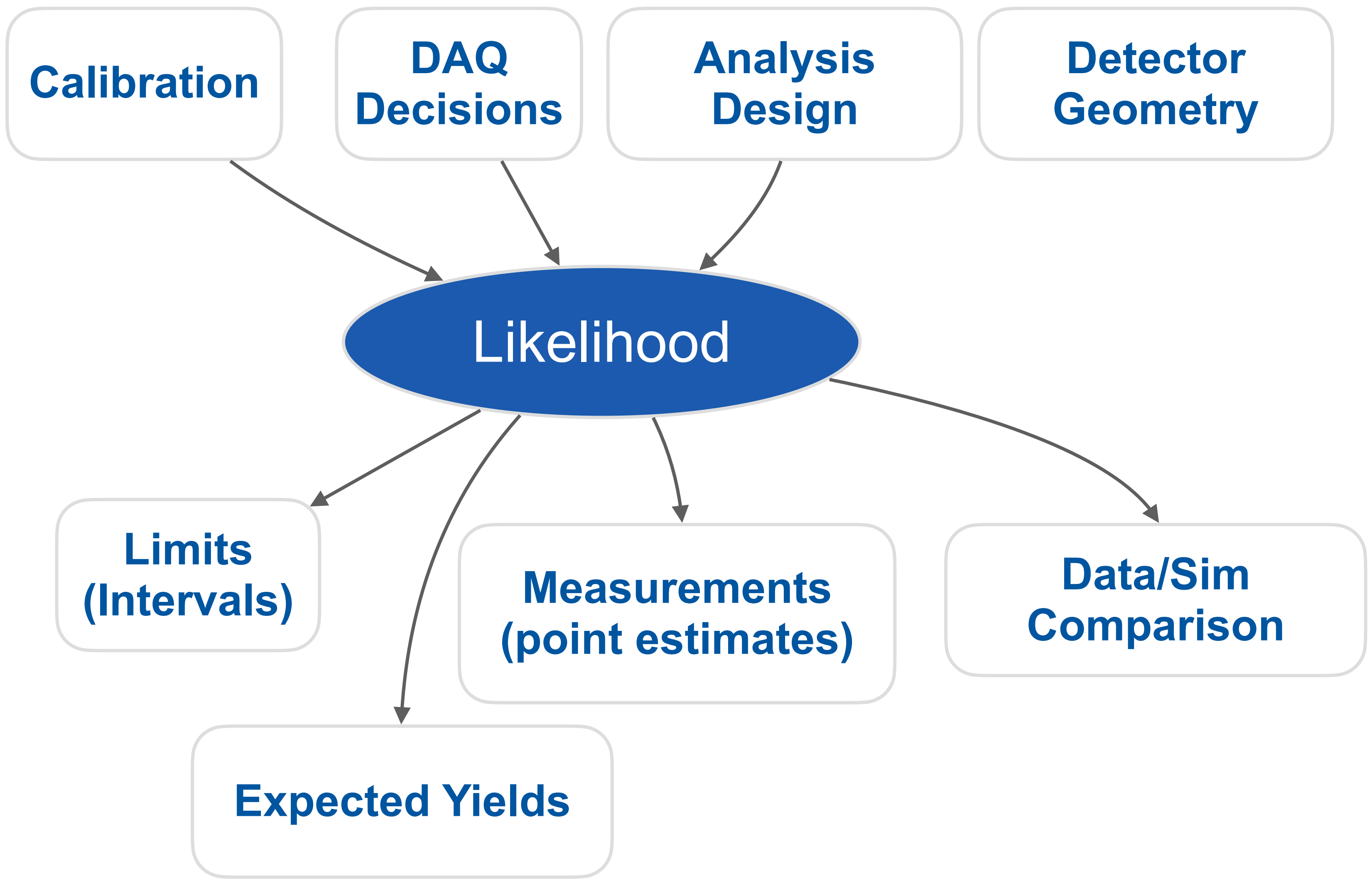
experimentalists



theorists

Big Picture Goals

Why focus on the likelihood?
It's the best data product we have: all other results usually derive from it



Unique as a high information-density product

- **almost every important decision is reflected in the likelihood**
  (if it doesn't affect the likelihood, what are you doing?)

Likelihoods are a good bottleneck through which all information flows

- **can recompute all important results without having to know details of analysis**
- **based on this it's clear: this should be shared!**

And we (ATLAS) now do share the likelihood

CERN 2000–005
30 May 2000

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

WORKSHOP ON CONFIDENCE LIMITS

CERN, Geneva, Switzerland
17–18 January 2000

PROCEEDINGS
Editors: F. James, L. Lyons, Y. Perrin

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

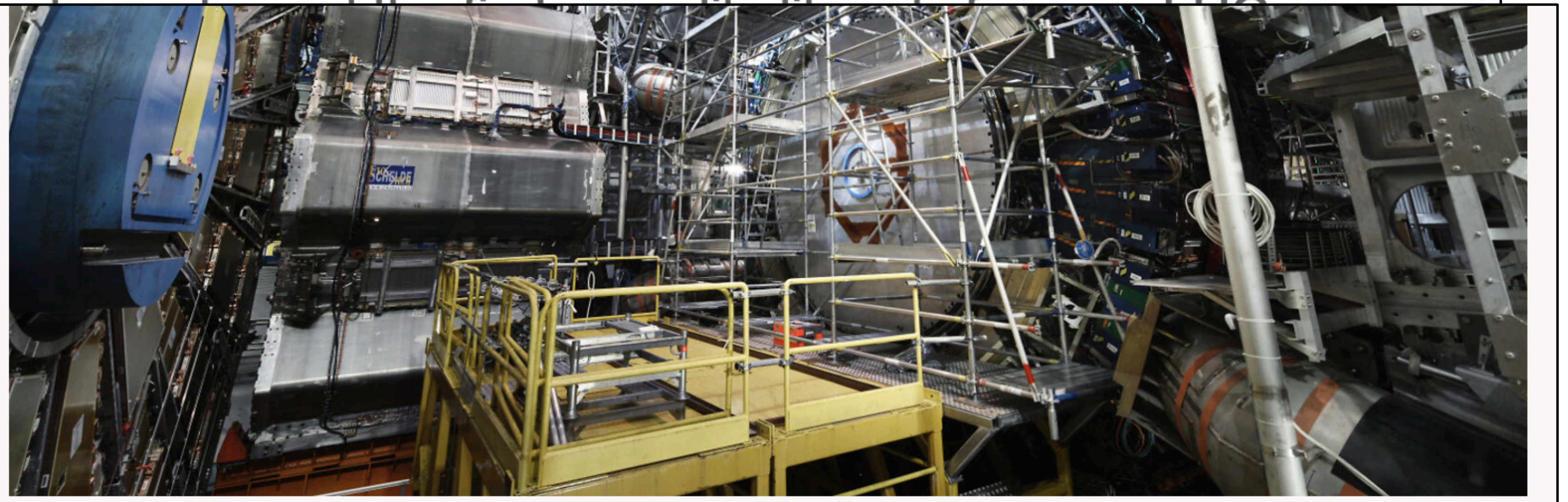
Any disagreement ? Carried unanimously. That's actually quite an achievement for this Workshop.

2000

New open release streamlines interactions with theoretical physicists

The ATLAS Collaboratio[...] experiment.

12th December 2019 | By Katarin[...]



Courtesy of CERN

ATLAS releases 'full orchestra' of analysis instruments

01/14/21 | By Stephanie Melchor

The ATLAS collaboration has begun to publish likelihood functions, information that will allow researchers to better understand and use their experiment's data in future analyses.

Meyrin, Switzerland, sits serenely near the Swiss-French border, surrounded by green fields and the beautiful Rhône river. But a hundred meters beneath the surface, protons traveling at nearly the speed of light collide and create spectacular displays of subatomic fireworks inside the experimental detectors of the Large Hadron Collider at CERN, the European particle physics laboratory.

One detector, called ATLAS, is five stories tall and has the largest volume of any particle detector in the world. It captures the trajectory of particles from collisions that happen a billion times a second and measures their energy and momentum. Those collisions produce incredible amounts of data for researchers to scour, searching for

2020

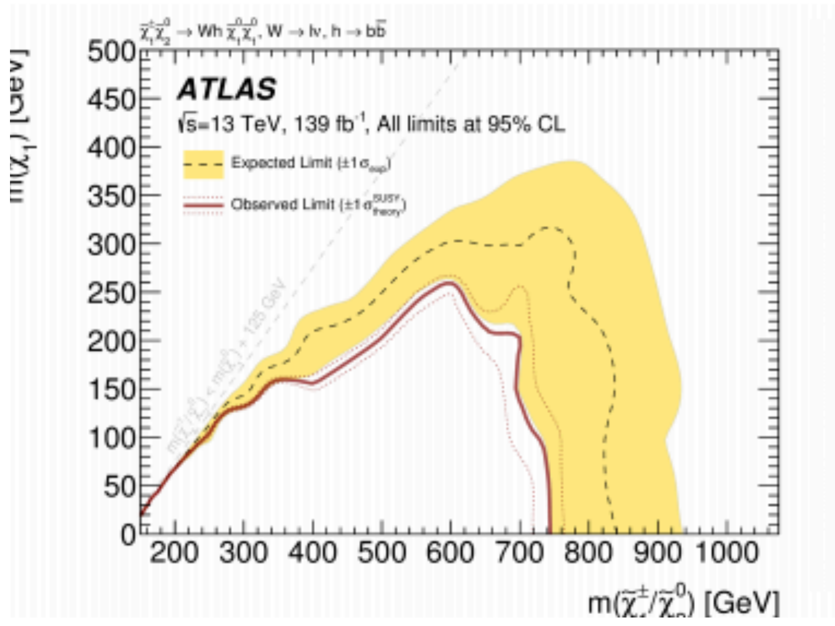
It's all on HepData and citable

Published Statistical Models

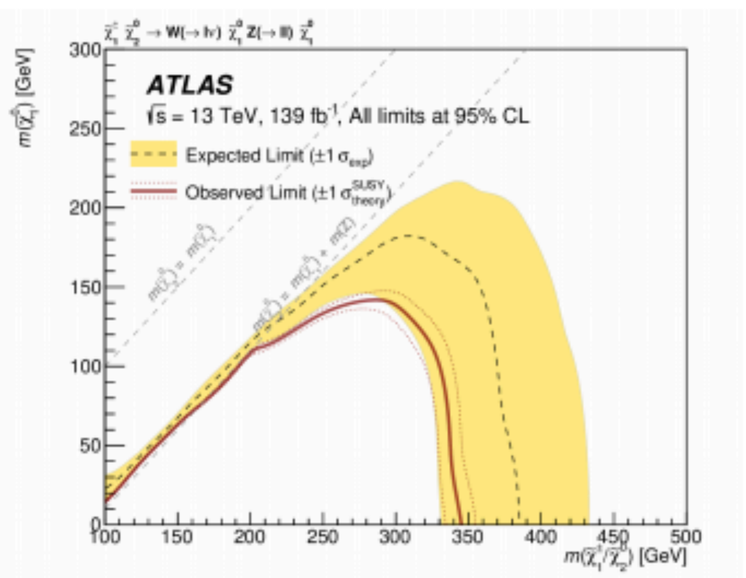
Updating list of HEPData entries for publications using `HistFactory` JSON statistical models:

- Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, b-jets 2019. URL: https://doi.org/10.17182/hepdata.89408, doi:10.17182/hepdata.89408.
- Search for chargino-neutralino production with mass splittings near the electroweak scale in three-lepton final state with the ATLAS detector. 2019. URL: https://doi.org/10.17182/hepdata.91127, doi:10.17182/hepdata.91127.
- Search for direct stau production in events with two hadronic τ-leptons in $\sqrt s = 13$ TeV pp collisions with th https://doi.org/10.17182/hepdata.92006, doi:10.17182/hepdata.92006.
- Search for direct production of electroweakinos in final states with one lepton, missing transverse momentum and a jets in (pp) collisions at $\sqrt s=13$ TeV with the ATLAS detector. 2020. URL: https://doi.org/10.17182/hepdata.90 doi:10.17182/hepdata.90607.v2.
- Search for displaced leptons in $\sqrt s = 13$ TeV pp collisions with the ATLAS detector. 2020. URL: https://doi.o doi:10.17182/hepdata.98796.
- Search for squarks and gluinos in final states with same-sign leptons and jets using 139 fb$^-1$ of data collected wi https://doi.org/10.17182/hepdata.91214.v3, doi:10.17182/hepdata.91214.v3.
- Search for trilepton resonances from chargino and neutralino pair production in $\sqrt s$ = 13 TeV pp collisions w https://doi.org/10.17182/hepdata.99806, doi:10.17182/hepdata.99806.
- Search for squarks and gluinos in final states with jets and missing transverse momentum using 139 fb$^-1$ of $\sq with the ATLAS detector. 2021. URL: https://doi.org/10.17182/hepdata.95664, doi:10.17182/hepdata.95664.

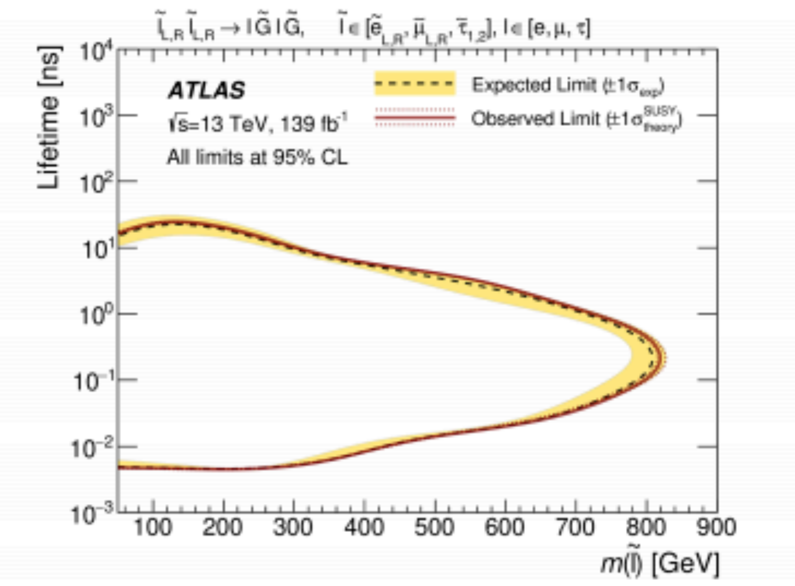
DOI 10.17182/hepdata.90607.v3



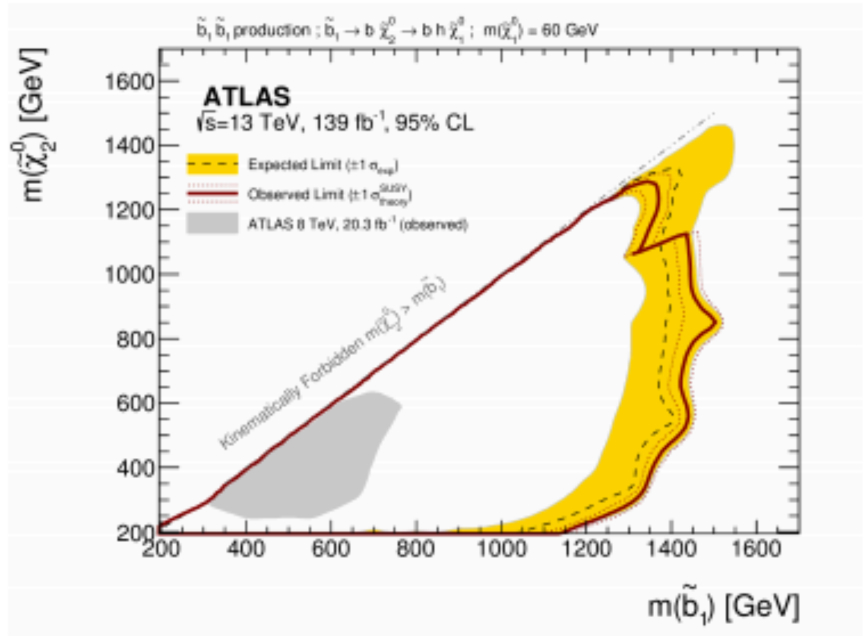
DOI 10.17182/hepdata.91127.v2



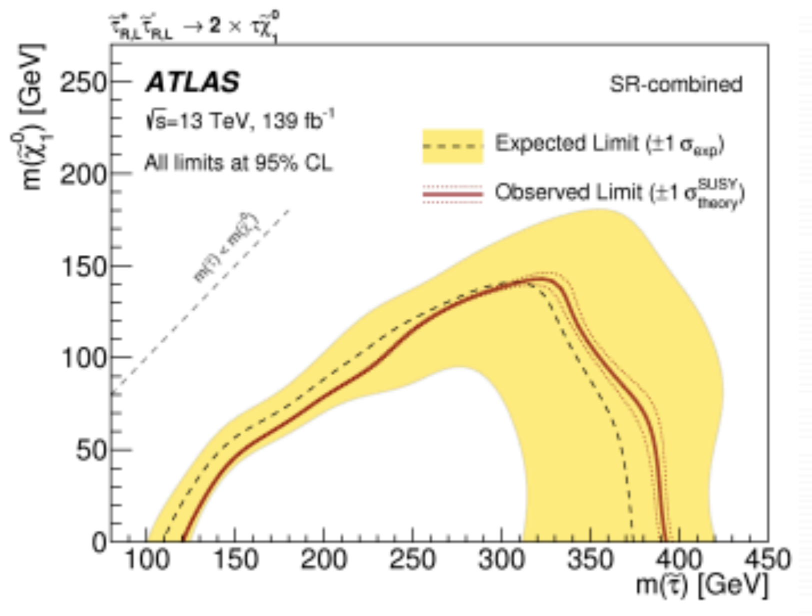
DOI 10.17182/hepdata.98796.v2



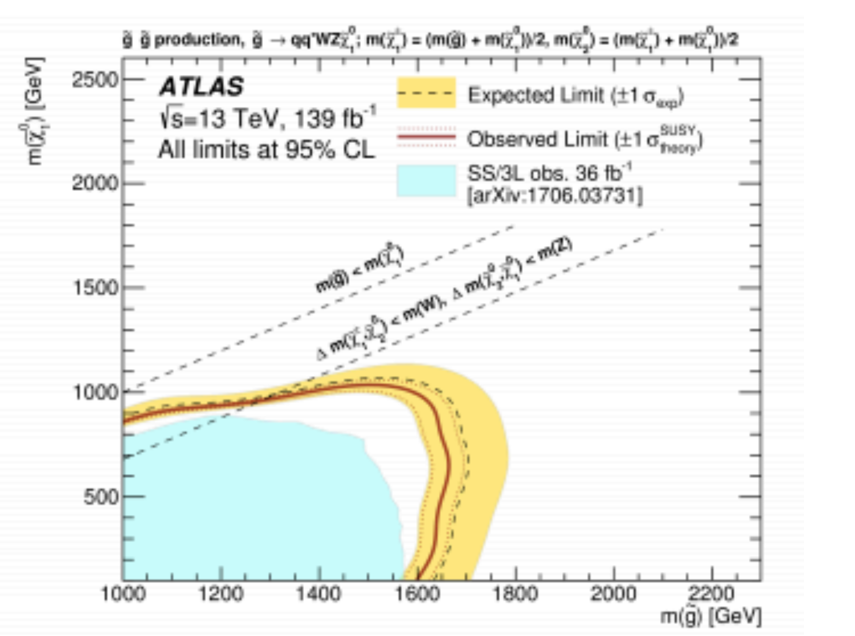
DOI 10.17182/hepdata.89408.v2



DOI 10.17182/hepdata.92006.v2

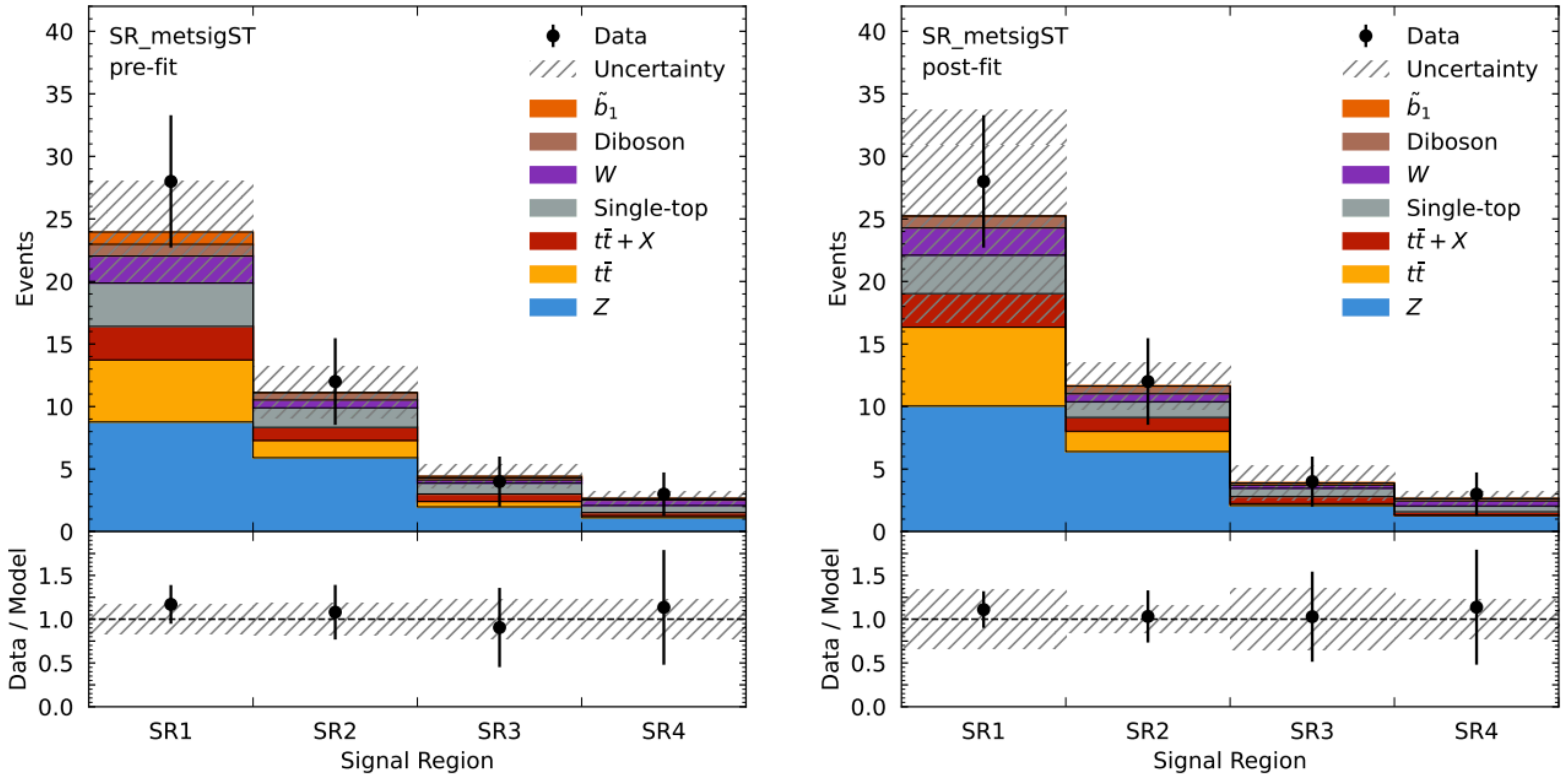


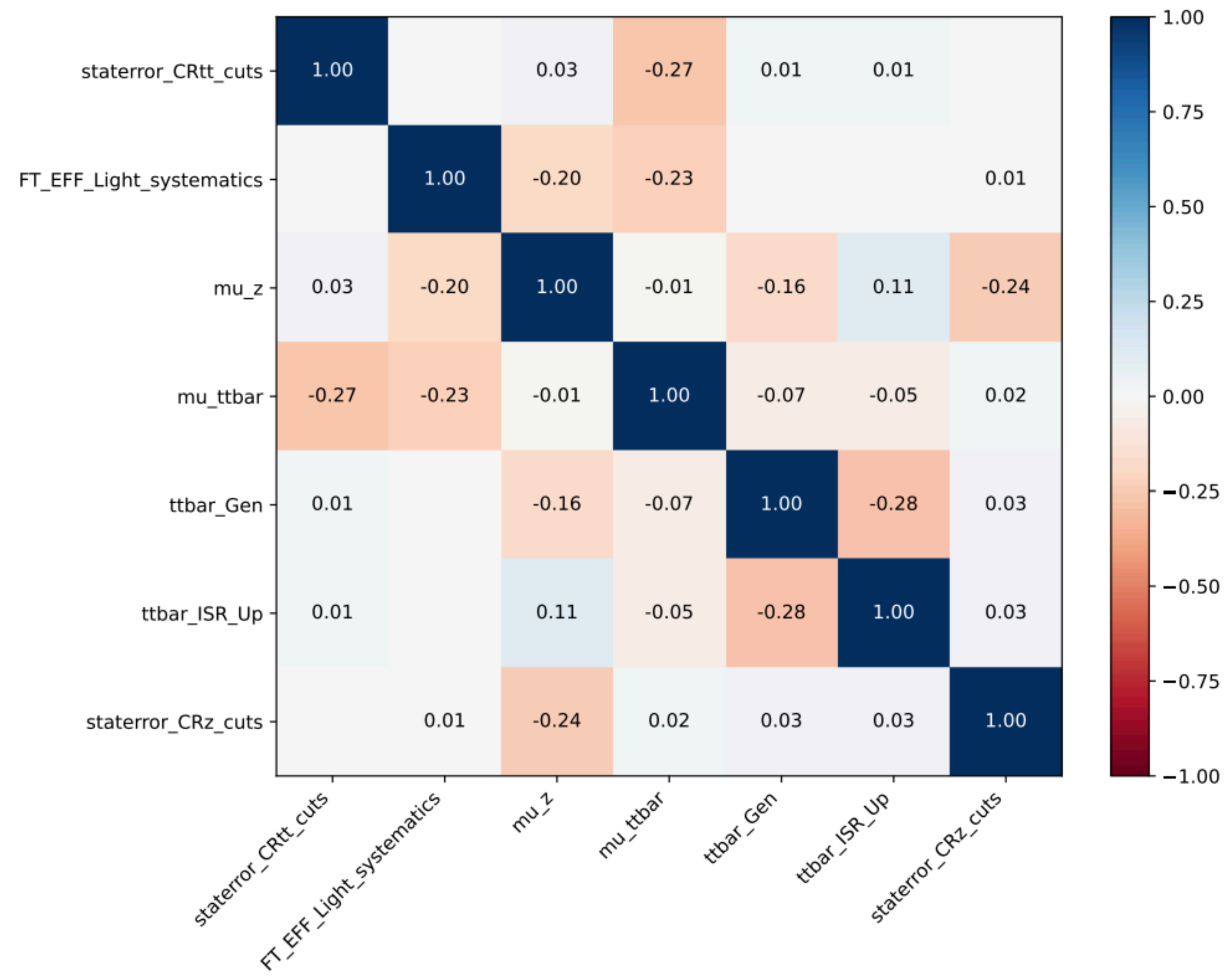
DOI 10.17182/hepdata.91214.v3



Can reproduce results very quickly with a few lines of Python

```
import json
import cabinetry
import pyhf
from cabinetry.model_utils import prediction
from pyhf.contrib.utils import download

# download the ATLAS bottom-squarks analysis probability models from HEPData
download("https://www.hepdata.net/record/resource/1935437?view=true", "bottom-squarks")

# construct a workspace from a background-only model and a signal hypothesis
bkg_only_workspace = pyhf.Workspace(json.load(open("bottom-squarks/RegionC/BkgOnly.json")))
patchset = pyhf.PatchSet(json.load(open("bottom-squarks/RegionC/patchset.json")))
workspace = patchset.apply(bkg_only_workspace, "sbottom_600_280_150")

# construct the probability model and observations
model, data = cabinetry.model_utils.model_and_data(workspace)

# produce visualizations of the pre-fit model and observed data
prefit_model = prediction(model)
cabinetry.visualize.data_mc(prefit_model, data)

# fit the model to the observed data
fit_results = cabinetry.fit.fit(model, data)

# produce visualizations of the post-fit model and observed data
postfit_model = prediction(model, fit_results=fit_results)
cabinetry.visualize.data_mc(postfit_model, data)
```





Quite a bit of excitement in the community

Twitterati

Will Kinney @WKCosmo · Sep 14
So much this. Publishing full likelihood codes is already commonplace in cosmology. It's difficult to overestimate the impact this has had.

Kyle Cranmer @KyleCranmer · Sep 13

Dr Fiona H. Panther @FiPanther · Sep 14
This is a great call to action. A thought: if your parameter estimation, or any result for that matter, cannot be reliably reproduced and all the inputs to it are fully public (and my view is they should be after proprietary periods end) it is a problem.

Kyle Cranmer @KyleCranmer · Sep 13
A call to action for the particle physics community. For 20 years we have agreed that we should publish likelihoods. We can do it technically, and

Workshops

Publication of statistical models: hands-on workshop

8–12 Nov 2021
CERN (online only)
Europe/Zurich timezone

- Overview
- Scientific Programme
- Timetable
- My Conference

The statistical models used to derive the results of experimental analyses value and are essential information for analysis preservation and reuse. I the scientific case for systematically publishing the full statistical models developments that make this practical, and illustrated by a variety of phys information on the statistical modelling can enhance the short- and long-t results

Papers

Publishing statistical models: Getting the most out of particle physics experiments

Kyle Cranmer
Philip Bechtle[4], Florian
Chrzaszcz[7], Andrea C
Nahuel Ferreiro Iachellini
Thomas Kuhr[13,16], Ar
Knut Dundas Morå[20],
Sekmen[22], Luca Silvestr
Robert Thorne[27], Wolf

A SModelS interface for pyhf likelihoods

Gaël Alguero[a], Sabine Kraml[a], Wolfgang Waltenberger[b,c]

[a]*Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, 53 Avenue des Martyrs, F-38026 Grenoble, France*
[b]*Institut für Hochenergiephysik, Österreichische Akademie der Wissenschaften,*

Jobs(!)

Postdoc position in research data infrastructure technologies

LMU Munich • Europe

hep-ex PostDoc

Deadline on Nov 30, 2021

Job description:
The Experimental Particle Physics Groups at the Ludwig-Maximilians-Universität München (LMU) invite applications for a postdoctoral research position for four years, starting early 2022.

The LMU is involved in the construction, software development, computing, and data analysis of the ATLAS and Belle II experiments. As partners in the PUNCH4NFDI consortium both groups collaborate on advancing research data infrastructures.

The successful candidate is expected to promote the joint analysis of datasets by developing technologies and procedures for the sharing of statistical models and to connect with the community to exploit synergies. The work will be embedded in task area 3, work package 4 and task are 6, work package 4 of the PUNCH4NFDI consortium.

This talk

- Explain a bit statistical Models we do publish
  some details on HistFactory, pyhf, etc...

  Note: this is only what's possible now, lots of new develoments & ideas during public likelihoods workshop for Combine, unbinned analyses, etc..

- How they can be used

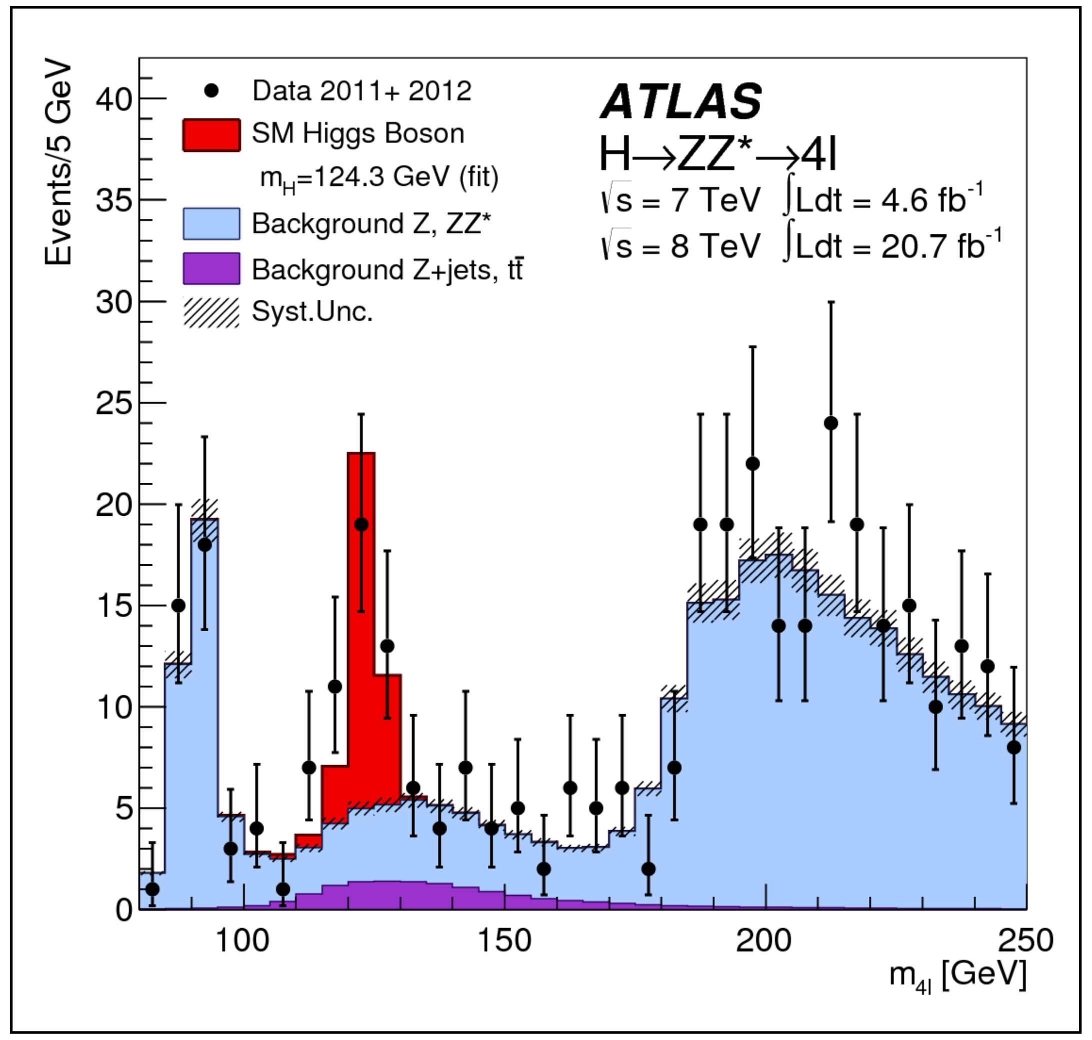
  - RECAST - partiularly interesting for LLP searches
  - statistical combination of multiple searches

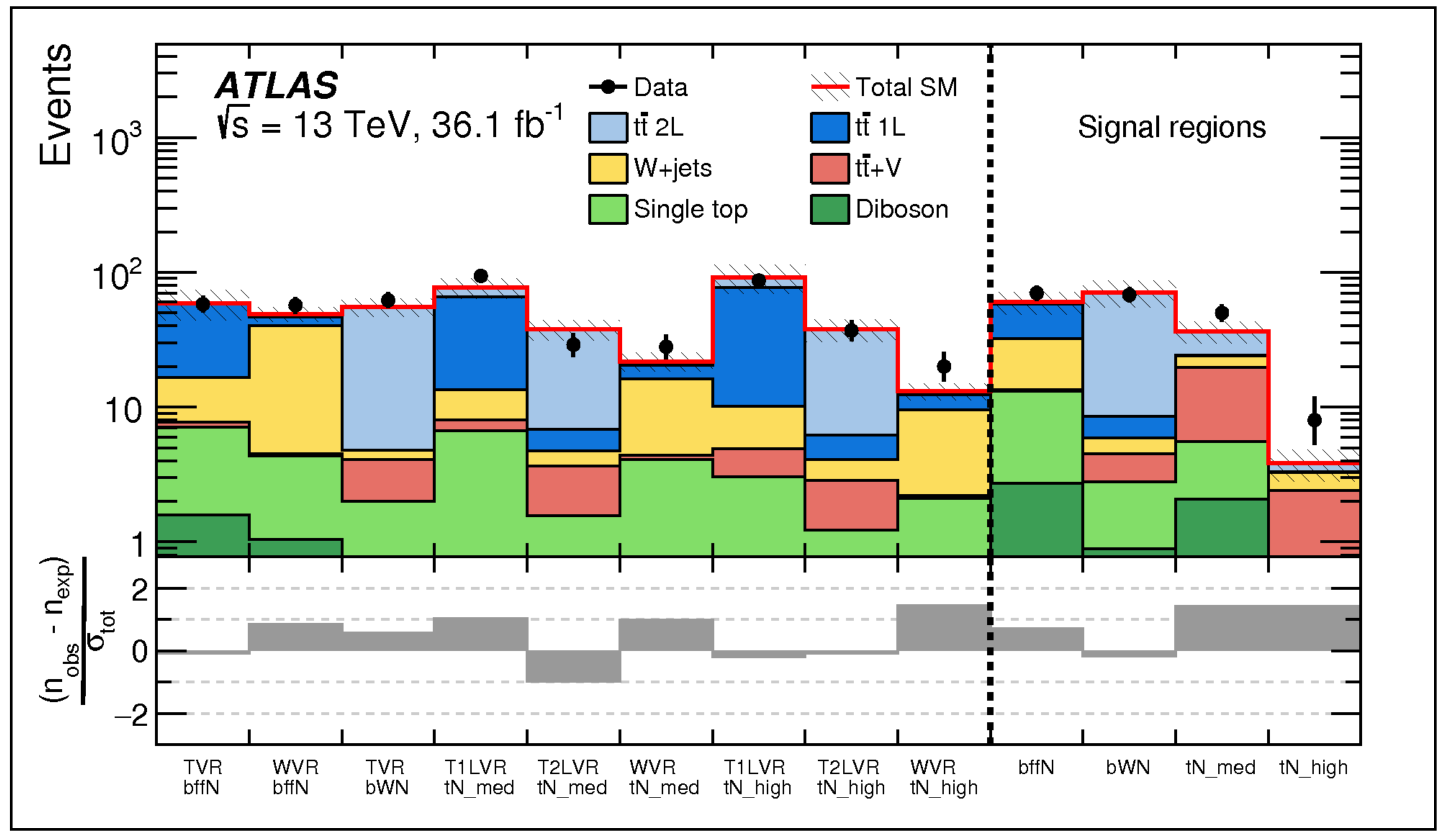
Lightning Intro to HistFactory

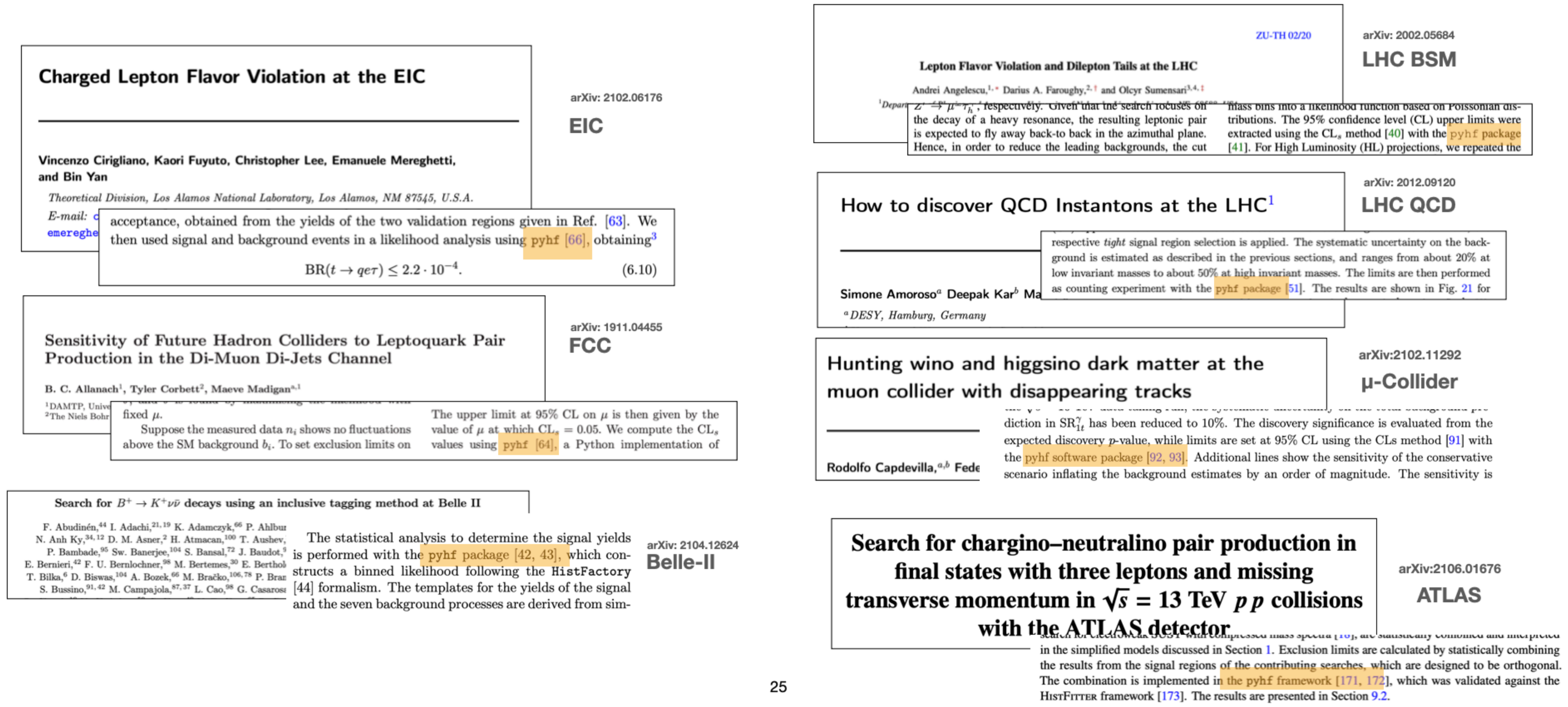
HistFactory

- simultaneous **binned fits** to multiple disjoint phase space regions ("channels")
- provides **standard building blocks** for modelling simulation-based and data-driven systematics (e.g. ABCD type methods in LLP)

Very wildly used in ATLAS, with additionally use in Bellle-II, LHCb, Pheno ...







Lightning Intro to HistFactory

An Example from LLP community

PHYSICAL REVIEW D **99,** 052005

Search for long-lived particles produced in *pp* col
that decay into displaced hadronic jets in the ATL

M. Aaboud *et al.*[*]
(ATLAS Collaboration)

(Received 21 November 2018; published 15 M

A search for the decay of neutral, weakly interacting, long-lived part
ATLAS detector at the LHC is presented. The analysis in this paper
collision data at $\sqrt{s} = 13$ TeV recorded in 2015–2016. The search empl
vertices of long-lived particles decaying into jets in the muon spectromete
and a novel technique that requires only one vertex in association with a
that improves the sensitivity for longer lifetimes. The observed numbers
expected background and limits for several benchmark signals are dete

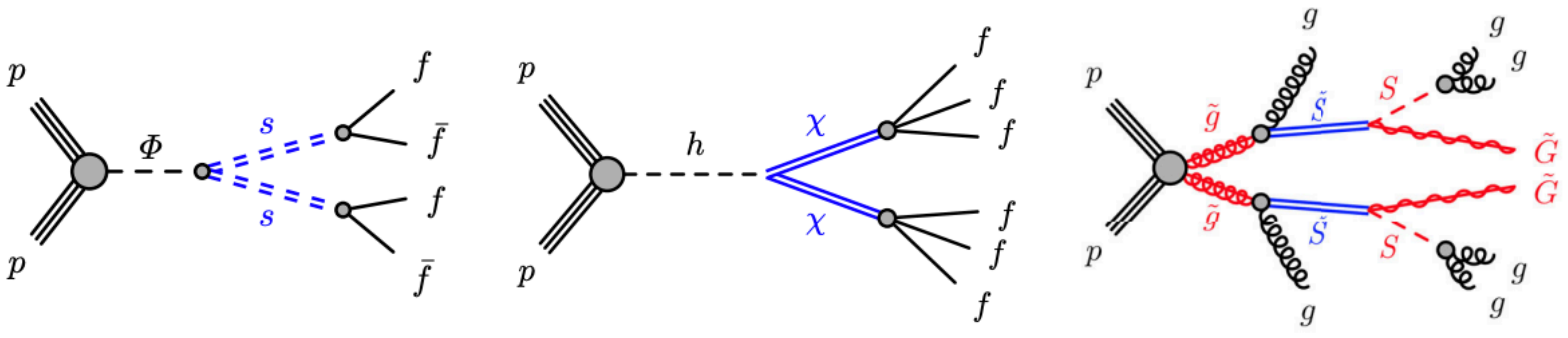
DOI: 10.1103/PhysRevD.99.052005

I. INTRODUCTION

The discovery of the Higgs boson at the LHC completed the Standard Model (SM) of elementary particles and focused attention on the many central features of our universe that the SM does not address: dark matter, neutrino mass, matter-antimatter asymmetry (baryogenesis), and the hierarchy problem (naturalness). Many beyond the Standard Model (BSM) theoretical constructs proposed in the past few years that address these phenomena predict the existence of long-lived particles (LLPs) with macro-

by the ATLAS a
collisions at $\sqrt{s}$
and LHCb Col
more recently b
[35]. To date, n
neutral LLPs.

This paper de
in proton-protc
36.1 fb^{-1} of dat
LHC during 20



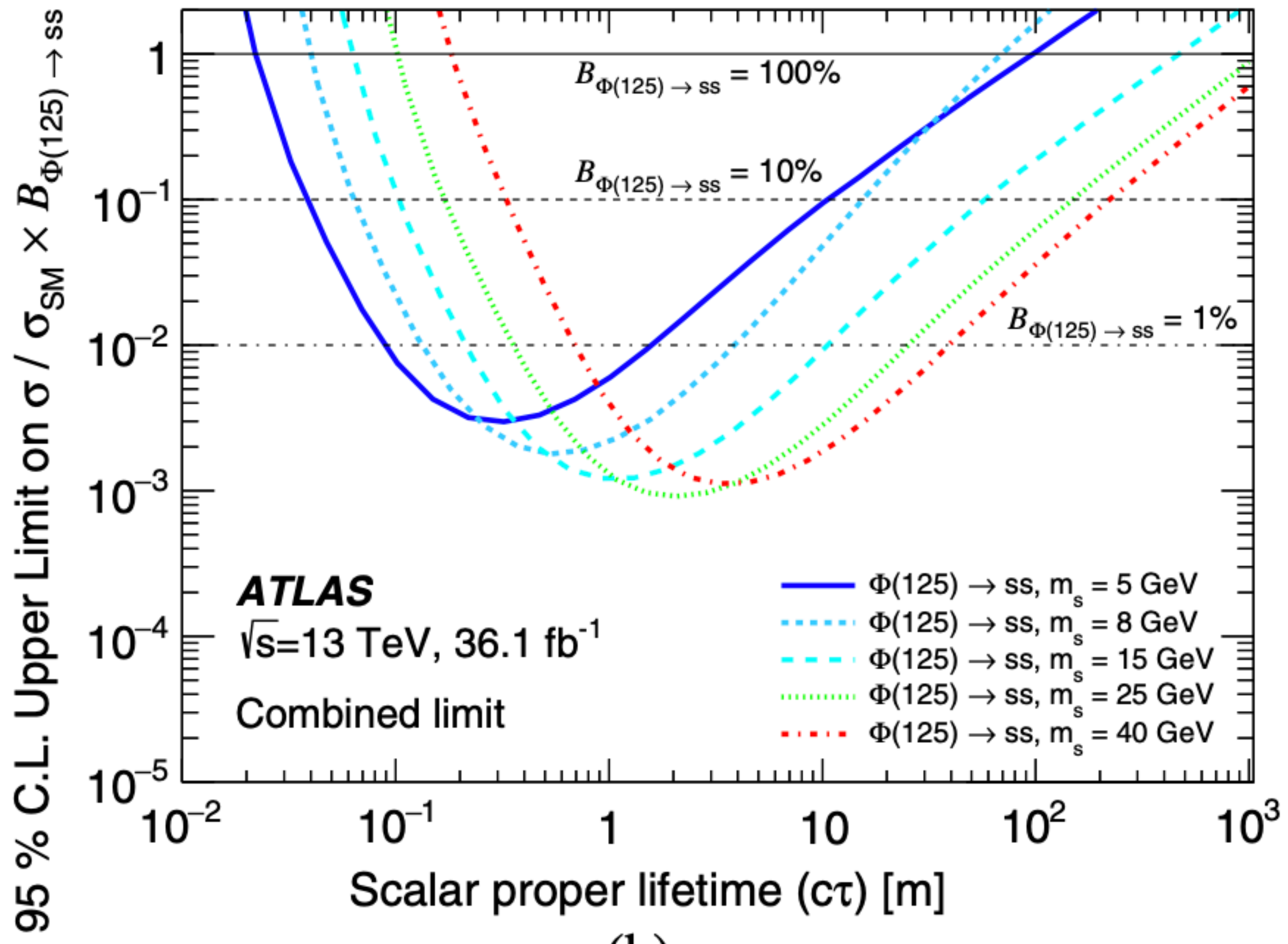
(a) (b) (c)

XI. RESULTS

For the 2MSVx strategy, 0.027 ± 0.011 background events are expected. After unblinding, no events passing the full signal selection were found.

For the 1MSVx+AO strategies, the number of observed events in the four regions of the ABCD plane and the background prediction in region A for events passing the SR selection are summarized in Table XI. No significant excess above the predicted number of background events is found.

Upper limits on the production cross section times branching fraction were derived using the CL$_s$ prescription [78], implemented with the RooStat [79] and HistFactory [80] packages using a profile likelihood function [81]. For the 2MSVx and 1MSVx+Jets strategies the likelihood includes a Poisson probability term describing the total number of observed events. For the 1MSVx + E_T^{miss} strategy the likelihood described in Sec. IX B 2 was used. For scalar boson benchmark samples with $m_\Phi \neq 125$ GeV, upper limits were set on $\sigma \times B$, where B represents the branching fraction for $\Phi \to ss$ assuming 100% branching fraction into fermion pairs. For scalar boson benchmark samples with $m_\Phi = 125$ GeV, upper limits were set on $\sigma/\sigma_{SM} \times B$, where σ_{SM} is the SM Higgs boson production cross section, 48.58 pb [82]. For the stealth SUSY benchmarks, upper limits were set on $\sigma/\sigma_{SUSY} \times B$, where σ_{SUSY} is the SUSY production cross



(b)

Lightning Intro to HistFactory

HistFactory

- simultaneous binned fits to multiple disjoint phase space regions ("channels")
- provides standard building blocks for systmatics

out main analysis
(joint of multiple channels)

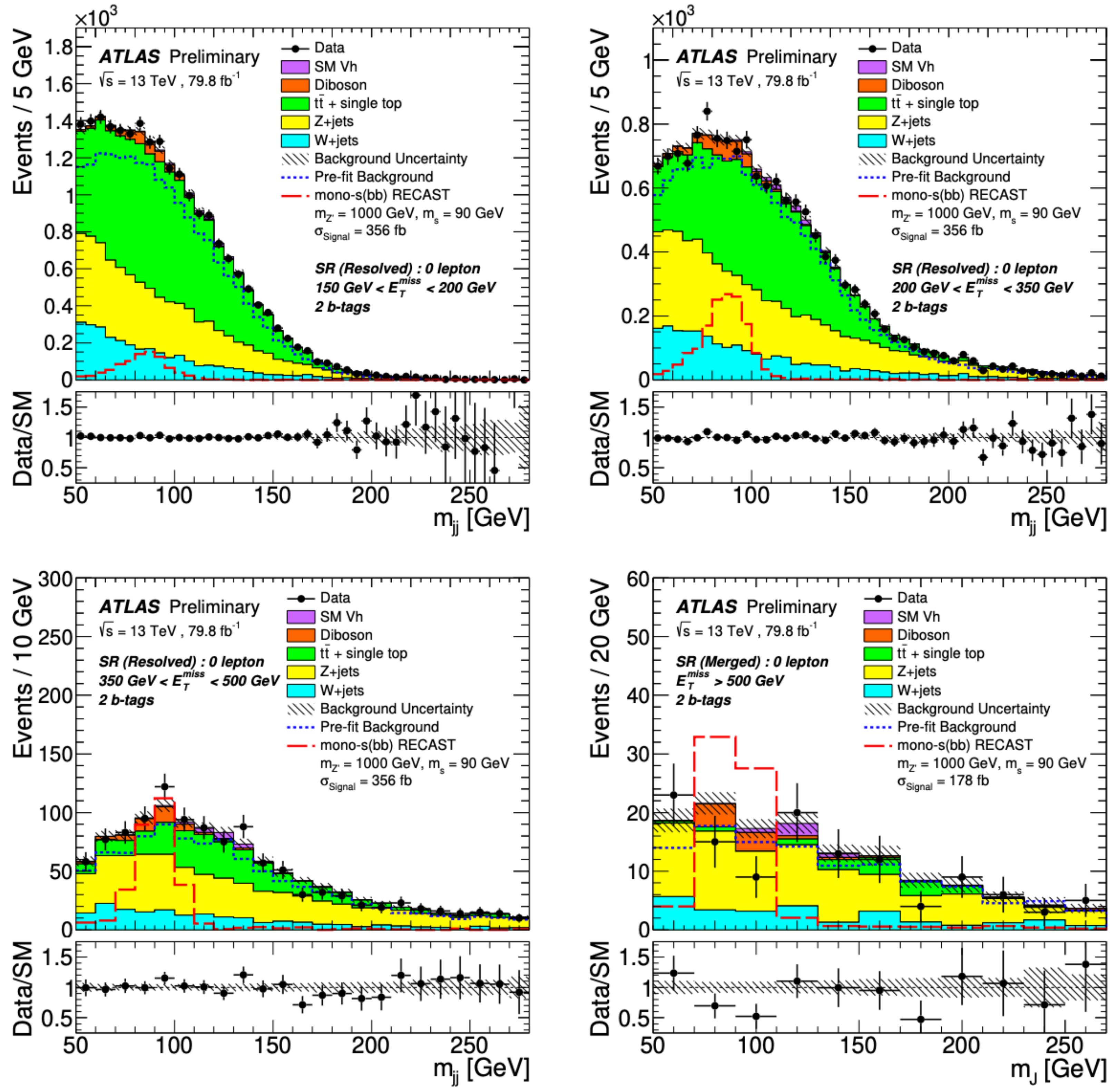
constraint terms
for systematics

$$f(\boldsymbol{n}, \boldsymbol{a} \mid \boldsymbol{\eta}, \boldsymbol{\chi}) = \underbrace{\prod_{c \in \text{channels}} \prod_{b \in \text{bins}_c} \text{Pois}\left(n_{cb} \mid \nu_{cb}(\boldsymbol{\eta}, \boldsymbol{\chi})\right)}_{\text{Simultaneous measurement of multiple channels}} \underbrace{\prod_{\chi \in \boldsymbol{\chi}} c_\chi(a_\chi \mid \chi)}_{\text{constraint terms for "auxiliary measurements"}}$$

$$\nu_{cb}(\boldsymbol{\phi}) = \sum_{s \in \text{samples}} \nu_{scb}(\boldsymbol{\eta}, \boldsymbol{\chi}) = \sum_{s \in \text{samples}} \left(\prod_{i \in \vec{\kappa}} \kappa_{i,scb}(\boldsymbol{\eta}, \boldsymbol{\chi})\right)\left(\nu^0_{scb}(\boldsymbol{\eta}, \boldsymbol{\chi}) + \sum_{j \in \vec{\Delta}} \Delta_{j,scb}(\boldsymbol{\eta}, \boldsymbol{\chi})\right)$$

nominal
expected
yield

systematics
affecting yields



Lightning Intro to HistFactory

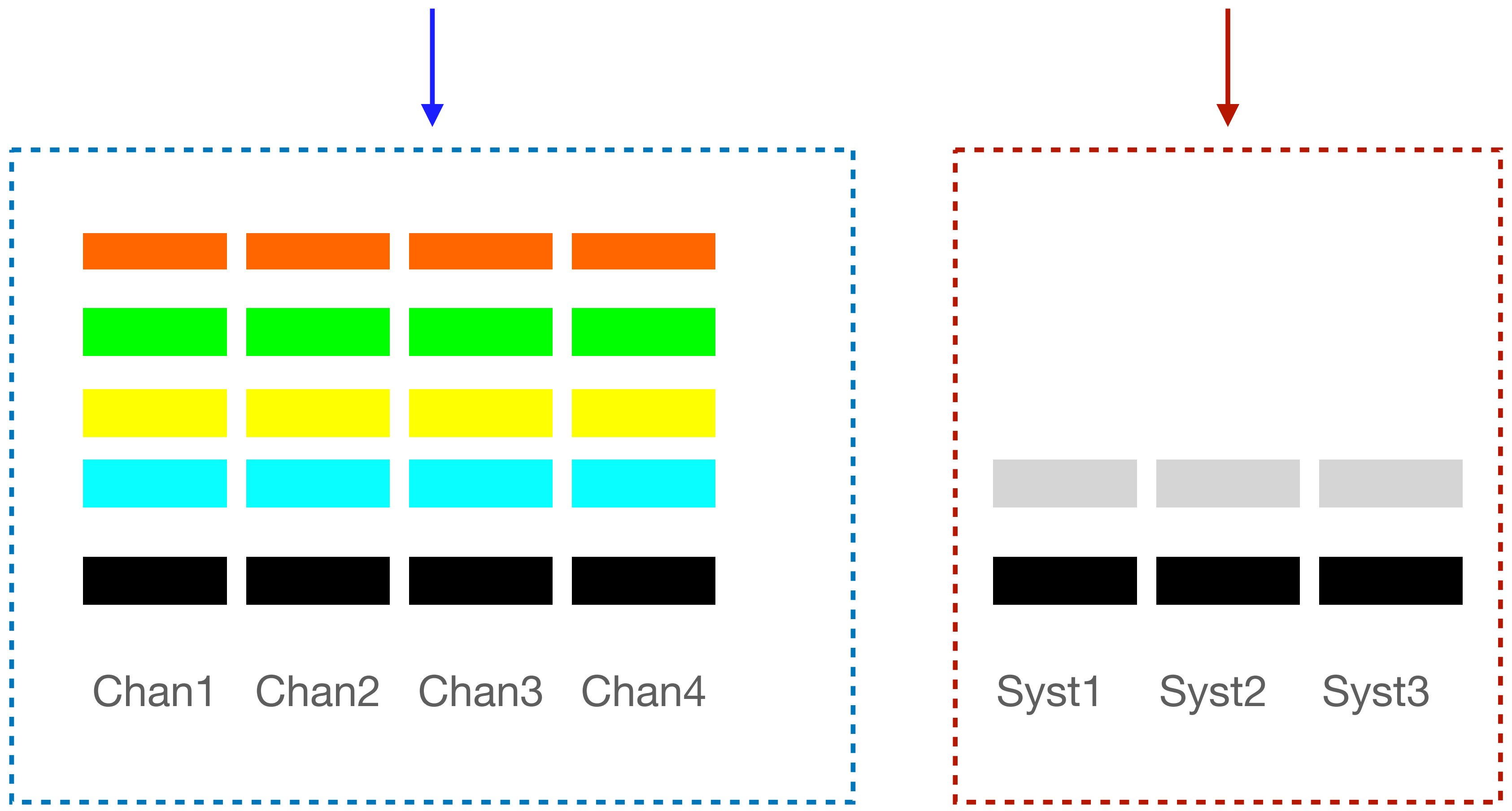
For a given HistFactory modeel you thus need to keep track of

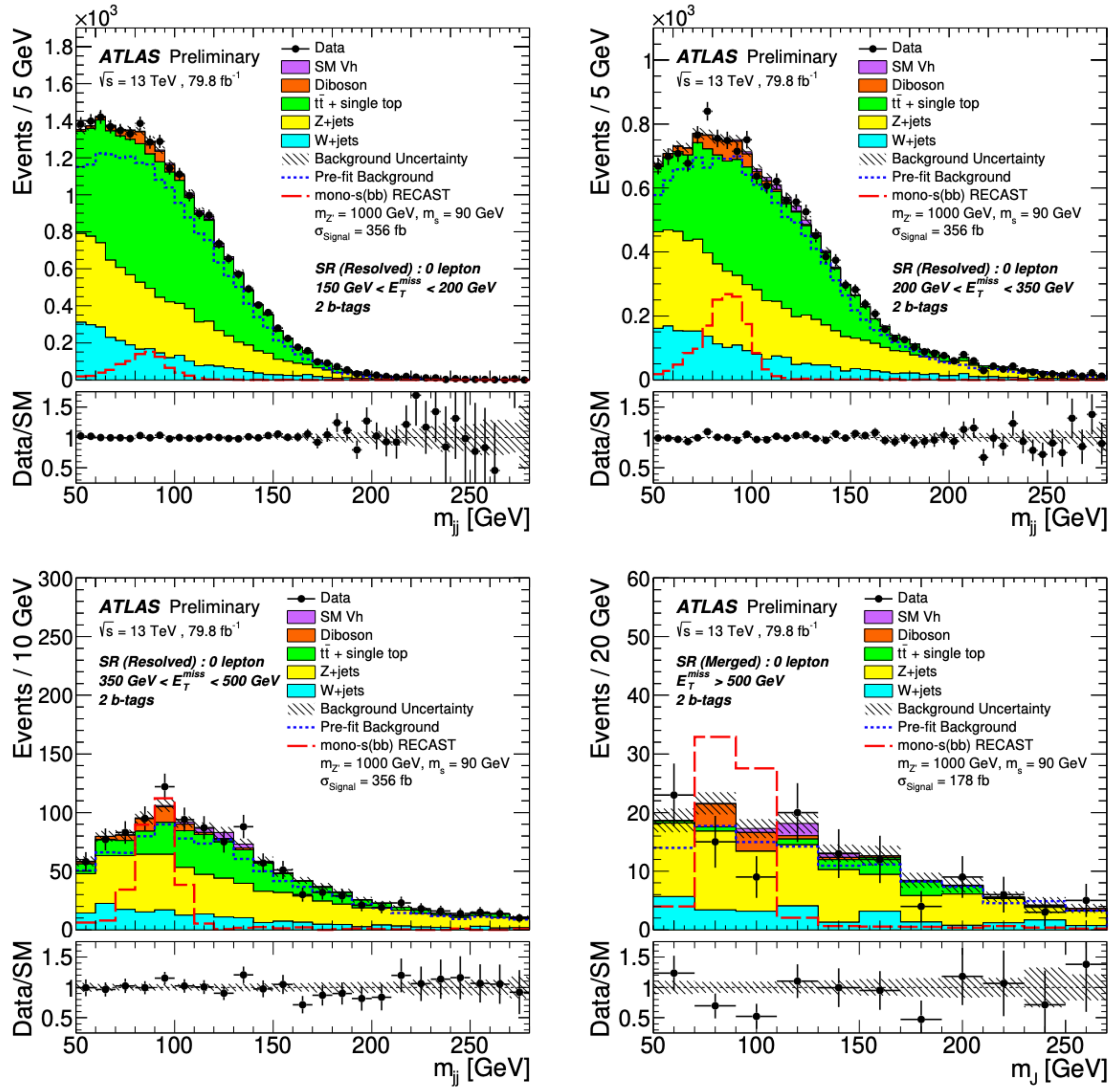
- **observed yields in all bins of all channels**
- **nominal expected yields (all bins, channels, samples)**
- **systematic effects on expectation**

out main analysis
(joint of multiple channels)

constraint terms
for systematics

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





Lightning Intro to HistFactory

For a given HistFactory modeel you thus need to keep track of

- observed yields in all bins of all channels
- nominal expected yields (all bins, channels, samples)
- systematic effects on expectation

We do this in a straight forward JSON Format

This is what's on HepData

HEPData

Repository for publication-related High-Energy Physics data

```
{
    "channels": [{
        "name": "singlechannel",
        "samples": [{
                "name": "sig",
                "data": [12.0, 11.0],
                "modifiers": [{ "name": "mu", "data": null, "type": "normfactor" }]
            },
            {
                "name": "bkg",
                "data": [50.0, 52.0],
                "modifiers": [{ "name": "uncorr_bkguncrt", "data": [3.0, 7.0], "type": "shapesys" }]
            }
        ]
    }],
    "data": {
        "singlechannel": [51.0, 48.0]
    },
    "toplvl": {
        "measurements": [{
            "config": { "poi": "mu" },
            "name": "singlechannel"
        }]
    }
}
```

nominal expected

systematic effects

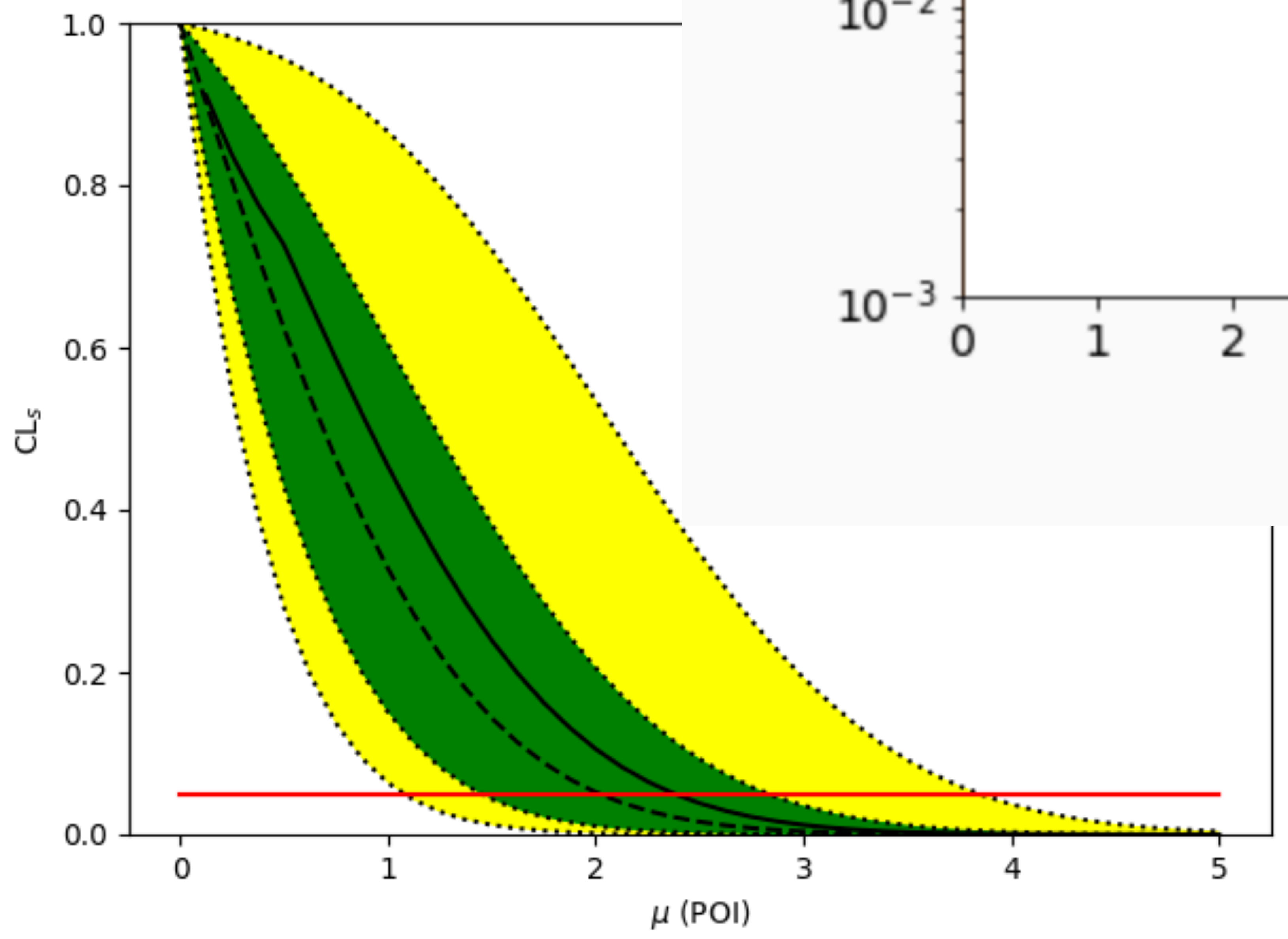
observed data

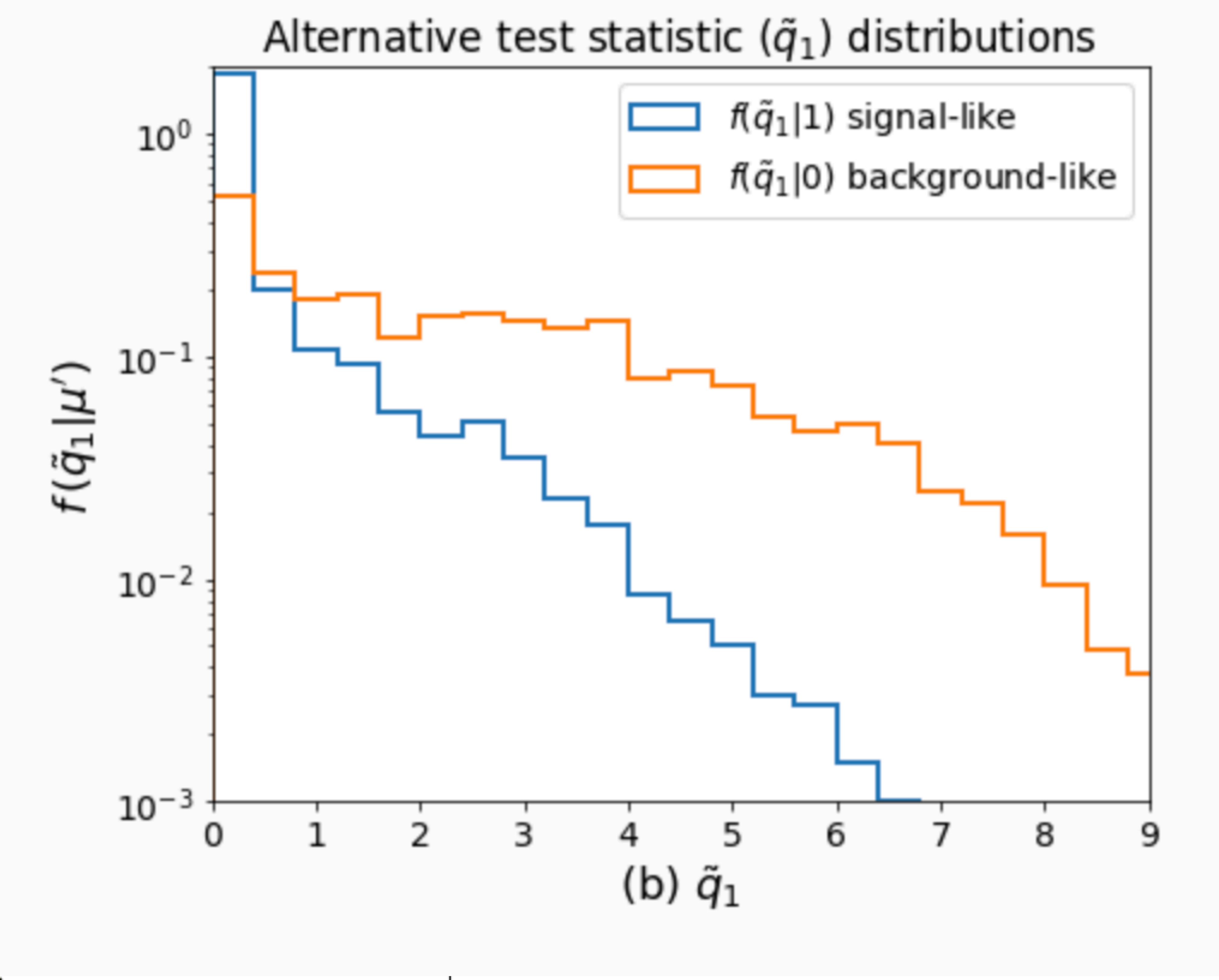
Once you have a JSON, getting limits is easy

pyhf has both asymptotic and toy-MC based inference APIs

- **for low-count LLP toys can become important**

```
$> pip install pyhf
$> pyhf cls workspace.json
{
    "CLs_exp": [
        0.008897411763217407,
        0.03524468002619176,
        0.1243148689002353,
        0.3514186235832989,
        0.6941411699405086
    ],
    "CLs_obs": 0.03607409335946063
}
```





Beyond reproducing

It's great to be able reproduce results, but doeesn't give us new science

- Much more exciting: reuse! This is what public L'hoods & other tools are about.

Two broad ways to reuse existing analyses: **RECAST** & **Combination**

Reinterpretation of Single Analysis under multiple models

Combination of multiple analyses w.r.t. one model (increased stat. power)

$$f_a(\mathrm{data}|\mathrm{model}_1) \quad f_a(\mathrm{data}|\mathrm{model}_2)$$

$$f_b(\mathrm{data}|\mathrm{model}_1) \quad f_b(\mathrm{data}|\mathrm{model}_2)$$

$$f_c(\mathrm{data}|\mathrm{model}_1) \quad f_c(\mathrm{data}|\mathrm{model}_2)$$

Beyond reproducing

RECAST: modifying one likelihood into a new likelihood ("patching")
Combination: taking N likelihoods and building a new likelihood ("stitching")

Reinterpretation of Single Analysis under multiple models

Combination of multiple analyses w.r.t. one model
(increased stat. power)

$$f_{\mathrm{a}}(\mathrm{data}|\mathrm{model}_1) \quad f_{\mathrm{a}}(\mathrm{data}|\mathrm{model}_2)$$

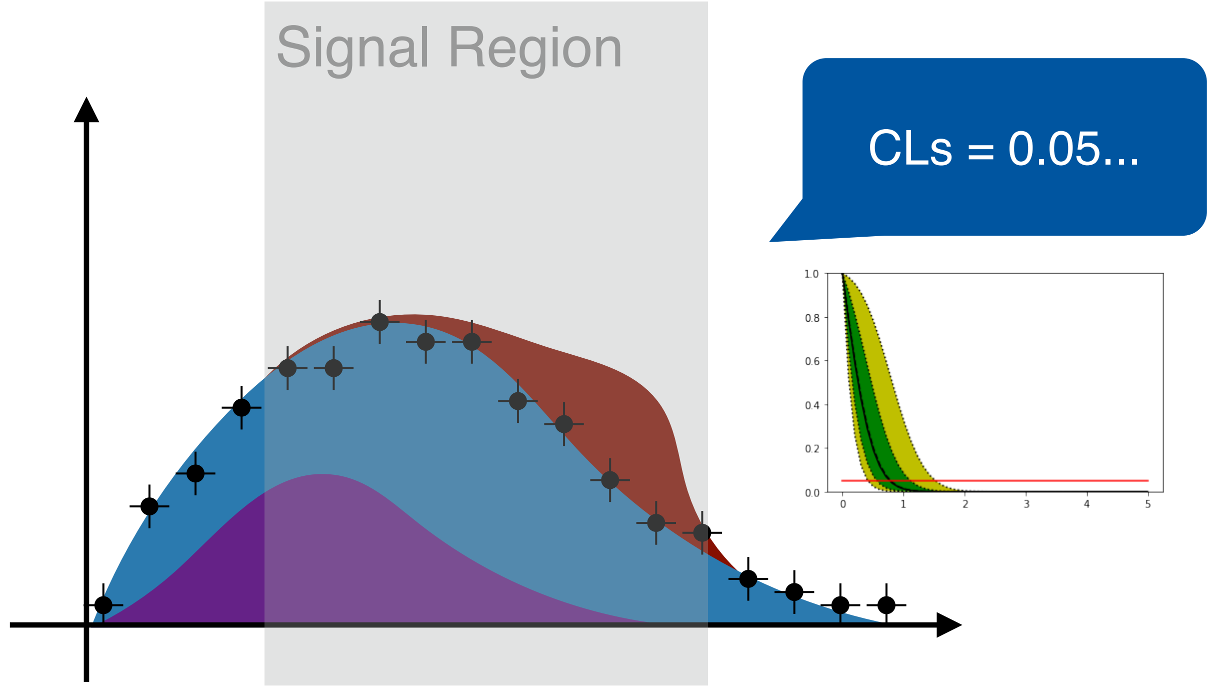
$$f_{\mathrm{b}}(\mathrm{data}|\mathrm{model}_1) \quad f_{\mathrm{b}}(\mathrm{data}|\mathrm{model}_2)$$

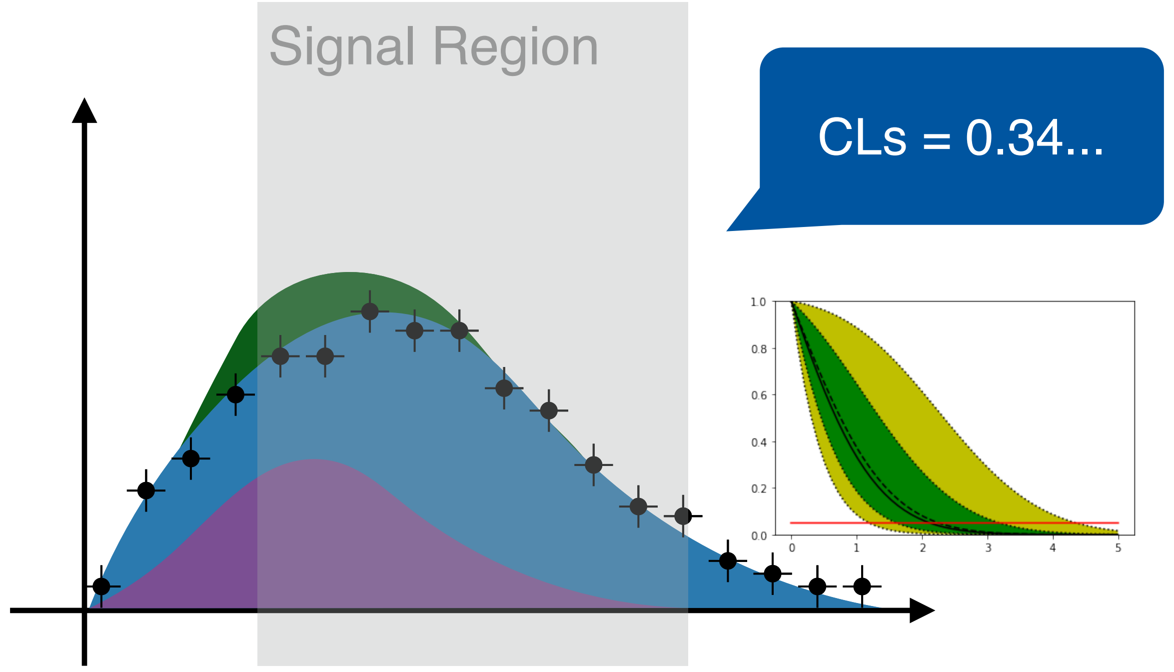
$$f_{\mathrm{c}}(\mathrm{data}|\mathrm{model}_1) \quad f_{\mathrm{c}}(\mathrm{data}|\mathrm{model}_2)$$

RECAST

RECAST reuses almost all of the statistical model

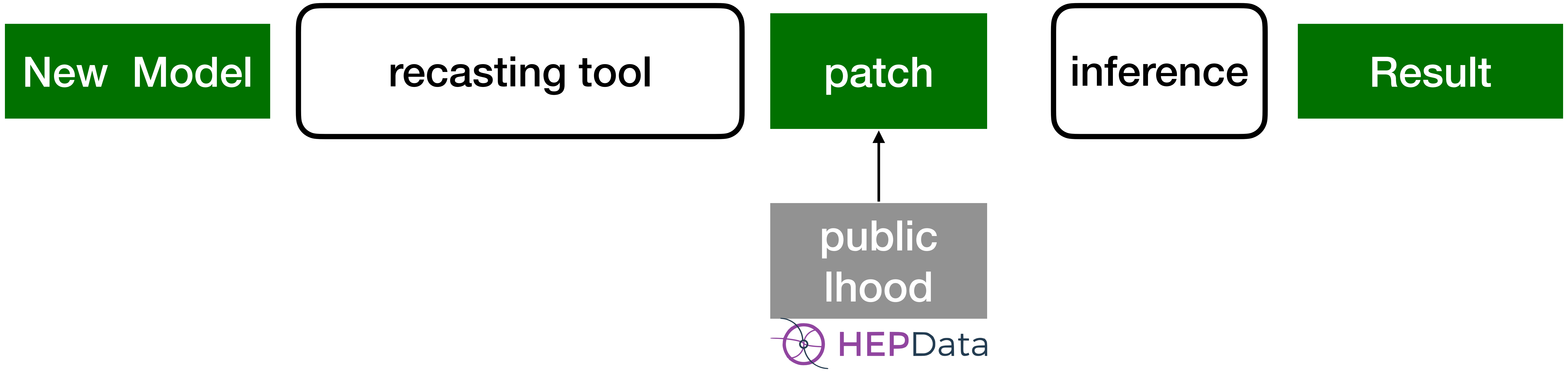
- same data, same backgrounds, different new signals





Three Step Procedure:

1) compute new signal 2) make new L'hood 3) redo stat. analysis



recasting = patch-generation machinery for public likelihoods

For 1) use your favorite recasting tool that gives you est. yields in anlysis regions

- Note (important also for LLP), you need yields for SR and CR regions!

For 2) pyhf introduced the idea of a "JSON Patch"

- a special format for the new yields you get from recasting tool
- modifies existing likelihood to incorporate thew new model
  - like a code patch "remove original signal", "add new signal"

Old Likelihood

```
{
    "channels": [
        { "name": "singlechannel",
          "samples": [
            { "name": "signal",
              "data": [7.0, 2.0],
              "modifiers": [ { "name": "mu", "type": "normfactor", "data": null} ]
            },
            { "name": "background",
              "data": [50.0, 60.0],
              "modifiers": [ {"name": "uncorr_bkguncrt", "type": "shapesys", "data": [5.0,12.0]} ]
            }
          ]
        }
    ],
    "data": {
        "singlechannel": [50, 60]
    },
    "measurements": [
        { "name": "Meas
    ]
}
```

Patch (from Step 1)

```
[{
  "op": "replace",
  "path": "/channels/0/samples/0/data",
  "value": [7.0, 2.0]
}]
```

```
jsonpatch likelihood.json patch.json > new.json
```

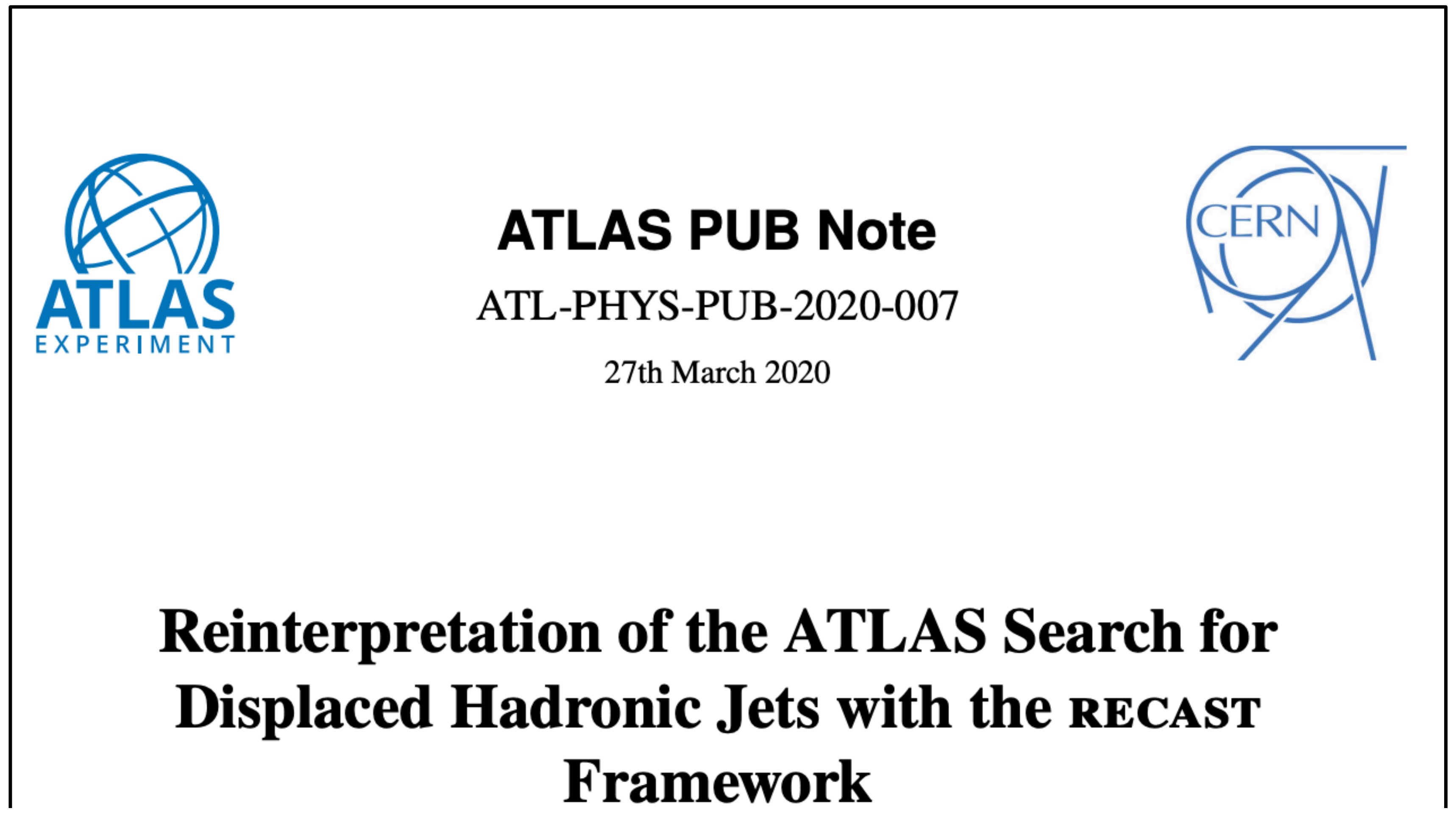
New Likeilhood

new yields injected

```
{
    "channels": [
        { "name": "singlechannel",
          "samples": [
            { "name": "signal",
              "data": [7.0, 2.0],
              "modifiers": [ { "name": "mu", "type": "normfactor", "data": null} ]
            },
            { "name": "background",
              "data": [50.0, 60.0],
              "modifiers": [ {"name": "uncorr_bkguncrt", "type": "shapesys", "data": [5.0,12.0]} ]
            }
          ]
        }
    ],
    "data": {
        "singlechannel": [50, 60]
    },
    "measurements": [
        { "name": "Measurement", "config": {"poi": "mu", "parameters": []} }
    ]
}
```

Example from LLP

Great Example of RECAST from ATLAS w/ CalRatio Analysis

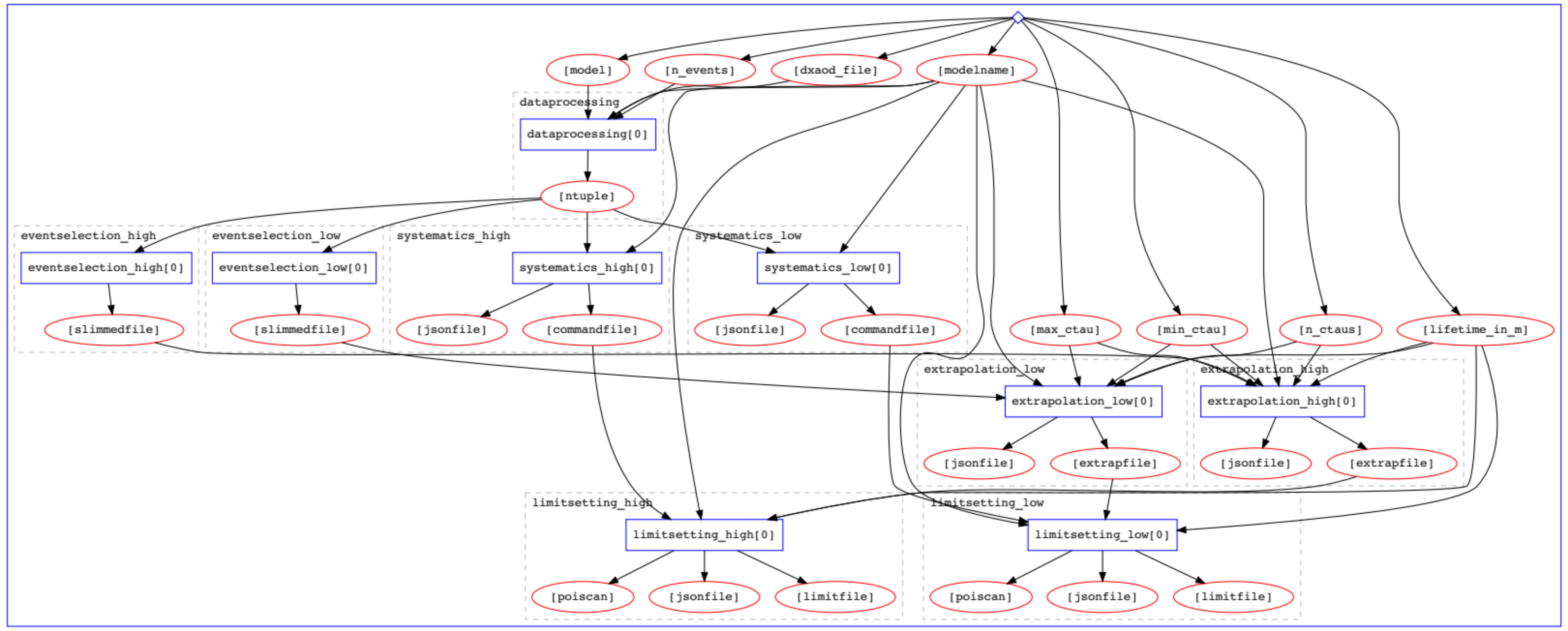


ATLAS PUB Note

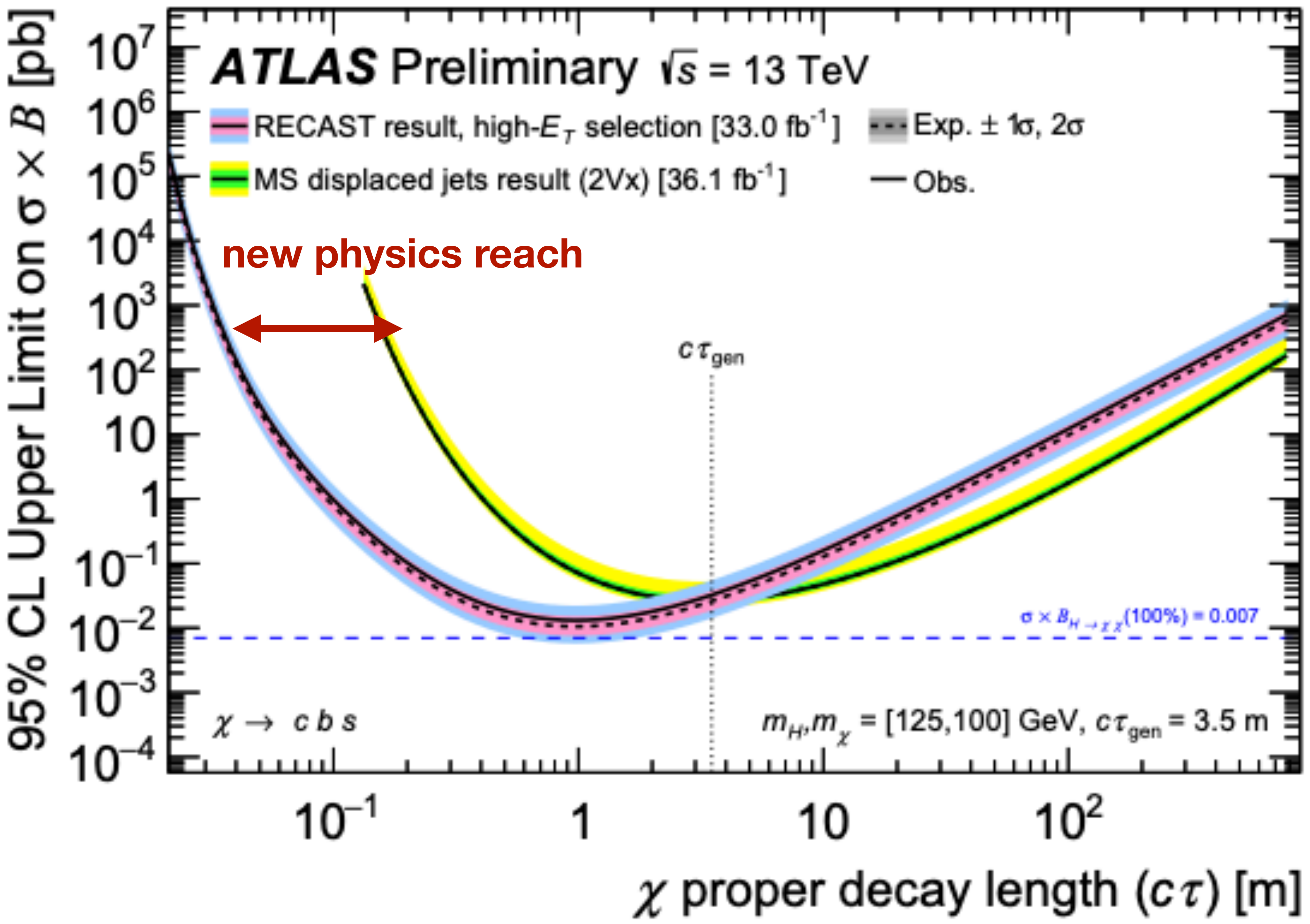
ATL-PHYS-PUB-2020-007

27th March 2020

Reinterpretation of the ATLAS Search for Displaced Hadronic Jets with the RECAST Framework



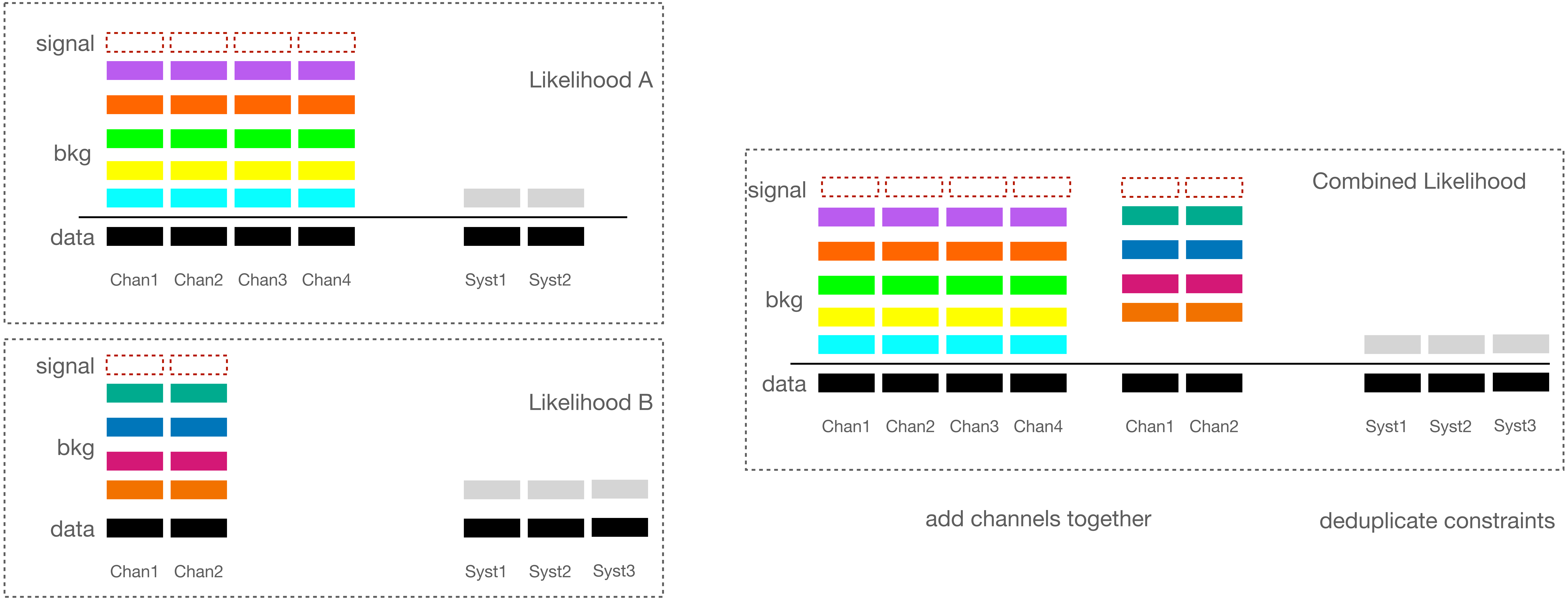
full collaboration-level RECAST important due to low-leve detector inputs & lots of ML



Combinations

For combinations you need to ensure three things

- **phase-space regions must be disjoint and uniquely named**
- **ensure consistency of nuisance parameter naming acrross input likelihoods**
- **avoidance of double counting of external constraint terms**



Combinations

For combinations you need to ensure three things

- phase-space regions must be disjoint and uniquely named
- ensure consistency of nuisance parameter naming acrross input likelihoods
- avoidance of double counting of external constraint terms

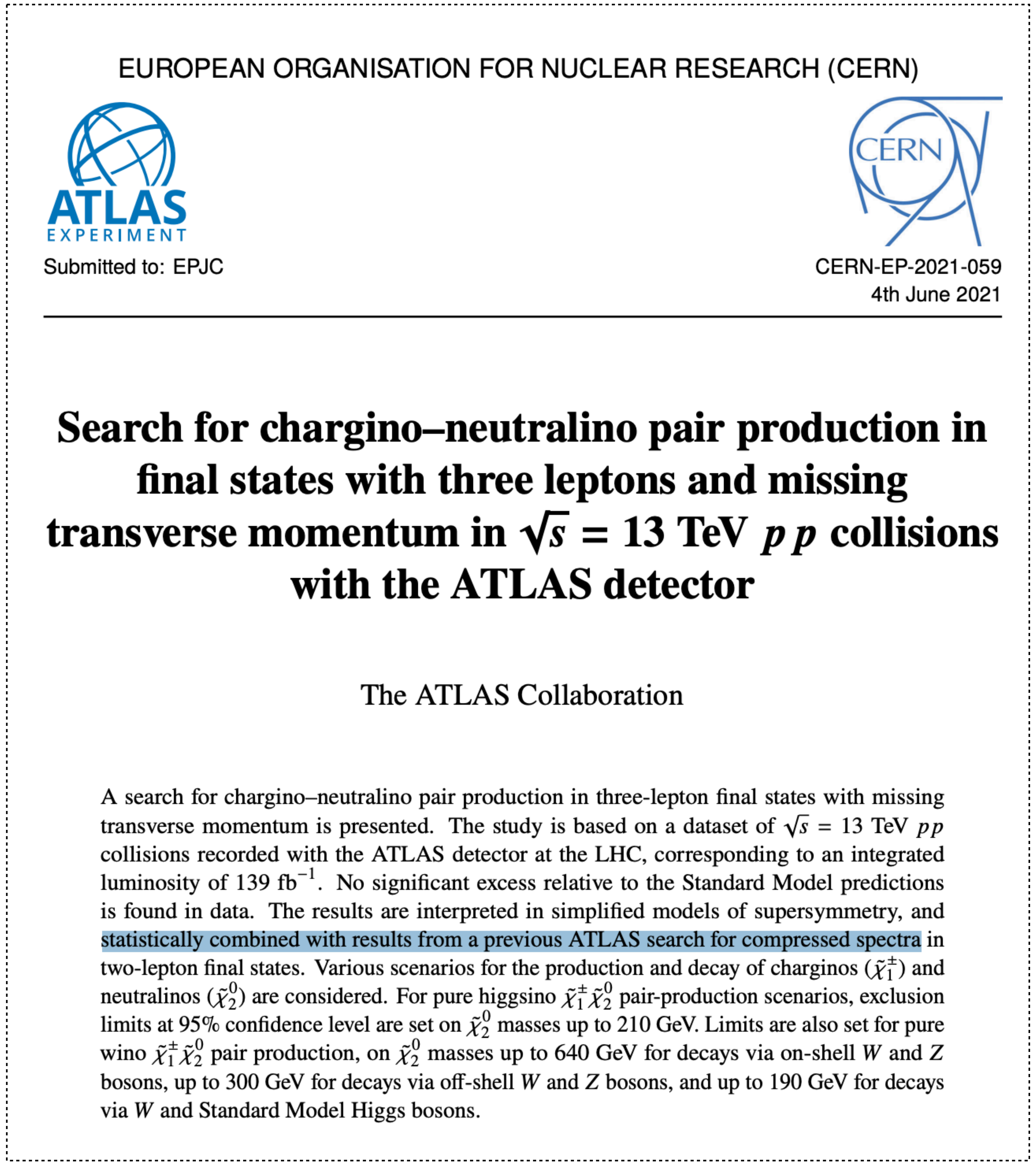
pyhf provides *some* tooling, but it's not as fully-featured

- expect some manual JSON hacking for combination work
- if people want to collaborate on JSON-combiner tooling let us know

```
lukasheinrich  mpb2019lheinric  ~  $  pyhf combine --help
Usage: pyhf combine [OPTIONS] [WORKSPACE_ONE] [WORKSPACE_TWO]

  Combine two workspaces into a single workspace.

  See :func:`pyhf.workspace.Workspace.combine` for more information.

Options:
  -j, --join [none|outer|left outer|right outer]
                                  The join operation to apply when combining
                                  the two workspaces.

  --output-file TEXT              The location of the output json file. If not
                                  specified, prints to screen.

  --merge-channels / --no-merge-channels
                                  Whether or not to deeply merge channels. Can
                                  only be done with left/right outer joins.

  -h, --help                      Show this message and exit.
```

Example from ATLAS SUSY:

all done with exactly the same JSONs as they are released



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

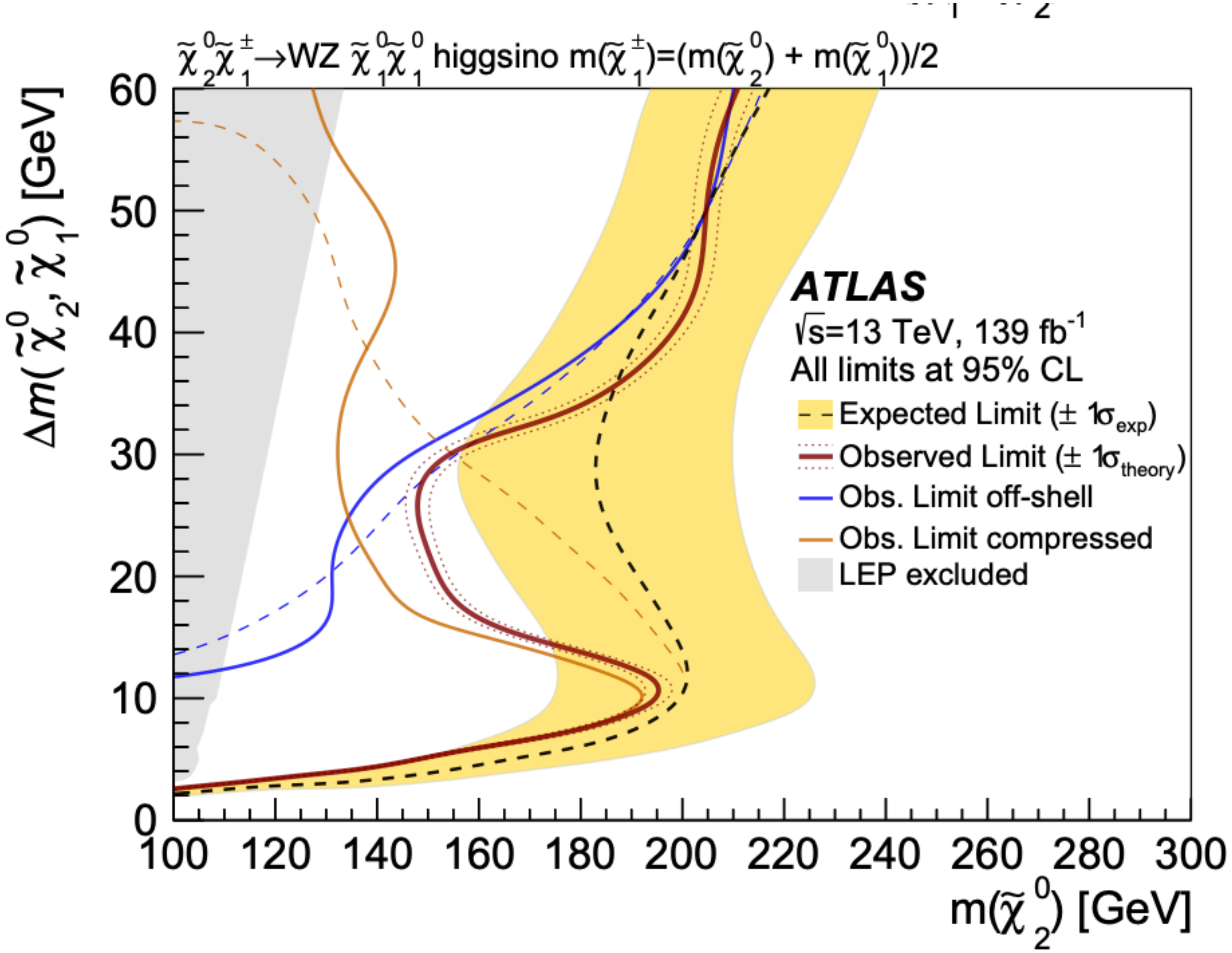
Submitted to: EPJC

CERN-EP-2021-059
4th June 2021

Search for chargino–neutralino pair production in final states with three leptons and missing transverse momentum in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

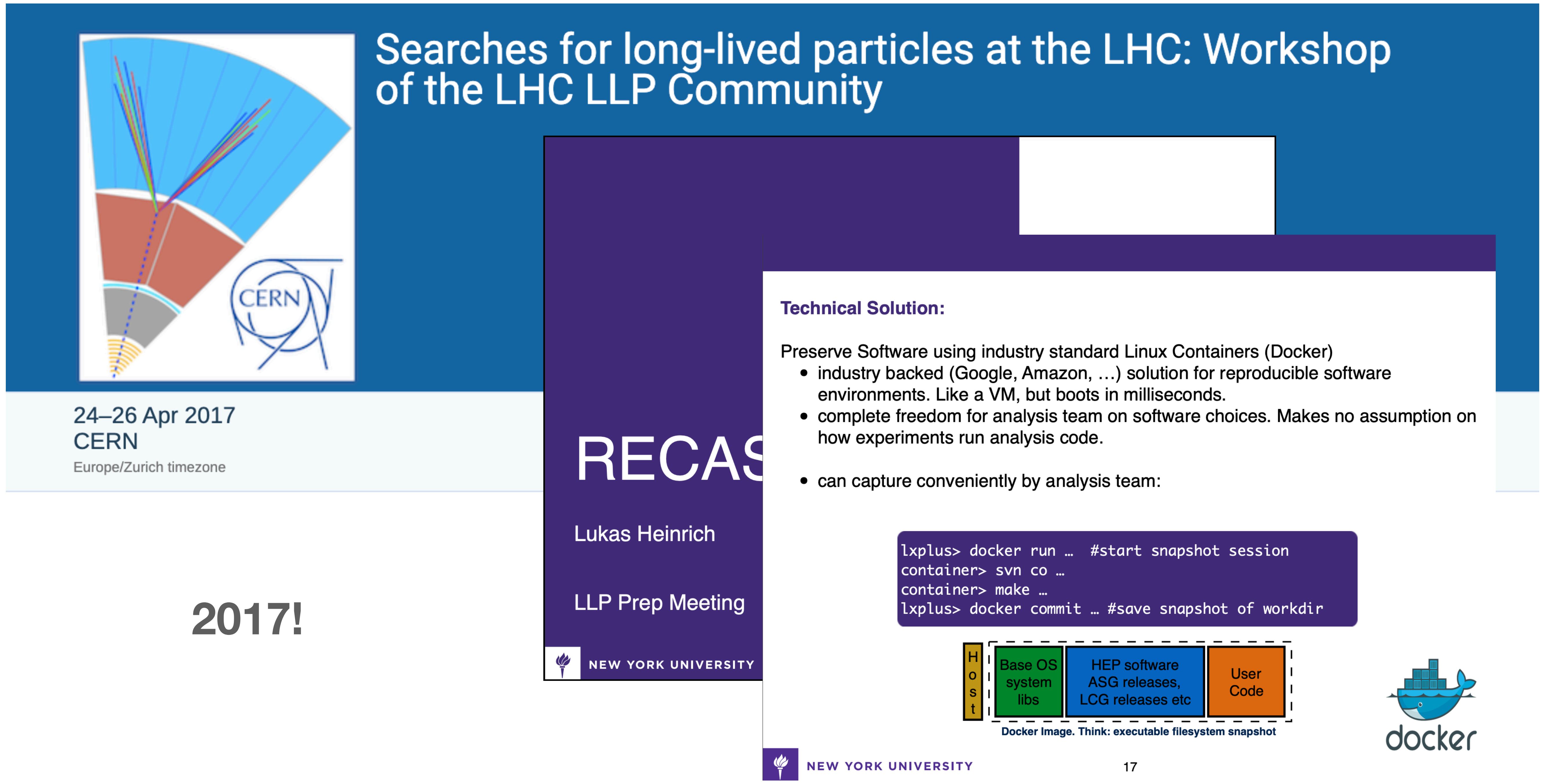
The ATLAS Collaboration

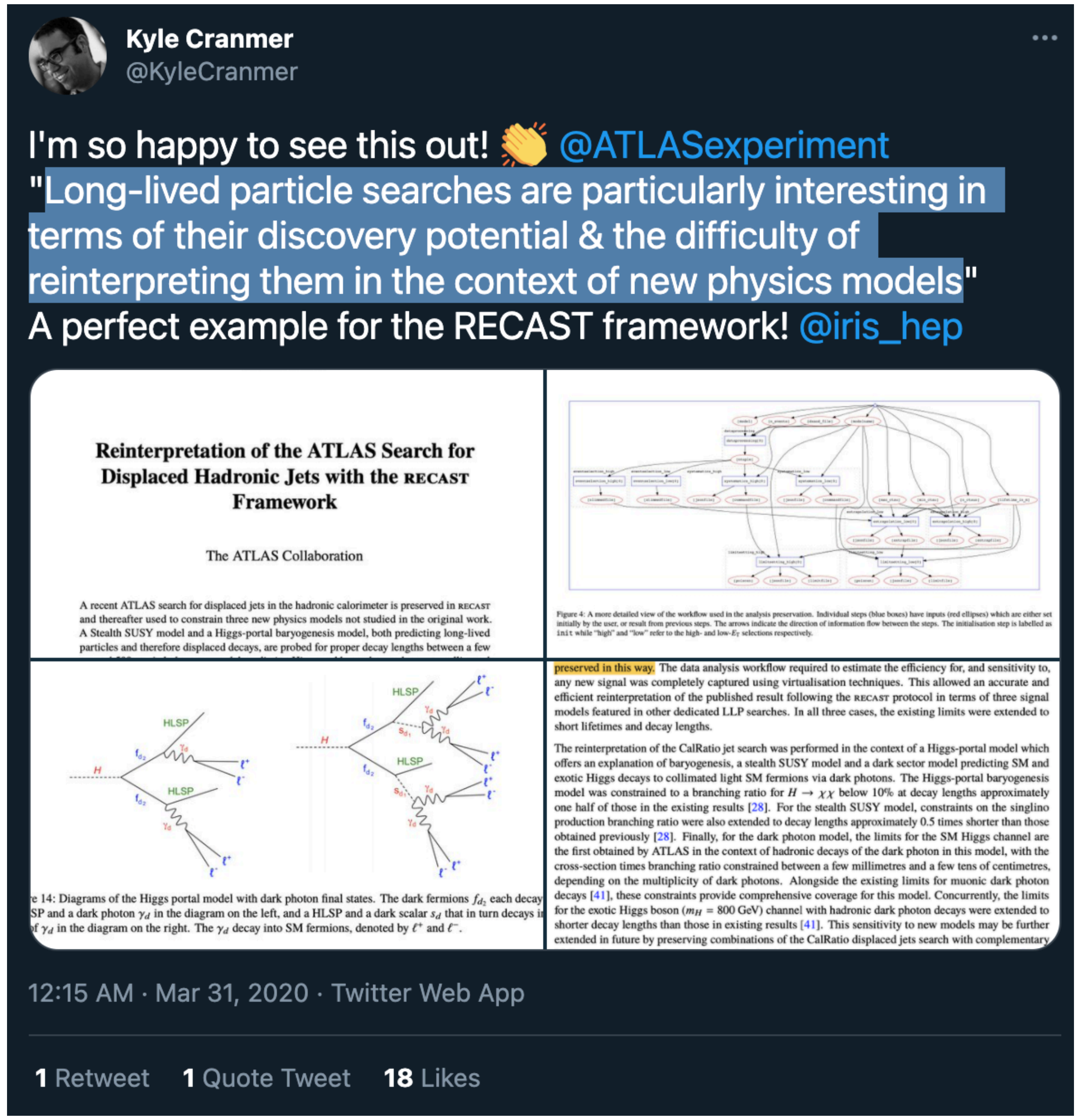
A search for chargino–neutralino pair production in three-lepton final states with missing transverse momentum is presented. The study is based on a dataset of $\sqrt{s}$ = 13 TeV pp collisions recorded with the ATLAS detector at the LHC, corresponding to an integrated luminosity of 139 fb^{-1}. No significant excess relative to the Standard Model predictions is found in data. The results are interpreted in simplified models of supersymmetry, and statistically combined with results from a previous ATLAS search for compressed spectra in two-lepton final states. Various scenarios for the production and decay of charginos ($\tilde{\chi}_1^\pm$) and neutralinos ($\tilde{\chi}_2^0$) are considered. For pure higgsino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair-production scenarios, exclusion limits at 95% confidence level are set on $\tilde{\chi}_2^0$ masses up to 210 GeV. Limits are also set for pure wino $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ pair production, on $\tilde{\chi}_2^0$ masses up to 640 GeV for decays via on-shell W and Z bosons, up to 300 GeV for decays via off-shell W and Z bosons, and up to 190 GeV for decays via W and Standard Model Higgs bosons.



Summary

- publishing Likelihood is becoming a new normal
- this enables new science through stat. combination & reinterpretation
- particularly powerful for LLP searches
- get in touch if you need help





LLP community has been a constant companion in getting here. Thanks!