Search Re-interpretation: How and Why in Collider Physics

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LPC Particules pLasmas Univers applications
Laboratoire de Physique de Clermont

Analysis preservation 101

What is it, and why ?

Introduction

- **Analysis Preservation** = enough info *"made available"* so results of analyses can be re-used **decades into future**.

- **LHC Run3 = final word on many topics for a generation**. Search results **unlikely to be superseded** until well into HL-LHC. In some cases, **not be superseded within span of the careers or lifetimes** of the current collaboration members!

- ***"Made available"***: within ATLAS/CMS/Other (internal) vs outside (public).
  In my honest opinion: **internal preservation is not helpful**.
  We will all be outside of our collaborations one day.

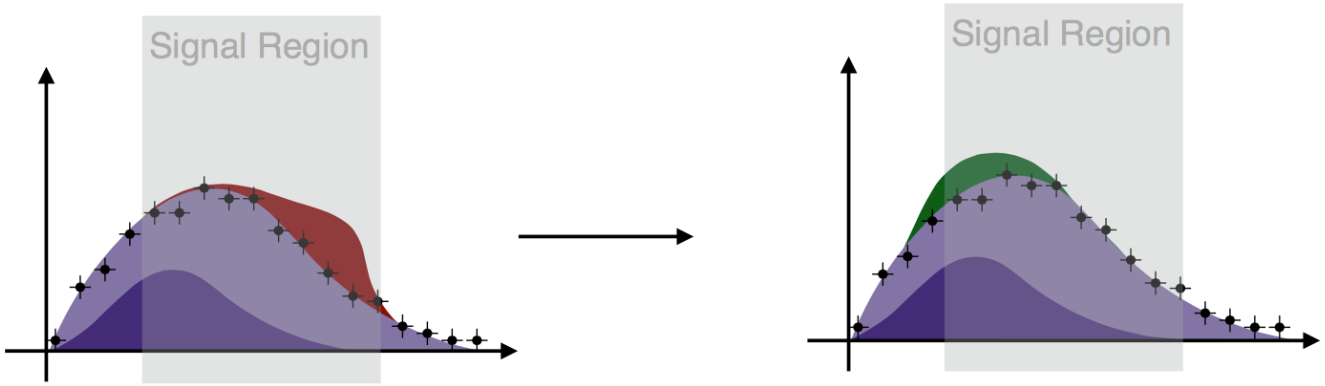
- **Single-use results are not impactful** in long-term. Want easy **re-interpretability** to facilitate long-term impact.

Re-interpretation

- Theorists: ***"What does your analysis result imply for my favourite model ?" (Or the model I will come up with 15 years from now)***

- Search papers usually consider only one (or at most a few) models at a time: usually simplified, benchmark models. Can't cover everything!

- What if my model had slightly **different kinematics**? Or **extra objects** in event?



- Need strategies to **answer these questions**, even if only approximately...
  ... **without re-running a whole analysis!**

Re-interpretation *for measurements*

- For unfolded **measurements:** largely a s**olved problem.**
  -> **unfolding** means that **no detector simulation or smearing** is needed.
  Compare truth-level predictions to truth-level data.

- (Almost) all measurements provide **Rivet routine** (**runnable code snippet** encoding fiducial region, **validated by analysers**, often cross-check for main analysis)
  - Main challenge = properly encoding correlations of observables+systematics
  - Rivet and HEPData are automatically sync'd by construction
  - -> This should be possible for STXS measurements... but as far as I know, isn't done routinely! (Easy win?)

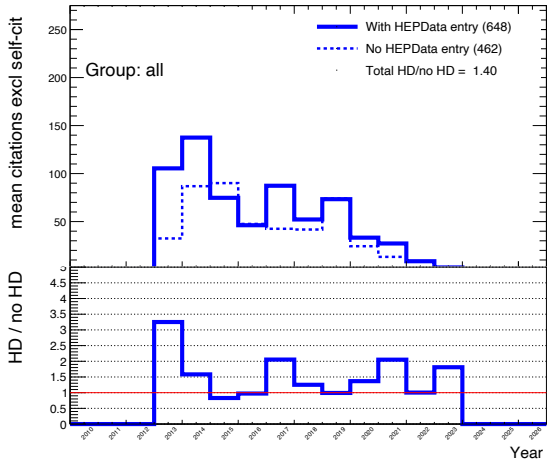
- As a result, measurements can **instantly** and **forever** be compared to latest SM predictions. **No further effort from theorists** apart from doing what they do best.
  - **Rapid feedback** to theory community

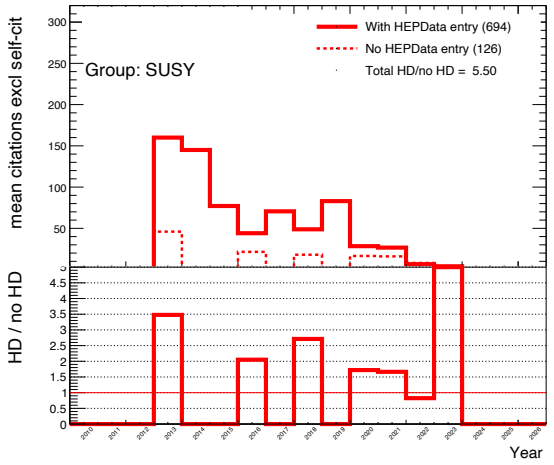
Re-interpretation *for searches*

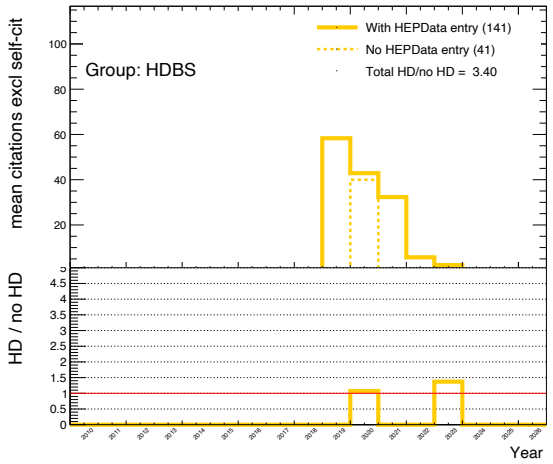
- Unfortunately, the situation is not as simple for Searches.
  - **Complex variables** and cutflows
  - **Heavy use of ML:** NNs and BDTs
  - Detector level hard for theorists: **no "blessed" ATLAS/CMS Delphes card**
  - **No validated runnable code snippets** systematically provided: theorists waste months validating their implementations, often give up.
    - Sacrificing long-term impact (=citations) of ATLAS/CMS papers.
  - A paper cannot ever really describe a **fit structure** in sufficient detail to always reproduce the results of the analysis
  - We don't always provide the right information that theorists want, and have **no mechanism to augment the re-interpretation** material after publication

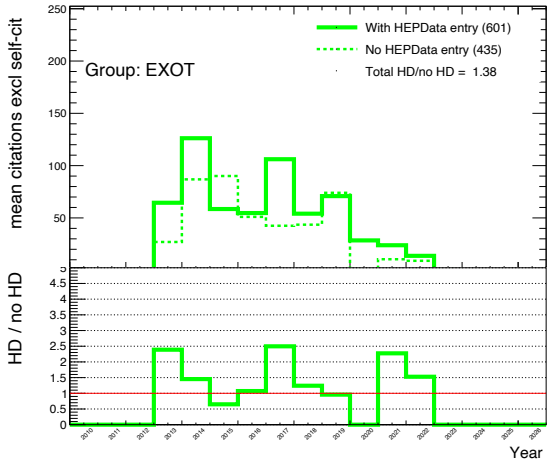
- But theorists **WANT TO USE** experimental results.

Theorists want to use experimental results... and they do when we empower them to!





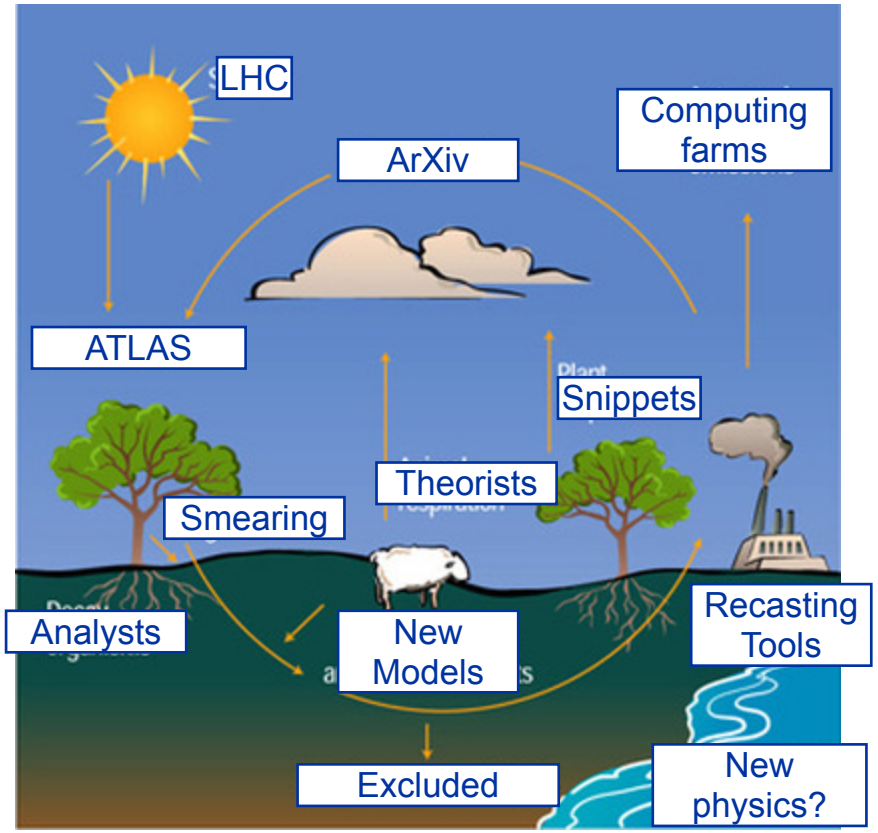


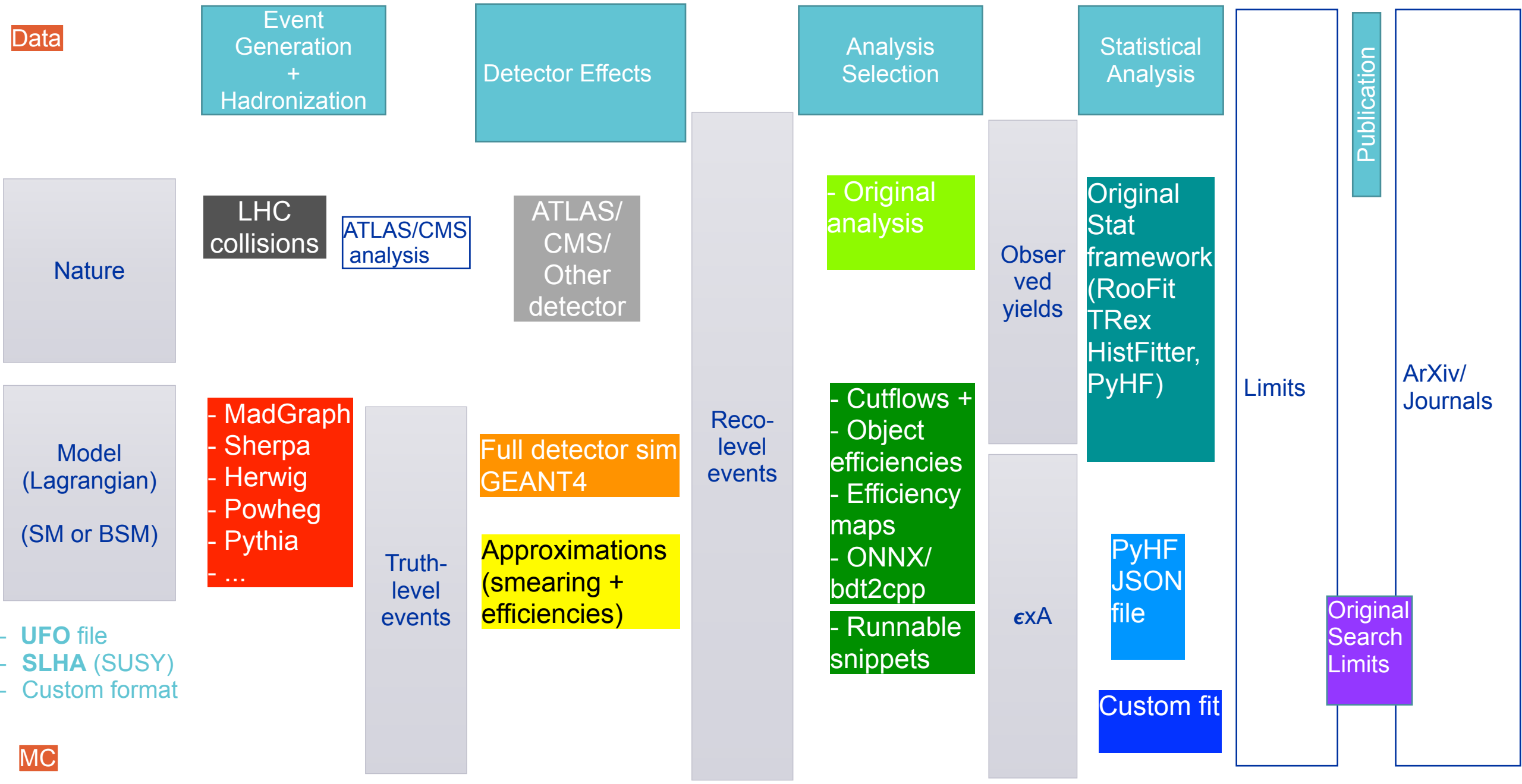


- Plots obtained by querying public information: citation numbers on inspire for all ATLAS search papers since 2013
- Separate by paper with HEPData entries versus those without
- **ATLAS Papers with HEPData were cited on average <u>40% more</u>.**

The LHC re-interpretation ecosystem

A (simplified and biased) snapshot

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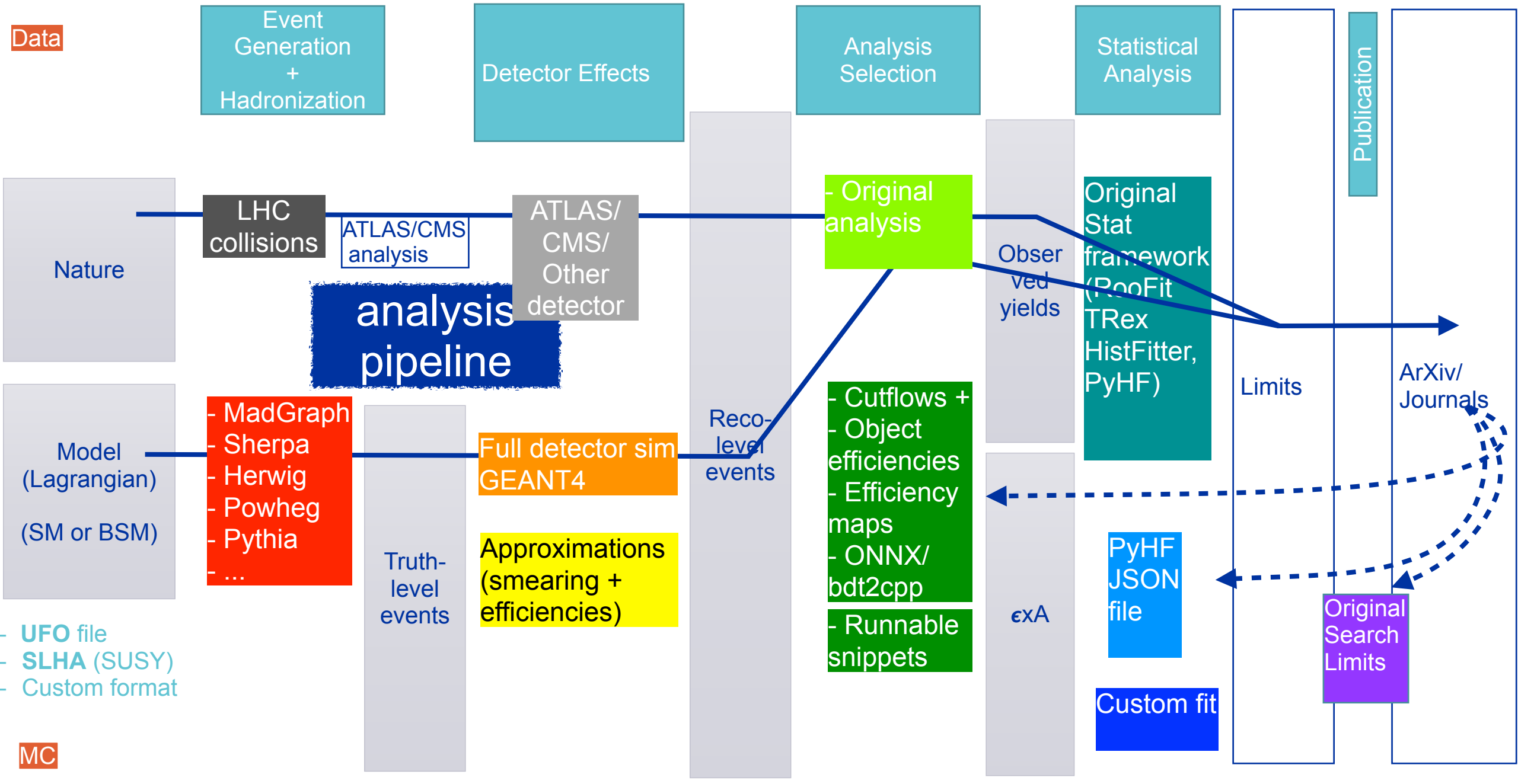
Event Generation + Hadronization
Detector Effects
Analysis Selection
Statistical Analysis
Publication
Nature
LHC collisions
ATLAS/CMS analysis
ATLAS/ CMS/ Other detector
- Original analysis
Observed yields
Original Stat framework (RooFit TRex HistFitter, PyHF)
Limits
ArXiv/ Journals
Model (Lagrangian)
(SM or BSM)
- MadGraph
- Sherpa
- Herwig
- Powheg
- Pythia
- ...
Truth-level events
Full detector sim GEANT4
Approximations (smearing + efficiencies)
Reco-level events
- Cutflows +
- Object efficiencies
- Efficiency maps
- ONNX/ bdt2cpp
- Runnable snippets
ϵxA
PyHF JSON file
Custom fit
Original Search Limits
- UFO file
- SLHA (SUSY)
- Custom format
MC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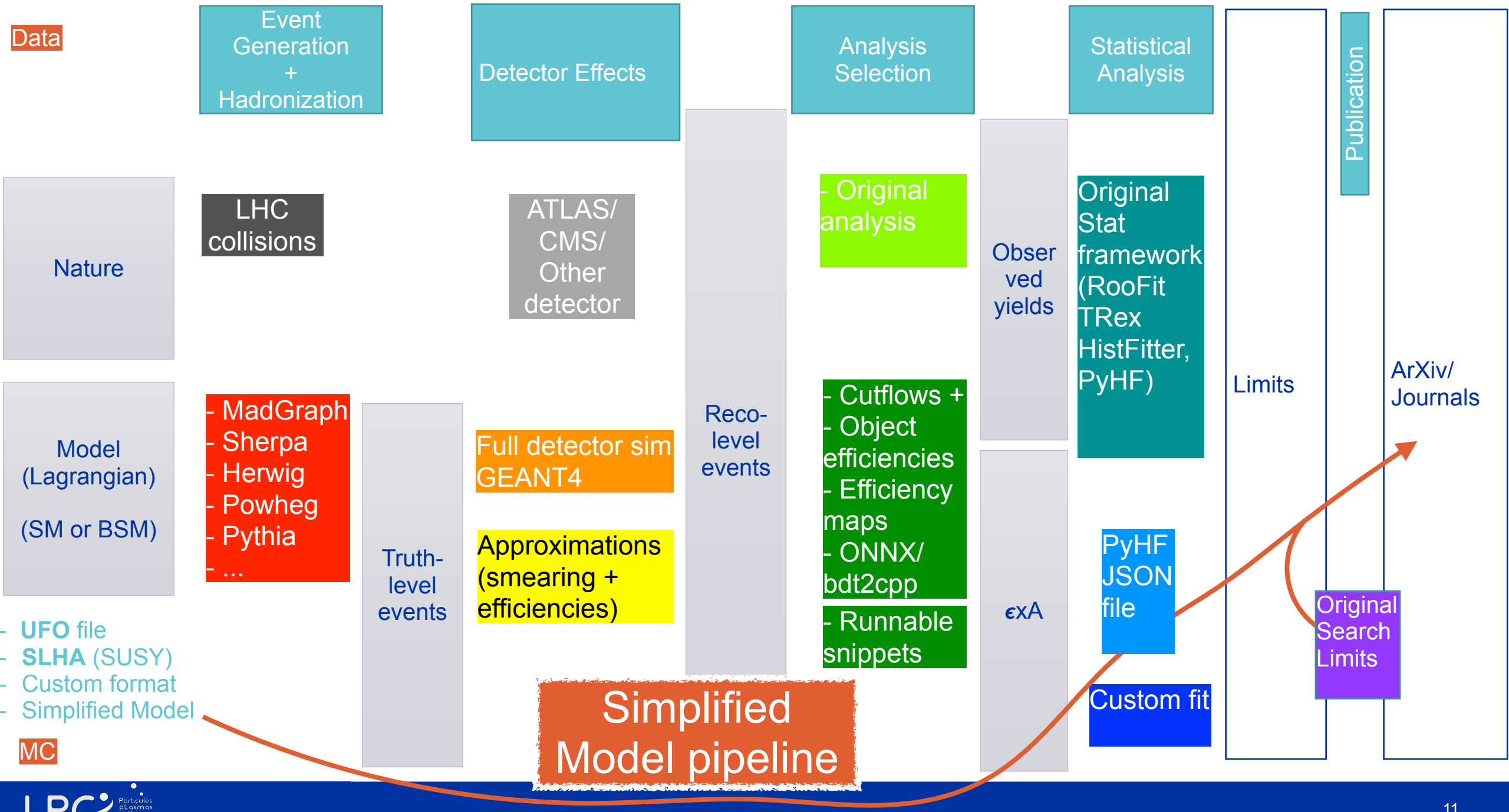
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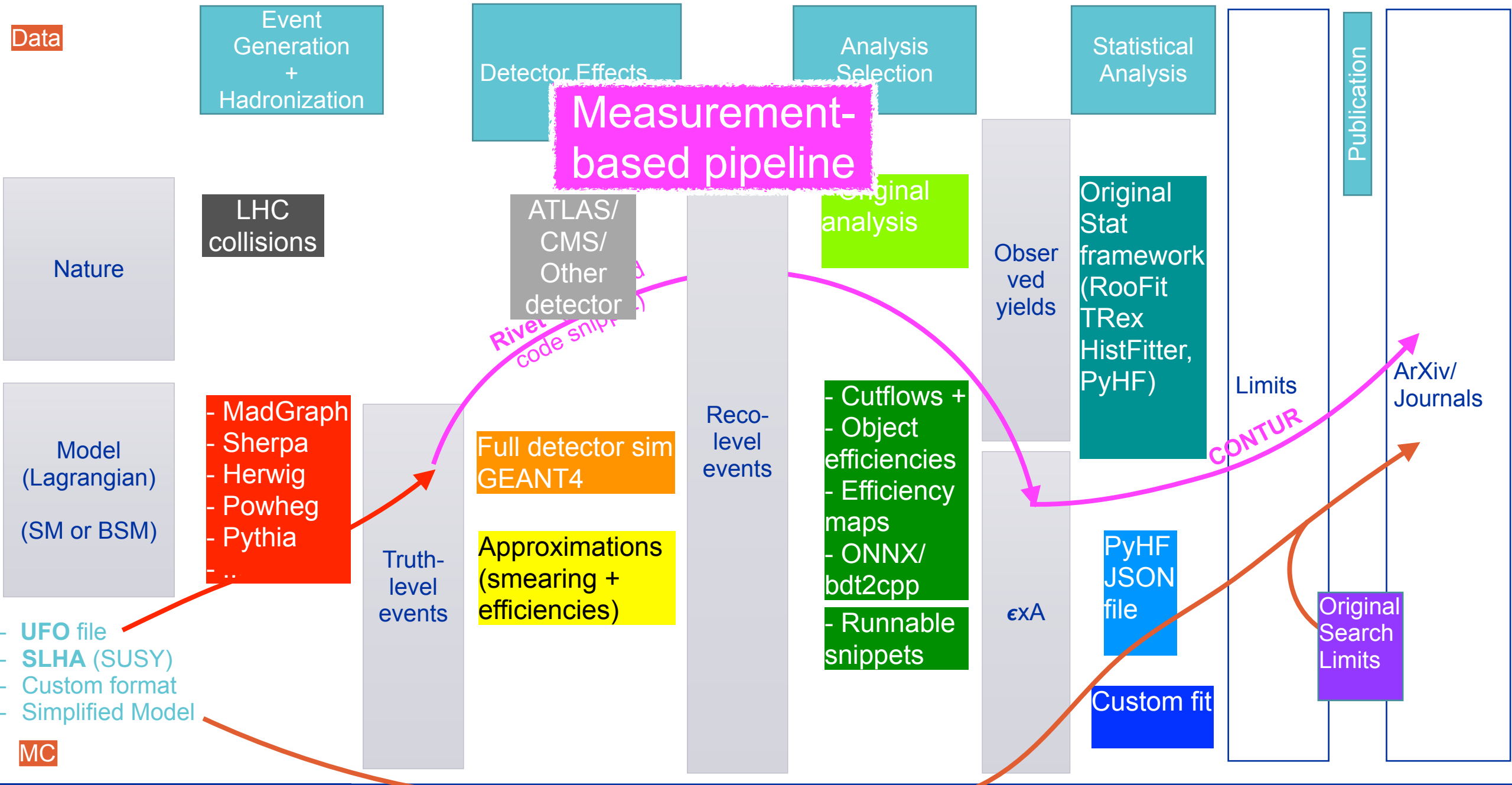
Simplified Model pipeline
SModelS, DarkCast, HiggsBounds, ZPEED, DarkEFT...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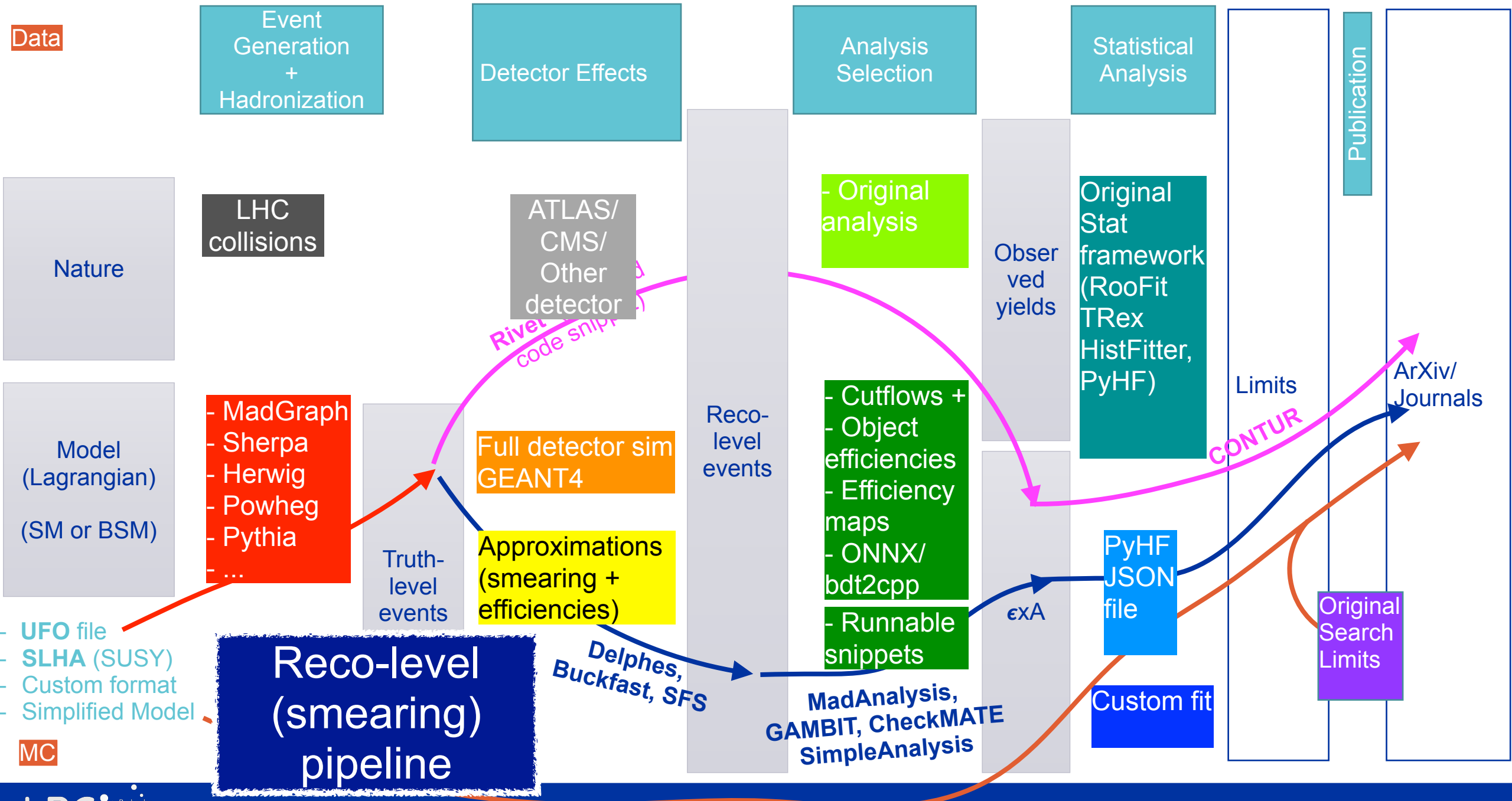
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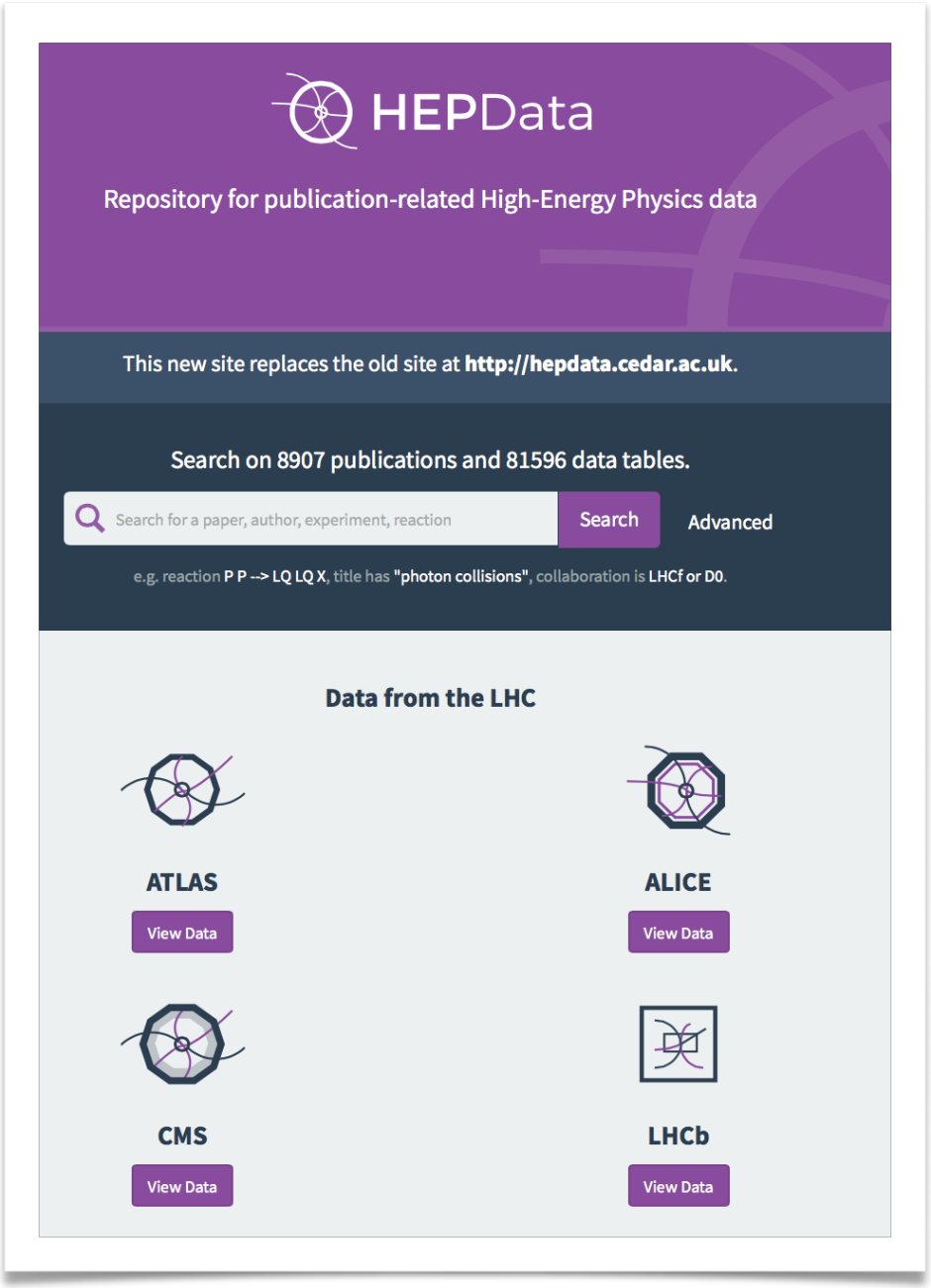
Delphes, Buckfast, SFS
MadAnalysis, GAMBIT, CheckMATE SimpleAnalysis
SModelS, DarkCast, HiggsBounds, ZPEED, DarkEFT...

What sort of information is available on HEPData?



Digitised plots for limits, yields and uncertainties

- Avoids using WebPlotDigitizer...
- Uncertainties often provided, at least stat/sys typically, but often in more detail.
- Can be downloaded as YAML, ROOT, CSV...

ATLAS Search for HH->yybb @ 13 TeV (link)

Category	High mass($m^*_{b\bar{b}\gamma\gamma}$ > 350 GeV) BDT tight						
SQRT(S)	13000 GeV						
LUMINOSITY	139 fb^{-1}						
Process	Data	HH	single H	$t\bar{t}\gamma\gamma$	$\gamma\gamma$bb	$\gamma\gamma$+other jets	Data-driven γj
$m_{\gamma\gamma}$ [GeV]	Events / 2.5 GeV						
105.0 - 107.5	3 +2.91818 -1.6327 stat	0.000023 ±0.000016 stat	0.000132 ±0.000063 stat	0.033172 ±0.013563 stat	1.601516 ±0.336797 stat	0.357747 ±0.200153 stat	0.180031 ±0.036000 stat
107.5 - 110.0	1 +2.29952 -0.827246 stat	0.000101 ±0.000033 stat	0.000075 ±0.000045 stat	0.013390 ±0.003939 stat	1.219675 ±0.289088 stat	0.370028 ±0.194770 stat	0.146073 ±0.032030 stat
110.0 - 112.5	3 +2.91818 -1.6327 stat	0.000184 ±0.000046 stat	0.000052 ±0.000036 stat	0.021150 ±0.009128 stat	1.094716 ±0.259780 stat	0.074552 ±0.052945 stat	0.107441 ±0.024361 stat
112.5 - 115.0	1e-10 +1e-10 +1e-10 stat	0.000405 ±0.000070 stat	0.000297 ±0.000103 stat	0.015468 ±0.005652 stat	0.956768 ±0.244774 stat	0.328200 ±0.160473 stat	0.118072 ±0.026894 stat

Hide Publication Information

Search for dark matter produced in association with a Higgs boson decaying to tau leptons at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS collaboration

Download All

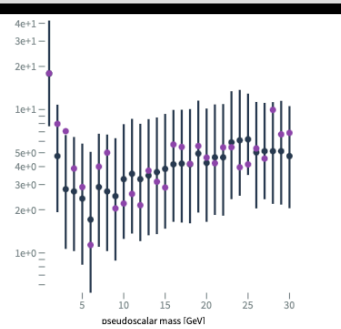
YAML with resource files
YAML
YODA
ROOT
CSV

10.17182/hepdata.140433.v1/t15

A comparison of the observed and expected yields in the four

CMS Search H->Za @ 13 TeV (link)

Limit		
SQRT(S)	13 TeV	
LUMINOSITY	138 fb^{-1}	
pseudoscalar mass [GeV]	Cross section upper limit at 95% CL [fb]	
1.0	17.889	17.822 -5.395 +9.733 1 s.d. -8.632 +21.908 2 s.d.
2.0	7.948	4.736 -1.517 +2.379 1 s.d. -2.368 +5.596 2 s.d.
3.0	7.064	2.783 -0.942 +1.465 1 s.d. -1.435 +3.572 2 s.d.
4.0	3.88	2.686 -0.909 +1.413 1 s.d. -1.385 +3.478 2 s.d.
5.0	2.879	2.393 -0.859 +1.258 1 s.d. -1.309 +3.155 2 s.d.
6.0	1.136	1.709 -0.648 +1.281 1 s.d. -0.988 +3.108 2 s.d.
7.0	3.997	2.881 -0.975 +1.516 1 s.d. -1.486 +3.595 2 s.d.

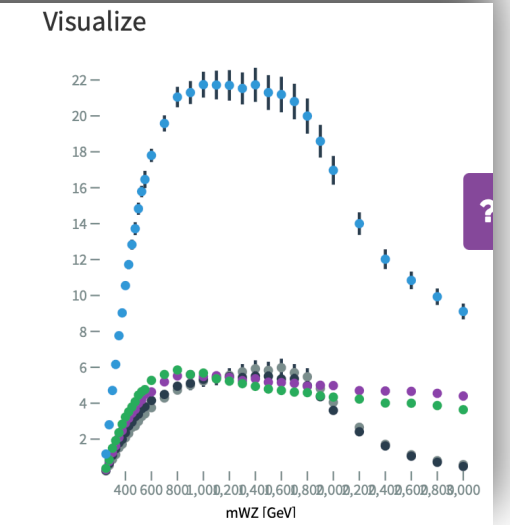


Efficiencies

- Many analysis provide efficiency maps
- In terms of various kinematic quantities
- Can help you select if you alternative model objects would pass an object or event selection, for re-interpretation purposes

ATLAS Search for resonant WZ-L>lvll (link)

mWZ [GeV]	all [%]	mmm [%]	mme [%]	eem [%
250	1.17 ±0.06 stat+syst	0.37 ±0.03 stat+syst	0.31 ±0.02 stat+syst	0.27 ±0.03 stat+sys
275	2.80 ±0.12 stat+syst	0.85 ±0.05 stat+syst	0.76 ±0.04 stat+syst	0.64 ±0.06 stat+sys
300	4.71 ±0.13 stat+syst	1.49 ±0.06 stat+syst	1.25 ±0.05 stat+syst	1.10 ±0.06 stat+sys
325	6.16 ±0.24 stat+syst	1.92 ±0.11 stat+syst	1.63 ±0.06 stat+syst	1.46 ±0.06 stat+sys



Likelihoods

13 TeV DM + H->tau tau (link): Likelihood available

- Serialised likelihoods for use with pyHF fitting framework
- Allows you to replicate exactly the fit structure (hard to describe accurately in a paper!)
- Typically a bkg-only fit structure and a set of signals to inject.


```
"channels": [
    {
        "name": "CR_Gbb_B_cuts",
        "samples": [
            {
                "data": [
                    1.5325825214385986
                ],
                "modifiers": [
                    {
                        "data": {
                            "hi": 1.00544,
                            "lo": 1.0
                        },
                        "name": "EG_reso",
                        "type": "normsys"
                    },
                    {
                        "data": {
                            "hi": 0.999999,
                            "lo": 1.02783
                        },
                        "name": "EG_scale",
                        "type": "normsys"
                    },
                    {
                        "data": {
                            "hi": 0.992028,
                            "lo": 1.00797
                        },
                        "name": "ELEC_ChargeID",
                        "type": "normsys"
                    },
                    {
                        "data": {
                            "hi": 0.999439,
                            "lo": 0.984617
                        },
                        "name": "ELEC_ID",
                        "type": "normsys"
                    },
                    {
                        "data": {
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                        },
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                        "type": "normsys"
                    }
```
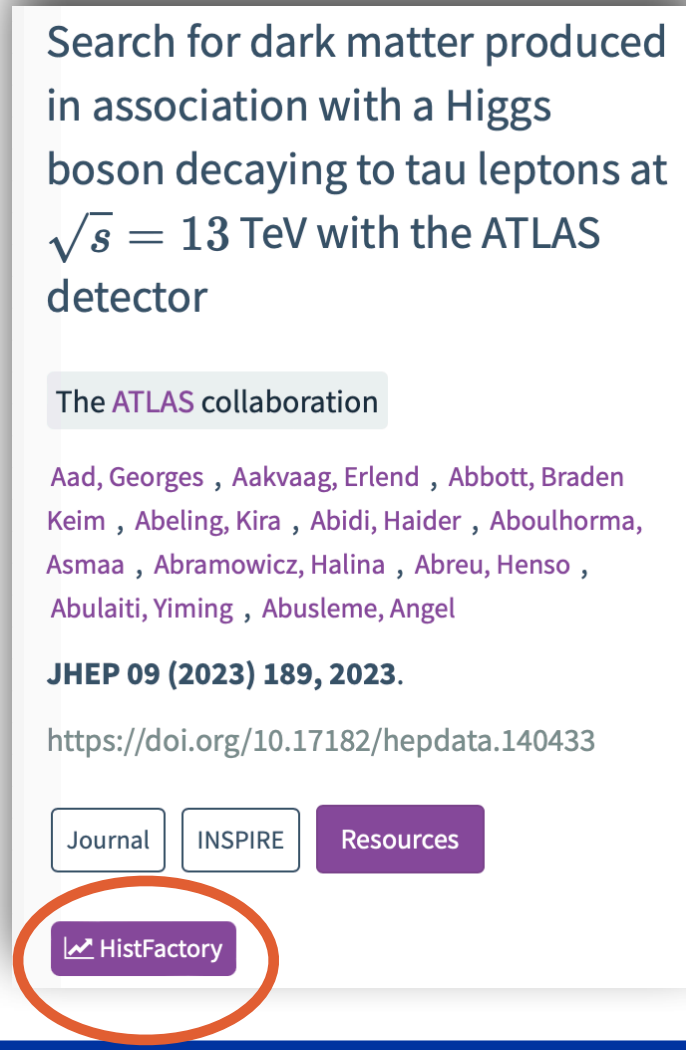




Cutflows and MC generation cards

- HEPData records often contain cutflows for well-defined signals, often with the corresponding instructions to generate THAT signal (eg SLHA, UFO files)

- Helps to validate your implementations of the selections

ATLAS 13TeV VBF H->inv (link)

Requirement	VBF Events	VBF Efficiency	VBF Efficiency w.r.t. last step	ggF Events	ggF Efficiency	ggF Efficiency w.r.t. last step
$\sigma \cdot L_{int}$	523500	1	1	6752600	1	1
Higgs boson $p_T > 75$ GeV	268000	0.51	0.51	268000	0.040	0.040
j1/j2: $p_T > 50/40$ GeV, $\Delta\eta_{jj} > 2$	47600	0.091	0.18	25900	0.0038	0.097
MET trigger	34100	0.065	0.72	17280	0.0026	0.67
Jet cleaning	33200	0.064	0.97	17020	0.0025	0.98
Signal lepton veto	33100	0.063	1.00	16850	0.0025	0.99
$N_{photon} = 0$	33000	0.063	1.00	16730	0.0025	0.99
$N_{jet} < 5$	31700	0.061	0.96	13660	0.0020	0.82
$C_i < 0.6$ for $2 < N_{jet} < 5$	28700	0.055	0.91	9300	0.0014	0.68
$m_i^{rel} < 0.05$ for $2 < N_{jet} < 5$	22800	0.044	0.79	5430	0.00080	0.58

Code Snippets

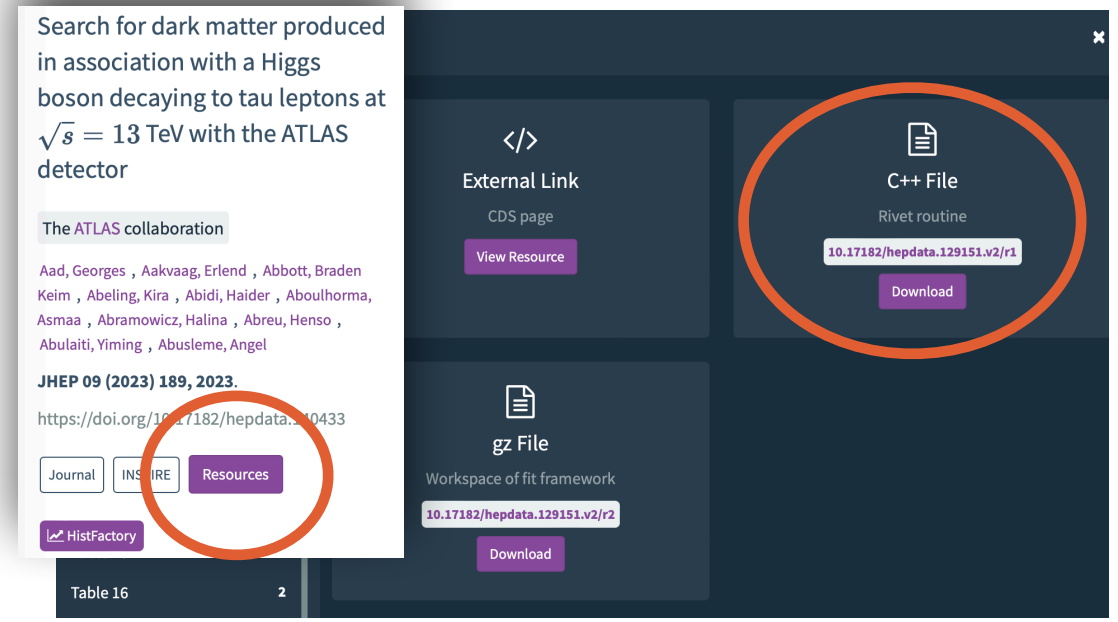
- Better than replicating a selection, is to provide runnable code snippet !

- Many ATLAS Searches do this with SimpleAnalysis. Measurements can do this in Rivet (could be done more broadly for Higgs measurements)

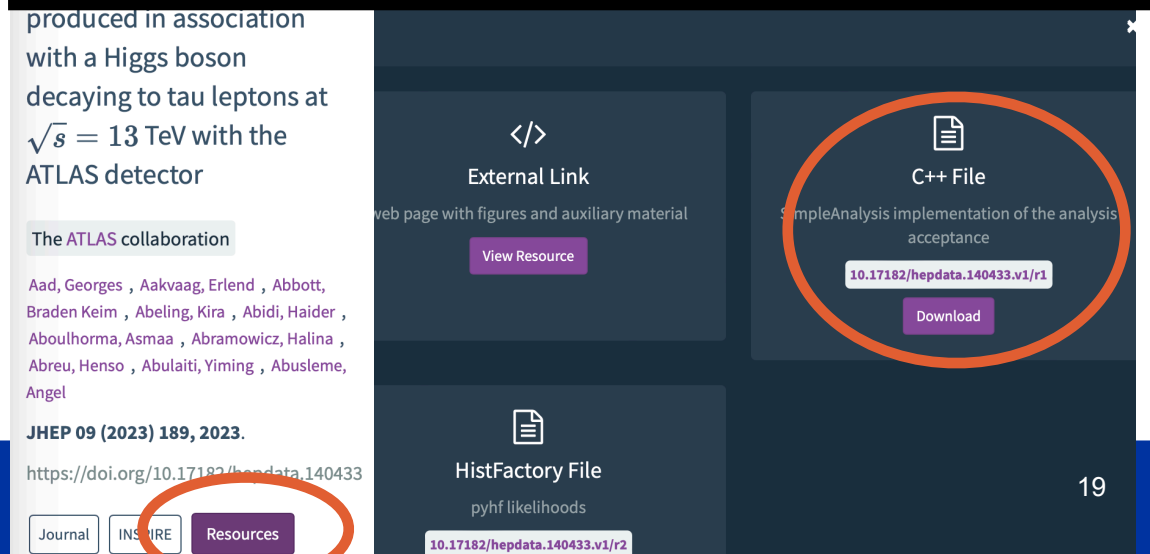
- SimpleAnalysis -> used to be "pseudo-code", but now runnable since recently.
  -> https://simpleanalysis.docs.cern.ch/
  -> https://cds.cern.ch/record/2805991

- Actually run the selection! only thing missing is smearing of truth->reco level quantities

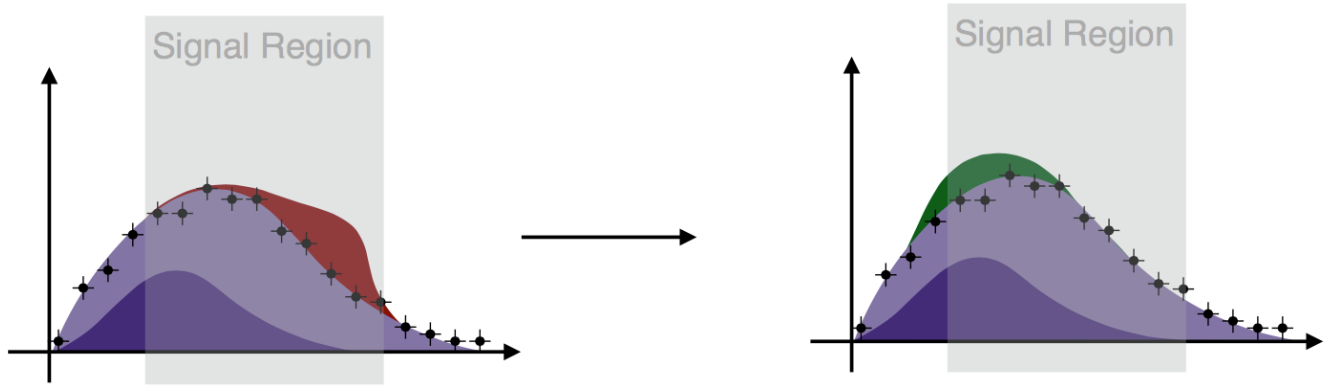
RIVET: ATLAS Search for resonant WZ-L>lvll (link)



SimpleAnalysis: ATLAS 13 TeV DM + H->tau tau (link):



Nice example of search re-interpretations

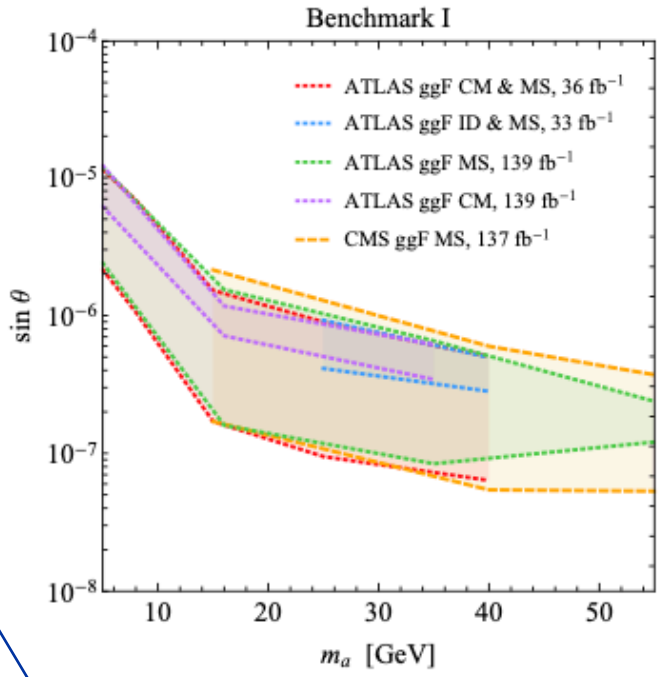


A few examples of nice recasted results!

Simplified model results

2302.02735 -> Recast LLP searches to 2HDM+a
(same final states/kinematics, no event gen needed!)

Makes use of:
- expected/observed limits
- paper information about benchmark model used
- Embeds simplified model in wider model



Citations!

Figure 2. 95% CL exclusion regions in the $m_a - \sin\theta$ plane for the 2HDM+a benchmark I scenario (3.3). The dotted red, blue, green and purple lines correspond to the limits following from the ATLAS searches [33, 34], [35], [43] and [44], respectively. The dashed yellow curves instead represent the bound that arises from the CMS search [38]. The parameter space between the lines is disfavoured. See main text for further details.

A few examples of nice recasted results!

Simplified model results

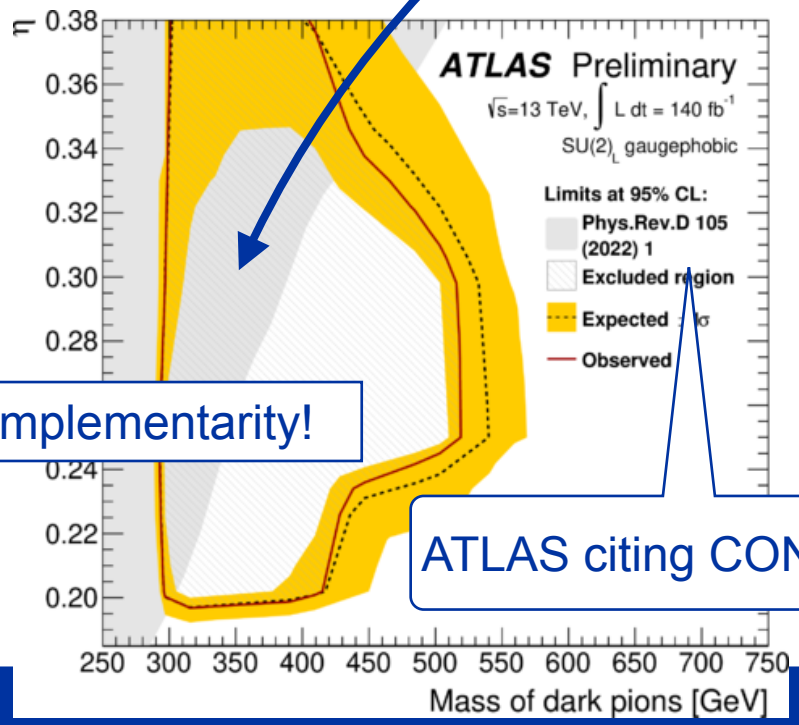
Measurement-based pipeline

2105.08494 -> CONTUR exploiting Rivet of SM measurements, control-region measurements (and some searches) to search for dark mesons

Makes use of:
- Truth-level rivet routines (runnable code snippets)
- Published differential cross-sections
- Published MC predictions for those cross-sections (important!)

*Full disclosure: I am co-author of this CONTUR paper

ATLAS-CONF-2023-021



Complementarity!

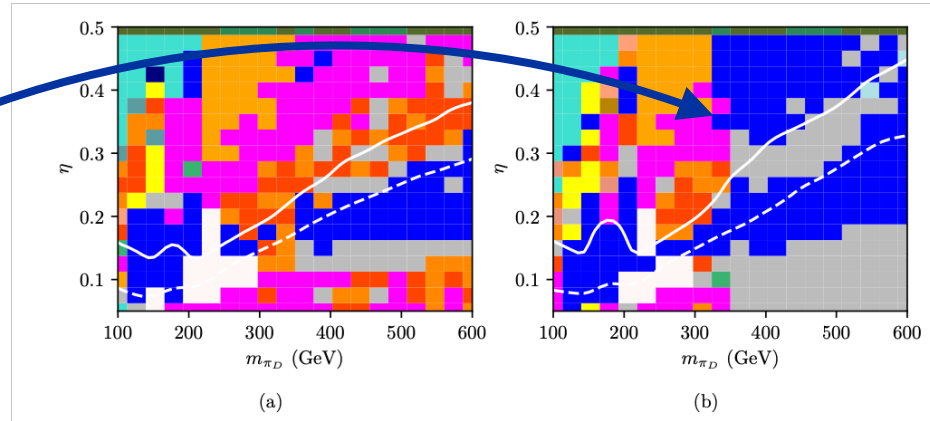


FIG. 5: Scans in $\eta - m_{\pi_D}$ for two sub-models, focussing on the $\eta < 0.5$ region and excluding the ATLAS dilepton search. (a) Gaugephilic $SU(2)_L$, (b) Gaugephobic $SU(2)_L$ The colours indicate the dominant signature pool giving the sensitivity. The white solid line is the 95% exclusion and the white dashed line is the 68% exclusion.

CMS ee+jet | CMS $\mu\mu$+jet | ATLAS ee+jet
ATLAS $\ell\ell$+jet | ATLAS $\mu\mu$+jet | ATLAS $\ell+E_T^{\text{miss}}$+jet
ATLAS $\mu+E_T^{\text{miss}}$+jet | ATLAS $e+E_T^{\text{miss}}$+jet | CMS $\ell+E_T^{\text{miss}}$+jet
ATLAS Hadronic $t\bar{t}$ | ATLAS $\ell_1\ell_2+E_T^{\text{miss}}$+jet | ATLAS high-mass DY $\ell\ell$
CMS high-mass DY $\ell\ell$ | ATLAS 4ℓ | ATLAS γ
ATLAS $\ell\ell\gamma$ | ATLAS $\gamma+E_T^{\text{miss}}$ | ATLAS jets

ATLAS citing CONTUR

CONTUR citing ATLAS

A few examples of nice recasted results!

Simplified model results

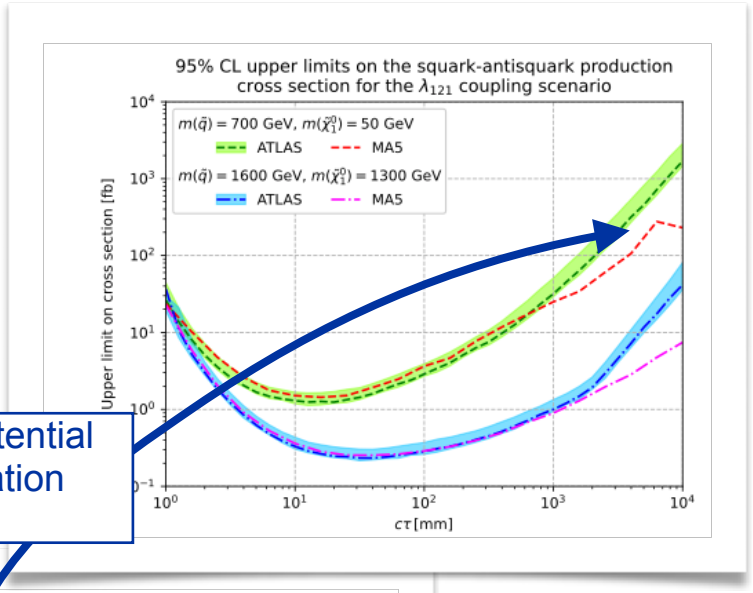
Measurement-based pipeline

Reco-level smearing pipeline

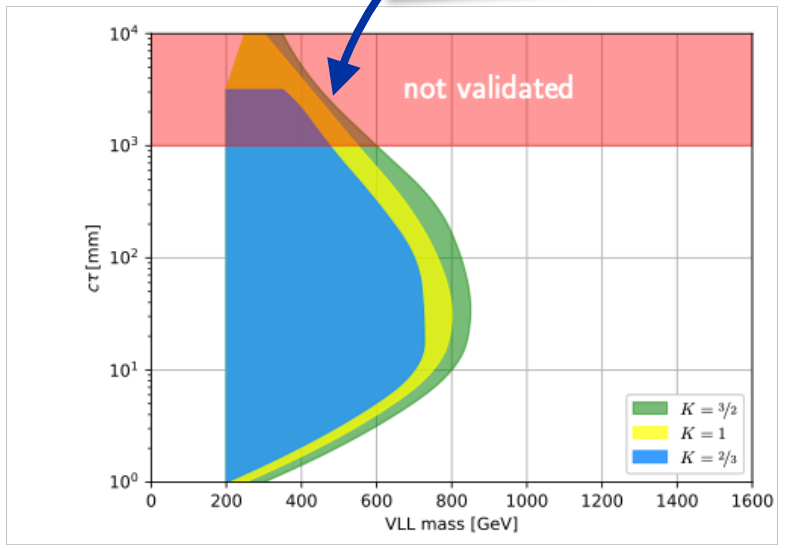
2112.05163 -> MadAnalysis 5 uses SUSY-2017-04 to set limits on long-lived vector-like leptons

Makes use of:
- Cutflows and benchmark model descriptions to write+validate runnable code snippet
- Per-object efficiency maps

This step could be made MUCH with SimpleAnalysis (but with smearing functions!)
(SA <-> MadAnalysis converter?)



Issues with validation: potential problem with re-interpretation material (or analysis?)



One last thing: summary of the most recent Re-interpretation Forum workshop

(Re)interpretation of the LHC results for new physics

29 August 2023 to 1 September 2023
Durham University
Europe/London timezone

Enter your search term

- Overview
- Registration
- Call for Abstracts
- Timetable
- Code of Conduct
- Contribution List
- Participant List
- Practical Information
  - Travel to Durham
  - Accommodation
  - Internet & Wi-Fi Access

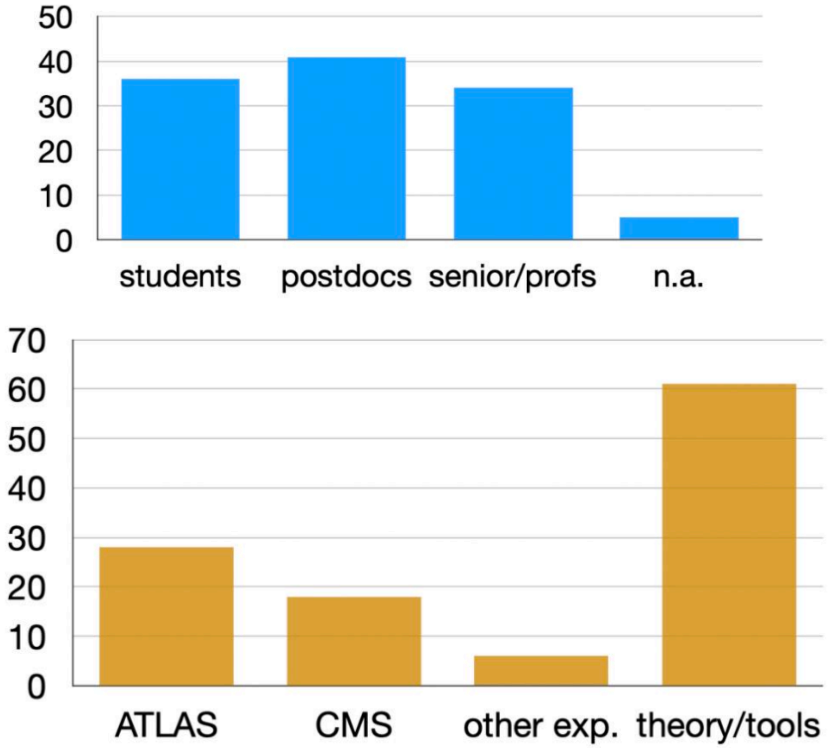
Local Organisers' Contact Info

jack.araz@durham.ac.uk
michael.spannowsky@d...

***** A national train strike on Friday, Sep 1, risks to make travel from the workshop exceedingly difficult! We're therefore trying to adapt the workshop program, accommodating the Friday talks on Wed/Thu instead. Please regularly check the timetable for short-notice updates. *****

This is the 8th general workshop of the "Forum on the interpretation of the LHC results for BSM studies", or LHC Reinterpretation Forum (RIF) for short. It aims to review new developments on the tools, phenomenology, and experimental sides and to prepare for the Run 3 results of the LHC. In this context, the major topics of this workshop will be:

https://conference.ippp.dur.ac.uk/event/1178/



Summary thanks to Luzhan (Tony) Yue!

One last thing: summary of the most recent Re-interpretation Forum workshop

- **Software and Tools**: updates from GAMBIT, CONTUR, CheckMATE, SModels, Mapyde (New! **Ma**dgraph+**Py**thia+**De**lphes) teams, and others.

- **HEPdata updates:** Bidirectional linking: allows theory predictions to be linked to the records which use them, and vice versa

- **Shareability** of stat and ML models: eg new tool spey, a hub of various likelihood implementations for hypothesis testing

- **PDFs:** updates on latest challenges and prospects of using LHC data

- **Re-interpretations:** Updates on various recasting projects which make use of published searches and measurements. (W mass, MSSM,...)

Summary thanks to Luzhan (Tony) Yue!

Summary

- **Analysis Preservation** is an important part of the analysis lifecyle:
  - Analyses with HEPData entries have **>40% more citations on average**.

- There is a buzzing **ecosystem of re-interpretation**:
  - Theorists are desperate to use experimental results if they can !
  - Experiments can make their life easier by **providing complete and validated** material (+ avoid them making mistakes / using WebPlotDigitizer to scrape values)
  - Good re-interpretation material mens more impactful results in the long run
  - Lots of types of re-interpretation

- Experiments do put **plenty of information on HEPData**, ready to exploit!
  - Sometimes you may find there is info missing to allow an accurate re-interpretation : it's important to let the collaborations know if that's the case, to try to do better next time
  - Not always possible to fix things post-hoc (people move on...)

- Possible "**easy win**": include **STXS results from Higgs in Rivet routines**, so they can be more easily/automatically exploited in the "measurement based pipeline"?

BACKUP

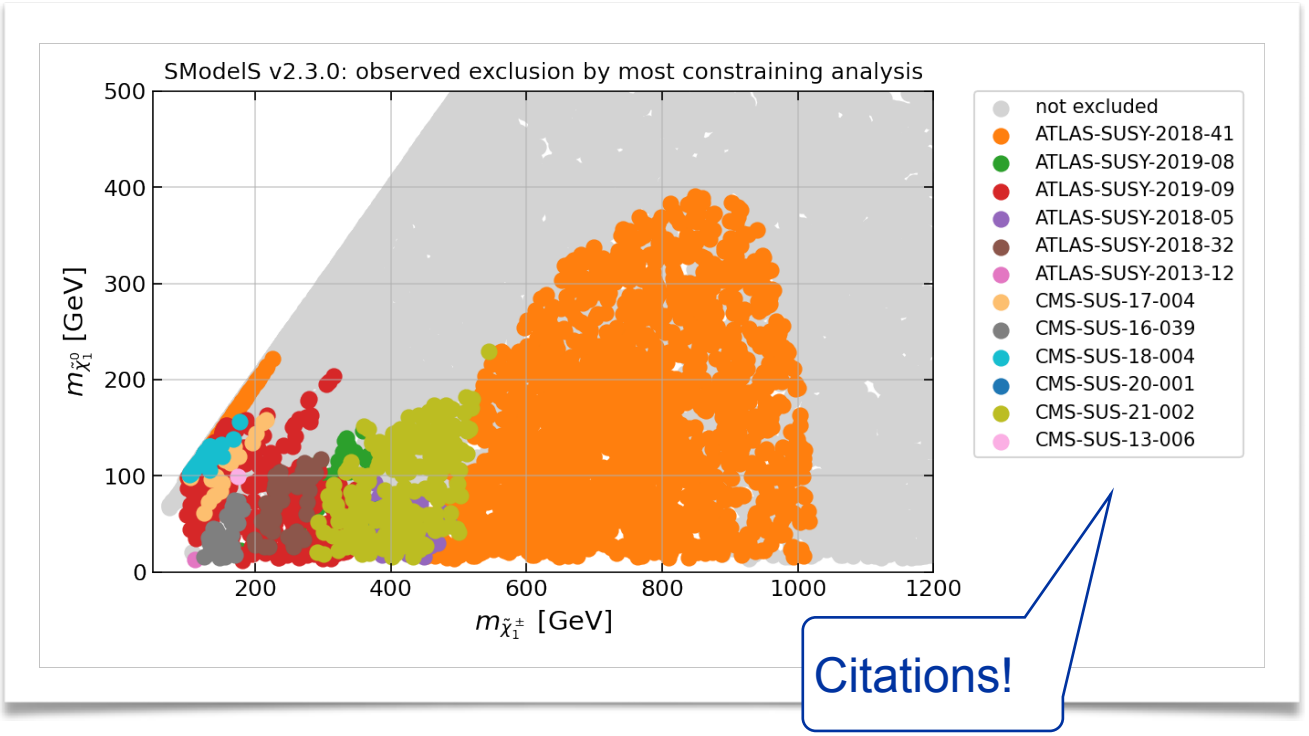
A few examples of nice recasted results!

Simplified model results

2302.02735 -> Recast LLP searches to 2HDM+a (same final states/kinematics, no event gen needed!)

2306.17676 -> SModelS ML-assisted search of Z_2-symmetry model-space. Uses efficiency maps and preserved pyHF likelihoods

Makes use of:
- Published limits in ATLAS papers
- Per-object efficiency maps as a function of kinematics
- Pyhf likelihoods to repeat the fits



A few examples of nice recasted results!

Simplified model results

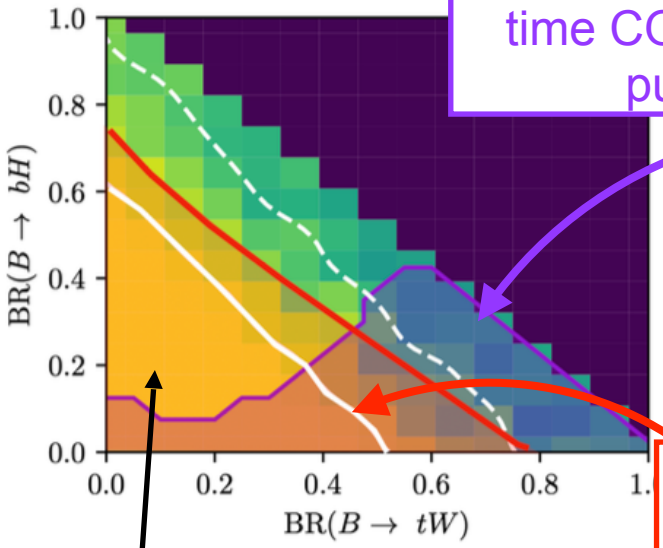
Measurement-based pipeline

2105.08494 -> CONTUR exploiting Rivet of SM measurements, control-region measurements (an some searches) to search for dark mesons

2006.07172 -> CONTUR exploiting Rivet to exclude VLQ regions complementary to ATLAS

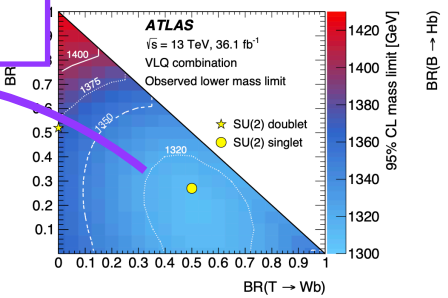
Makes use of:
- Truth-level rivet routines (runnable code snippets)
- Published differential cross-sections
- Published MC predictions for those cross-sections (important!)

*Full disclosure: I am co-author of this CONTUR paper



ATLAS exclusion at the time CONTUR paper published

1808.02343

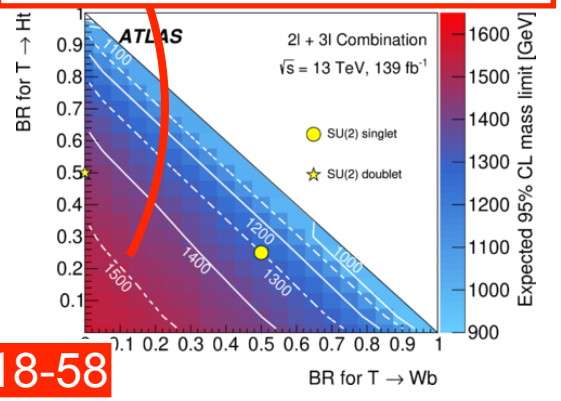


(a)

Figure 4: Observed lower limits at 95% CL on the mass of … $\mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}($… for the SU(2) singlet and … LQ mass [8].

CONTUR sensitivity comes mainly from Z+jets measurements !

Only superseded O(2) years later by ATLAS direct search



EXOT-2018-58

Some regions also excluded by Control-Region measurements from 2019 LQ search!

A few examples of nice recasted results!

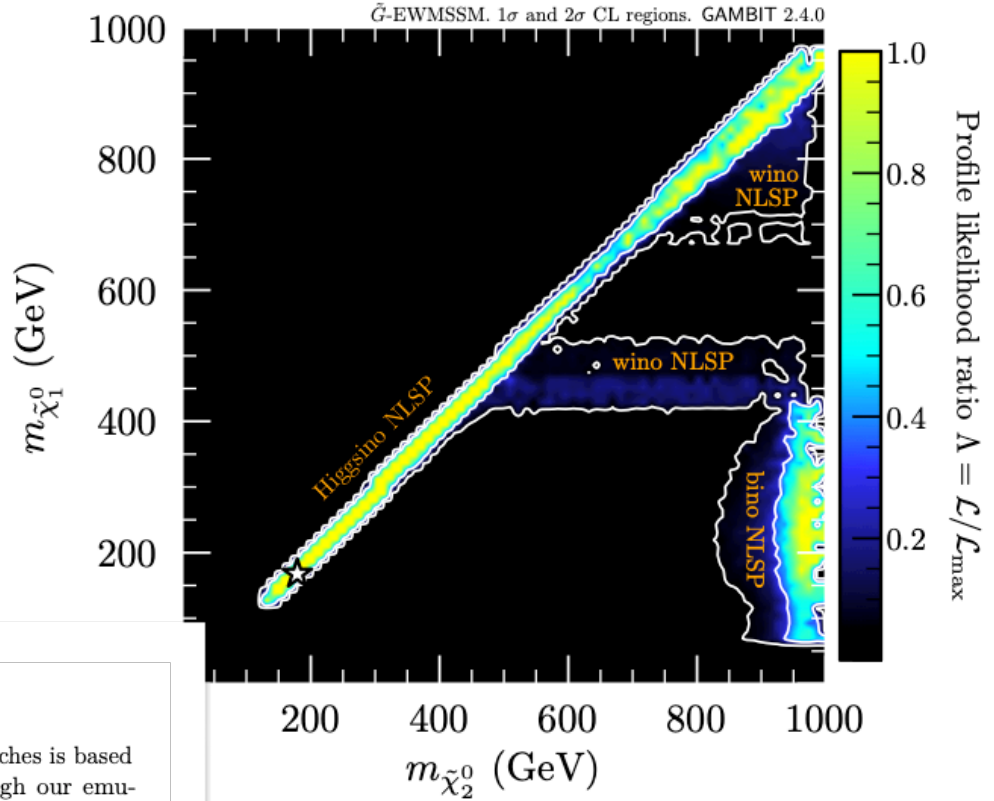
Simplified model results

Measurement-based pipeline

Reco-level smearing pipeline

2112.05163 -> MadAnalysis 5 uses SUSY-2017-04 to set limits on long-lived vector-like leptons

2303.09082 -> GAMBIT uses 15 ATLAS searches from SUSY+EXOT+HDBS (+12 CMS) + CONTUR database to explore MSSM with eV-scale gravitino



3.1 LHC searches

The likelihood contribution from LHC searches is based on passing simulated signal events through our emulations of the 13 TeV ATLAS and CMS searches in Refs. [100–126]. Reproducing a collider search to sufficient accuracy can be challenging, e.g. due to limited available information about technical details of the analysis, or due to limitations in the tool-chain used for fast event simulation. In some cases we can therefore only

Makes use of:
- Cutflows and benchmark model descriptions to write+validate runnable code snippet
- Per-object efficiency maps