Search Re-interpretation: How and Why in Collider Physics

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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 Search results **unlikely to be superceded** until well into HL-LHC. In some cases, **not be superceded within span of the careers or lifetimes** of the current collaboration members!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.

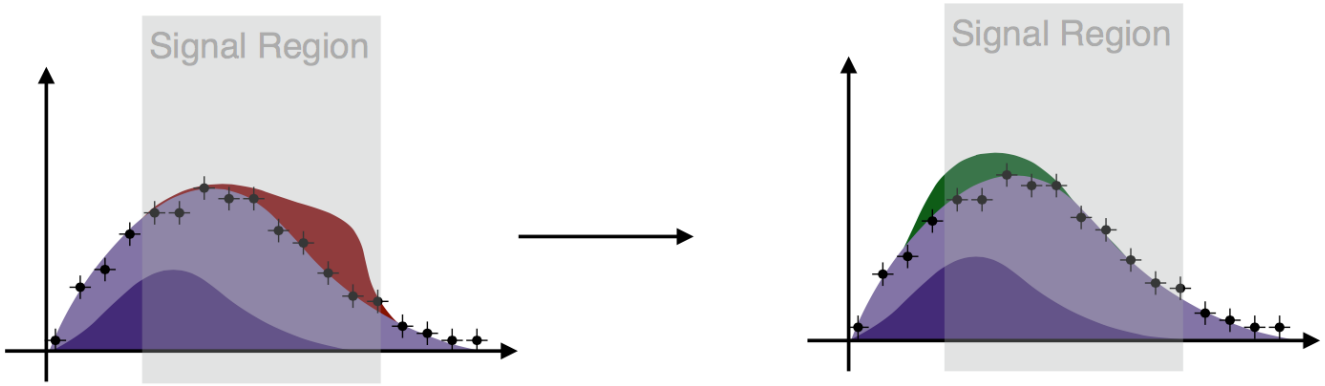
- **Single-use results are not impactful** in long-term. Want easy **re-interpretability** to facilitate long-term impact.

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 **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

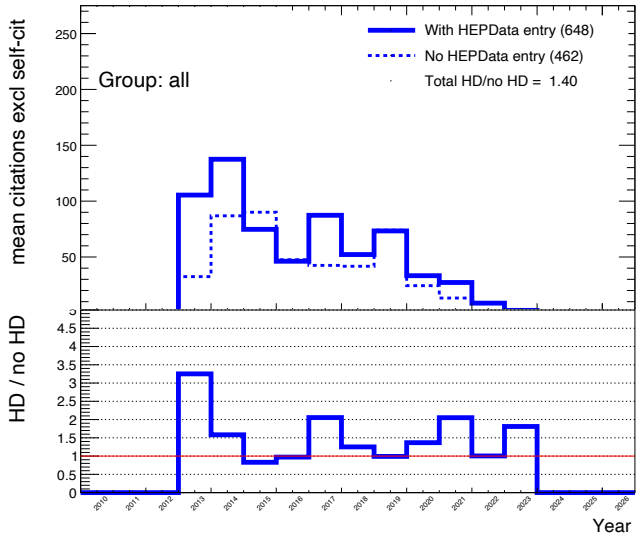
- As a result, measurements can **instantly** and **forever** be compared to latest SM predictions. **No further effort from theorists** apart from doing what they do best.
  - **Rapid feedback** to theory community

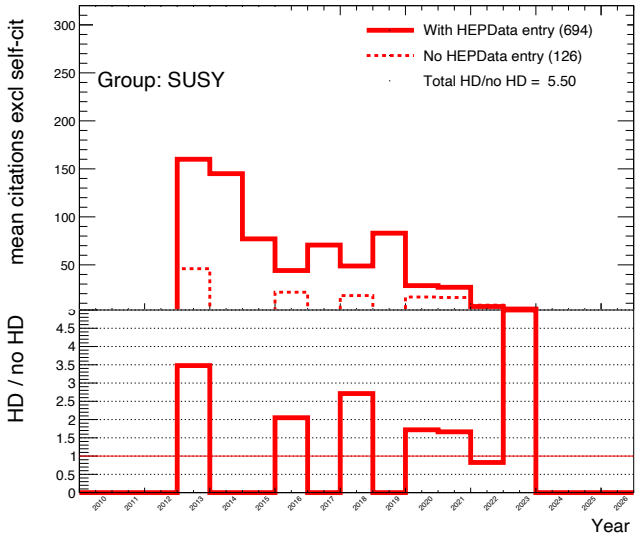
Re-interpretation *for searches*

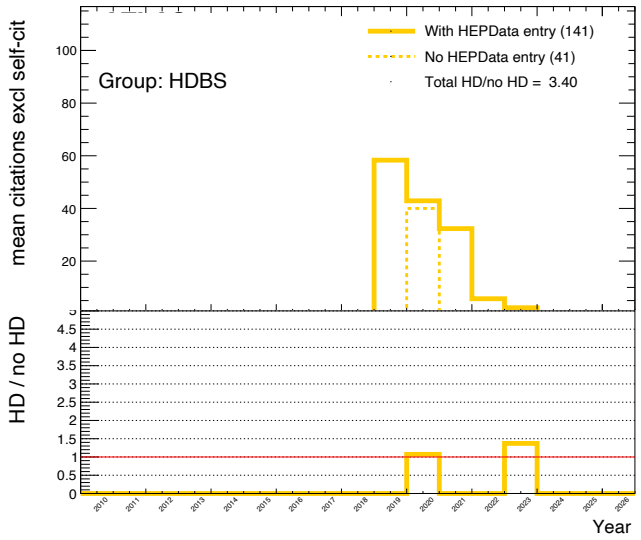
- Unfortunately, the situation is not as simple for Searches.
  - **Complex variables** and cutflows
  - **Heavy use of ML:** NNs and BDTs
  - Detector level hard for theorists: **no "blessed" ATLAS/CMS Delphes card**
  - **No validated runnable code snippets** systematically provided: theorists waste 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

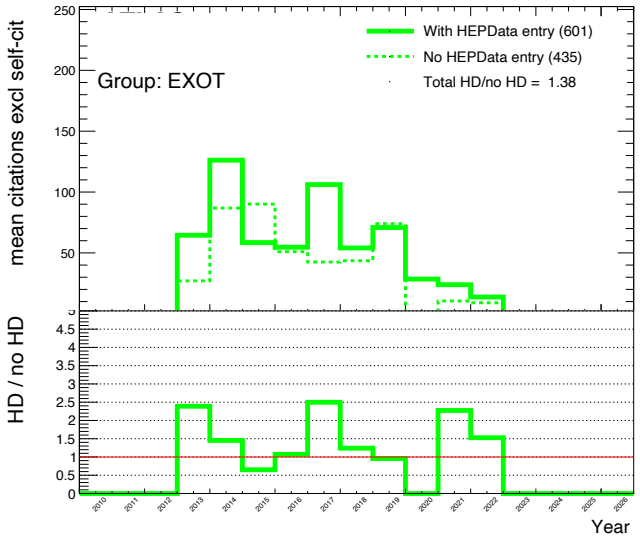
- But theorists **WANT TO USE** experimental results.

Theorists want to use our results... and they do!





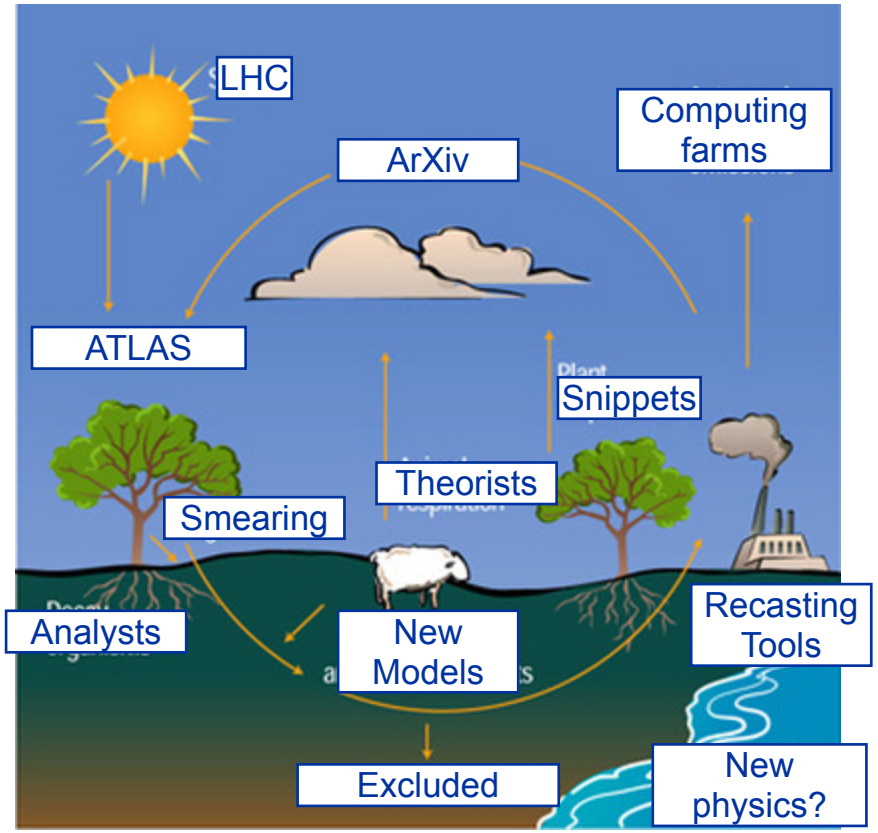


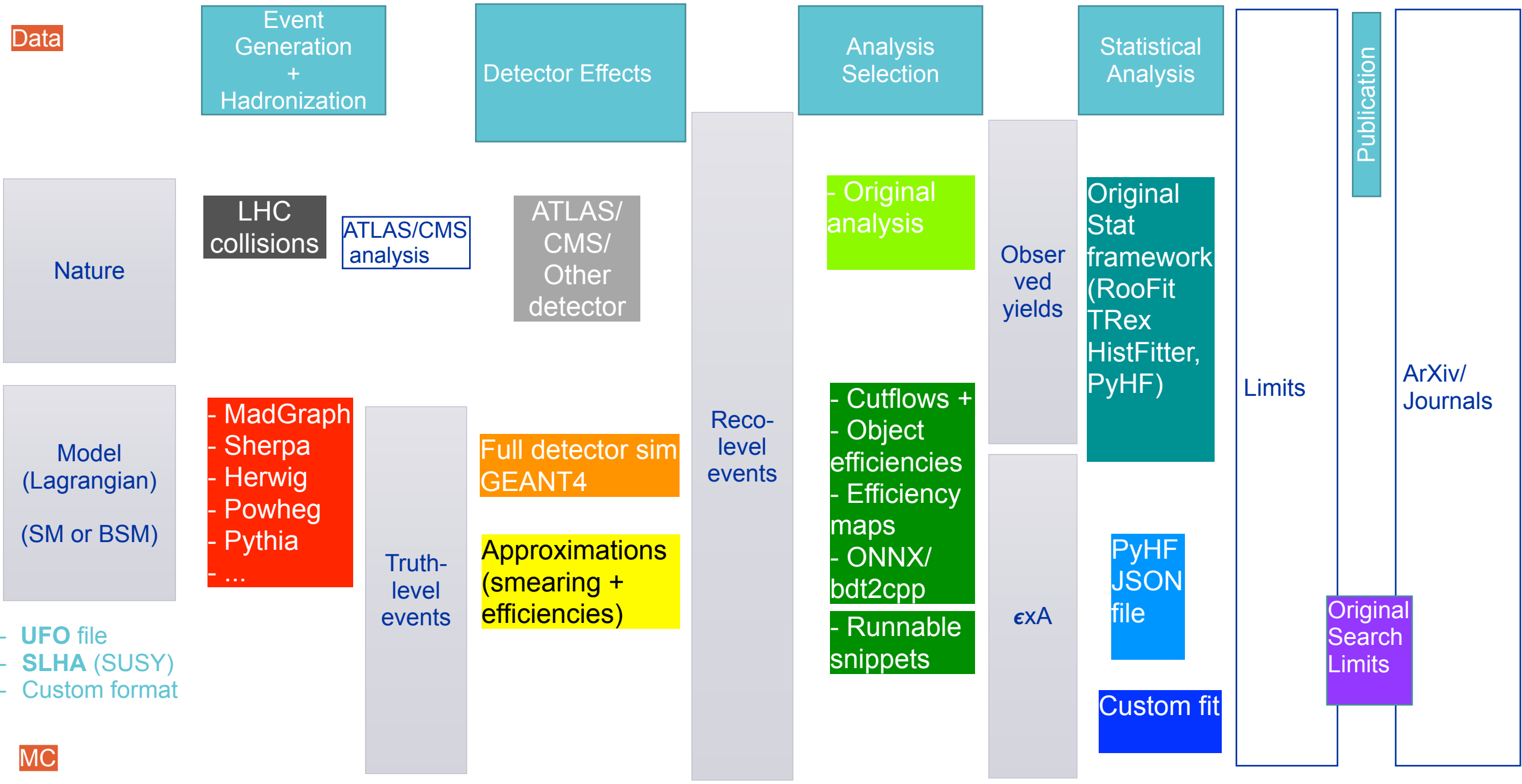


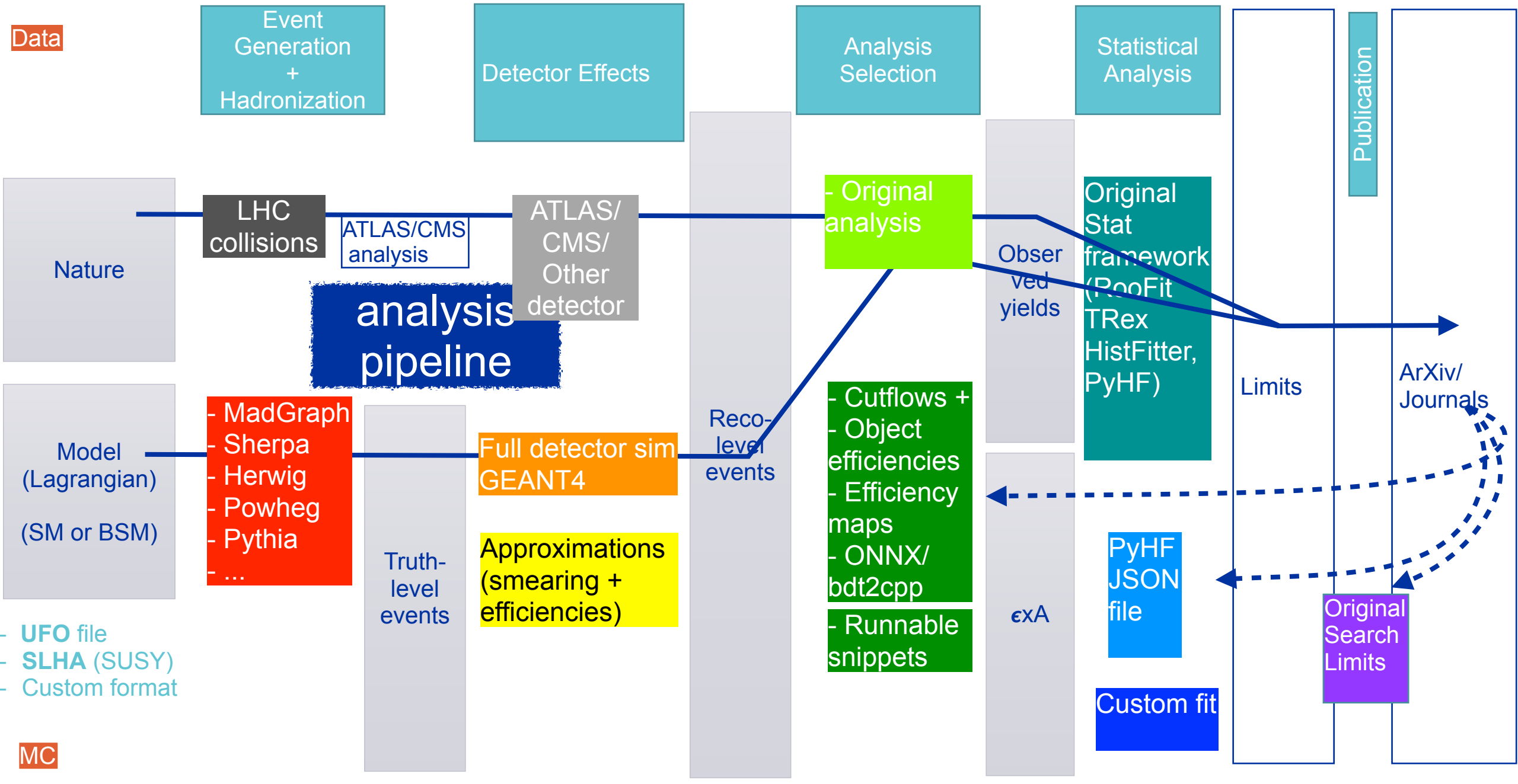
- Plots obtained by querying citation numbers on inspire for all ATLAS search papers since 2013
- Separate by paper with HEPData entries versus those without
- **ATLAS Papers with HEPData were cited on average <u>40% more</u>.**

The LHC re-interpretation ecosystem

A (simplified and biased) snapshot




Data
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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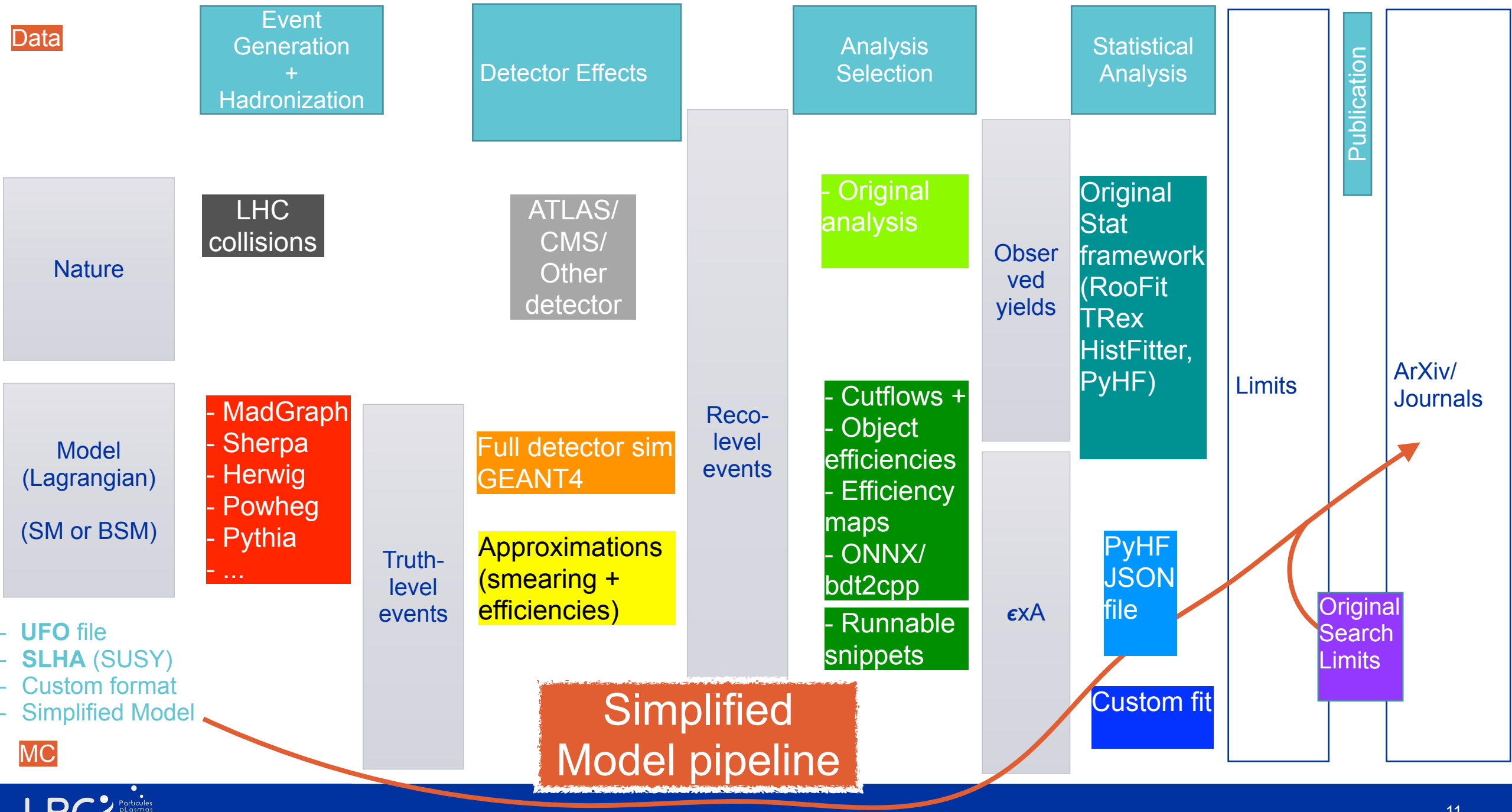
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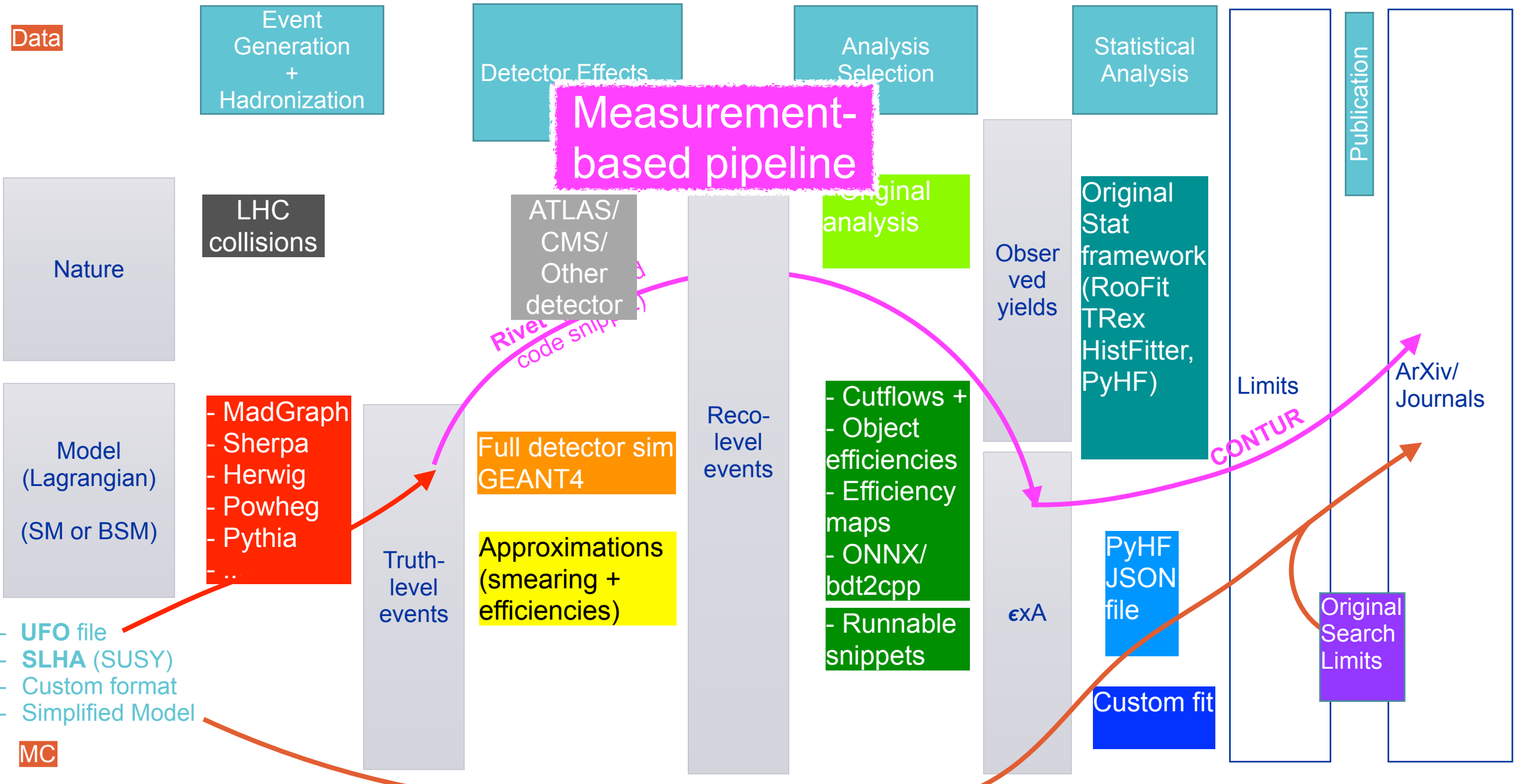
Simplified Model pipeline
SModelS, DarkCast, HiggsBounds, ZPEED, DarkEFT...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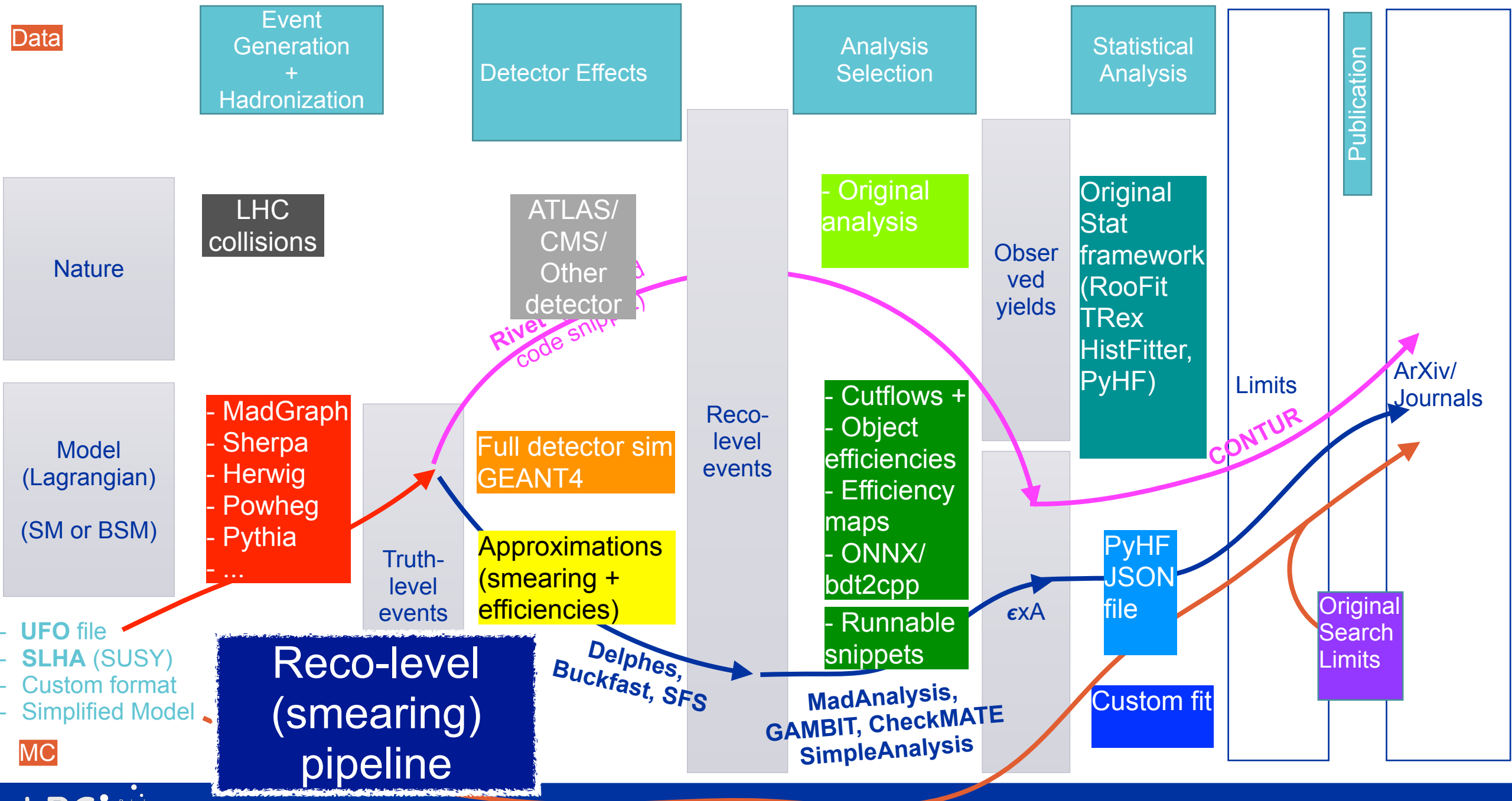
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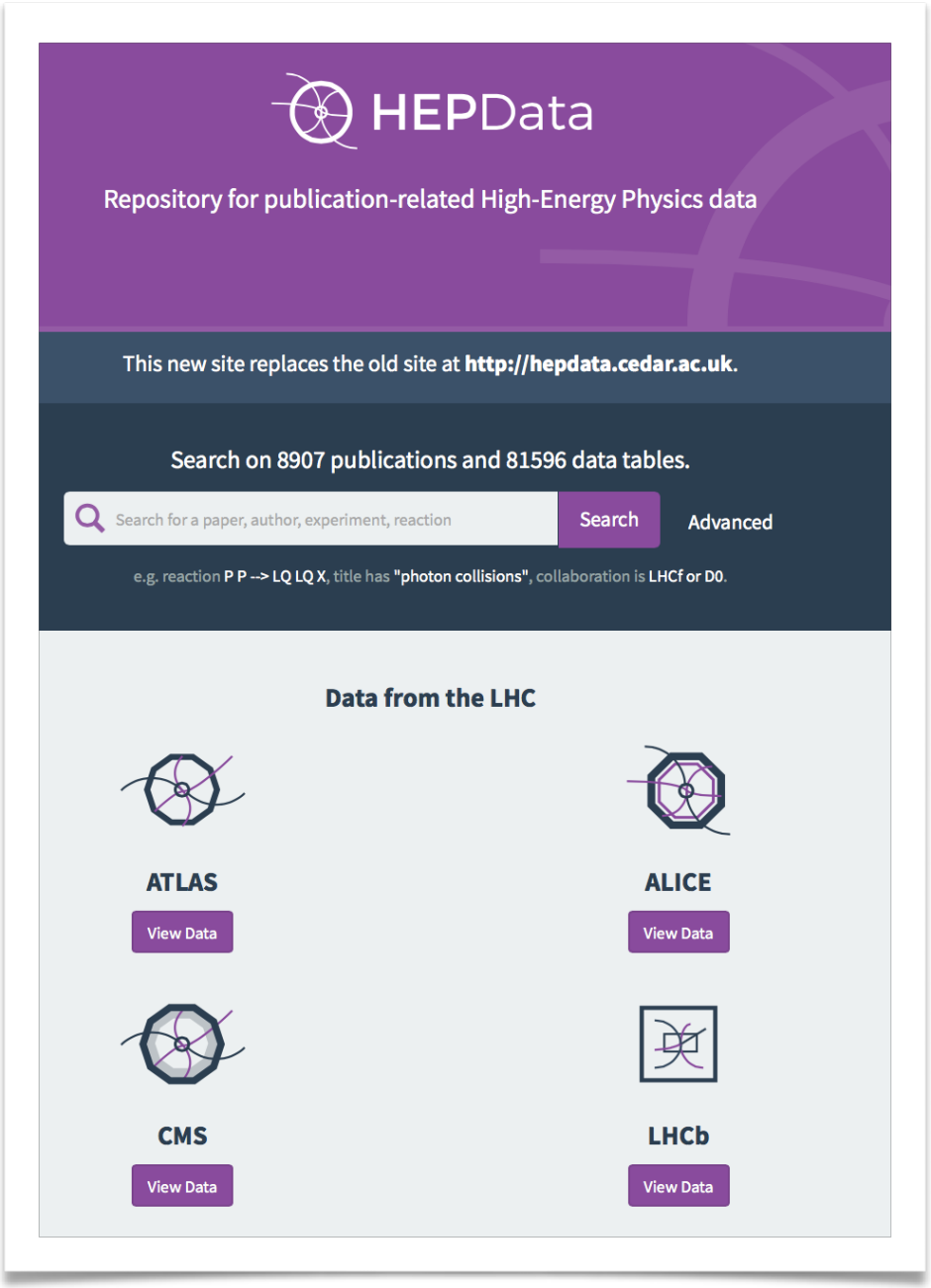
Reco-level (smearing) pipeline
Delphes, Buckfast, SFS
MadAnalysis, GAMBIT, CheckMATE SimpleAnalysis
SModelS, DarkCast, HiggsBounds, ZPEED, DarkEFT...

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...

13 TeV squarks+gluinos -> jets+MET @36/fb (link)

	DATA	SM BACKGROUND	SIGNAL
SQRT(S)	13000.0 GEV		
m_{eff}(incl.) [GeV]	**Events / 200 GeV**		
900.0 (bin: 800.0 - 1000.0)	0.0	0.0 +0.0 −0.0 sys	0.0
1100.0 (bin: 1000.0 - 1200.0)	0.0	0.0 +0.0 −0.0 sys	0.0
1300.0 (bin: 1200.0 - 1400.0)	15.0 ±3.873	19.01 ±1.941 stat +6.238 −4.106 sys	4.842 ±2.397
1500.0 (bin: 1400.0 - 1600.0)	166.0 ±12.88	153.9 ±5.601 stat +28.62 −30.08 sys	29.98 ±4.981

Hide Publication Information

Search for squarks and gluinos in final states with jets and missing transverse momentum using 36 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data with the ATLAS detector

Download All

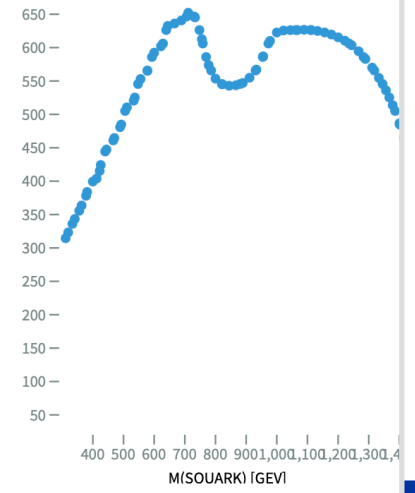
- YAML with resource files
- YAML
- YODA
- ROOT
- CSV

Data from Figure 10a

Showing 50 of 114 values — Show All 114 values

SQRT(S)	13000.0 GEV
M(SQUARK) [GEV]	**M(NEUTRALINO1) [GEV]**
1520.0	20.2
1522.0	40.4
1524.0	60.61
1527.0	80.81
1528.0	101.0
1527.0	121.2
1525.0	141.4

Visualize

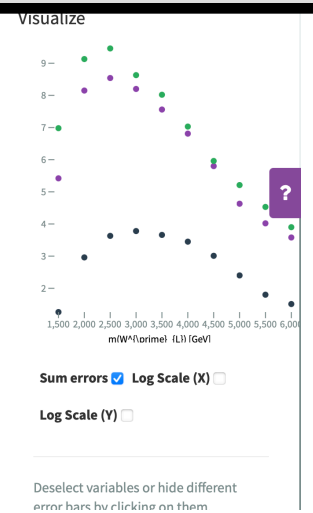


Efficiencies

- 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

13 TeV Vector boson resonance -> tb @139/fb (link): Event-level eff x acc

SQRT(S)	13000 GeV		
LUMINOSITY	139 fb^{-1}		
m(W'_L) [GeV]	Acc. × Eff. (SR1) [%]	Acc. × Eff. (SR2) [%]	Acc. × Eff. (SR3) [%]
1500.0	6.98	5.42	1.26
2000.0	9.13	8.15	2.96
2500.0	9.46	8.54	3.63
3000.0	8.63	8.2	3.78
3500.0	8.02	7.56	3.66
4000.0	7.03	6.81	3.45
4500.0	5.96	5.8	3.01
5000.0	5.21	4.63	2.4
5500.0	4.53	4.02	1.8
6000.0	3.9	3.58	1.51



13 TeV LLP search for Displaced vertex + jets @139/fb (link): per-vertex efficiencies

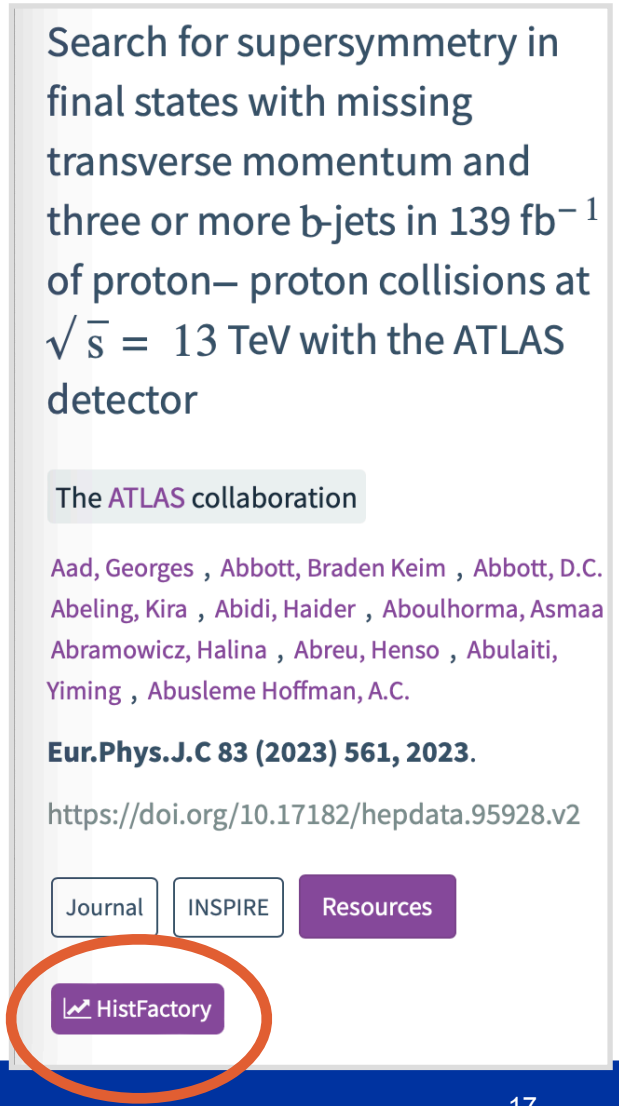
Luminosity		139 fb^{-1}
Energy		13 TeV
m_DV [GeV]	n_tracks	Efficiency
10.0 - 15.0	5.0 - 6.0	0.0
10.0 - 15.0	6.0 - 7.0	0.0
10.0 - 15.0	7.0 - 10.0	0.0092379 ±0.0046402 stat
10.0 - 15.0	10.0 - 15.0	0.0077821 ±0.0022552 stat

Likelihoods

- 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.

13 TeV SUSY MET+bjets @139/fb (link):
Likelihood available


```
"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": {
                            "hi": 0.993112,
                            "lo": 0.990944
                        },
                        "name": "ELEC_iso",
                        "type": "normsys"
```

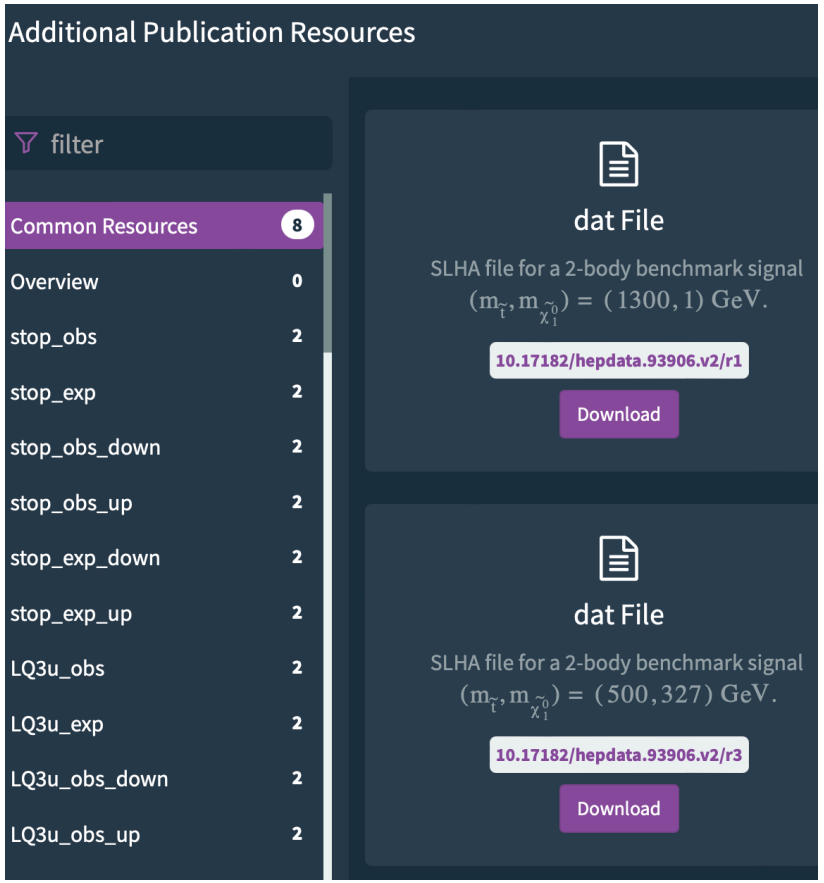



Cutflows and MC generation cards

- HEPData records often contain cutflows for well-defined signals, ideally with the corresponding instructions to generate THAT signal (eg SLHA files)
- Helps to validate your implementations of the selections

13TeV Heavy top ->tt +MET @139/fb (link):
Cutflow... and corresponding SLHA/MC card

region	SRA-TT	
Cut	**Weighted yield**	**Unweighted yield**
Total	123.3	30000
Derivation skim	122.2	29755
$E_T^{miss} > 250$ GeV	109.2	26606
$N_j \geq 4$	95.8	23395
$N_b \geq 2$	47.1	11651
Lepton veto	30.7	7627
$p_T^{j4} > 40$ GeV	27.9	6924
$p_T^{j2} > 80$ GeV	27.8	6898
$\lvert\Delta\phi_{min}(p_{T,l-4}, p_T^{miss})\rvert > 0.4$	24.1	6000
Pass E_T^{miss} trigger	24.1	6000
$S > 5$	24.1	5994



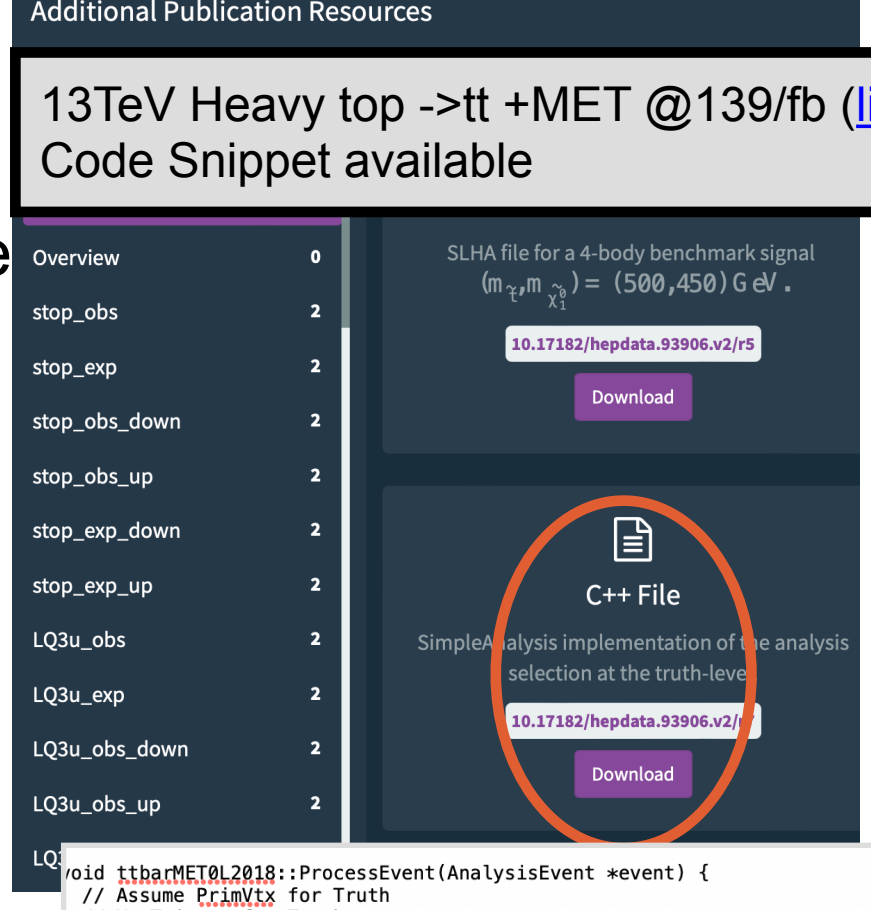
Code Snippets

- Even better than replicating a selection, is if the analysers provide a runnable code snippet for the selection!

- Many ATLAS Searches do this with SimpleAnalysis.

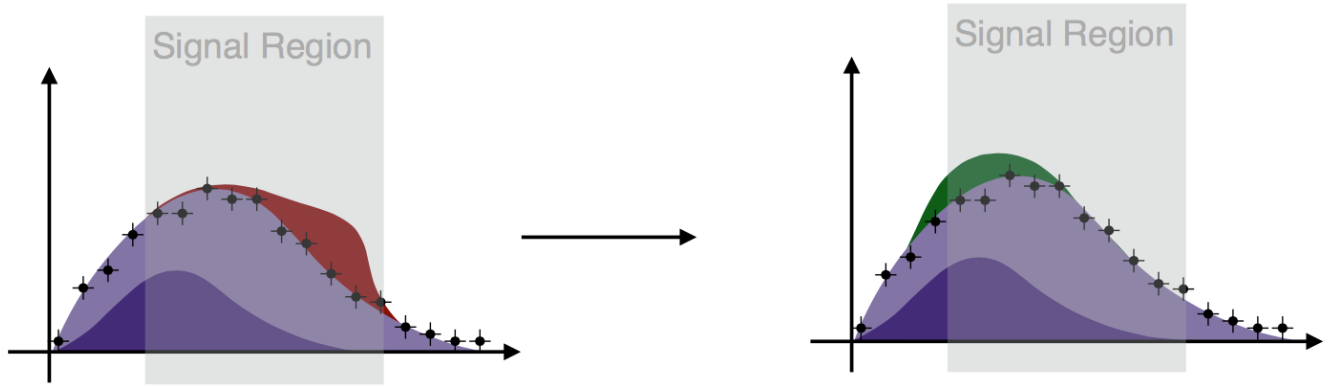
- SimpleAnalysis -> used to be "pseudo-code", but now is actually runnable since recently.
  -> https://simpleanalysis.docs.cern.ch/
  -> https://cds.cern.ch/record/2805991

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




```
void ttbarMET0L2018::ProcessEvent(AnalysisEvent *event) {
 // Assume PrimVtx for Truth
 // No Trigger for Truth

 // Get Baseline Objects
 auto baseJets = event->getJets(20., 2.8, JVT59Jet);
 auto baseElectrons = event->getElectrons(4.5, 2.47, ELooseBLLH | EZ05mm);
 auto baseMuons = event->getMuons(4.0, 2.7, MuMedium | MuZ05mm);

 // Get Truth Met + Object-Based MetSig
 auto metVec = event->getMET();
 float Met = metVec.Pt();
 double MetSig = event->getMETSignificance();

 // Overlap Removal
 auto radiusCalcLepton = [] (const AnalysisObject& lepton, const AnalysisObje
 auto muJetSpecial = [] (const AnalysisObject& jet, const AnalysisObject& muo
   if (jet.pass(NOT(BTag77MV2c10)) && (jet.pass(LessThan3Tracks) || muon.Pt()
   else return 0.;
 };
 baseMuons = overlapRemoval(baseMuons, baseElectrons, 0.01, NOT(MuCaloTaggedO
 baseElectrons = overlapRemoval(baseElectrons, baseMuons, 0.01);

 baseJets = overlapRemoval(baseJets, baseElectrons, 0.2, NOT(BTag77MV2c10));
 baseElectrons = overlapRemoval(baseElectrons, baseJets, 0.2);
```

Nice example of search re-interpretations

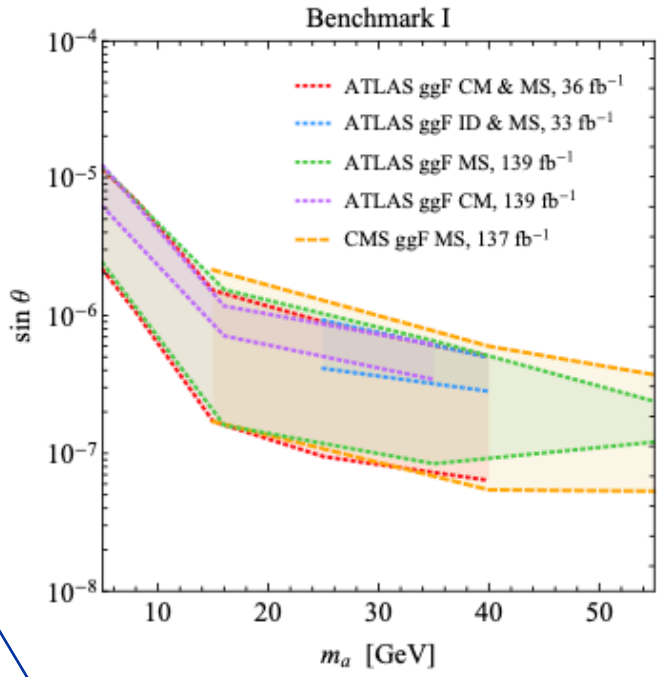


A few examples of nice recasted results!

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.

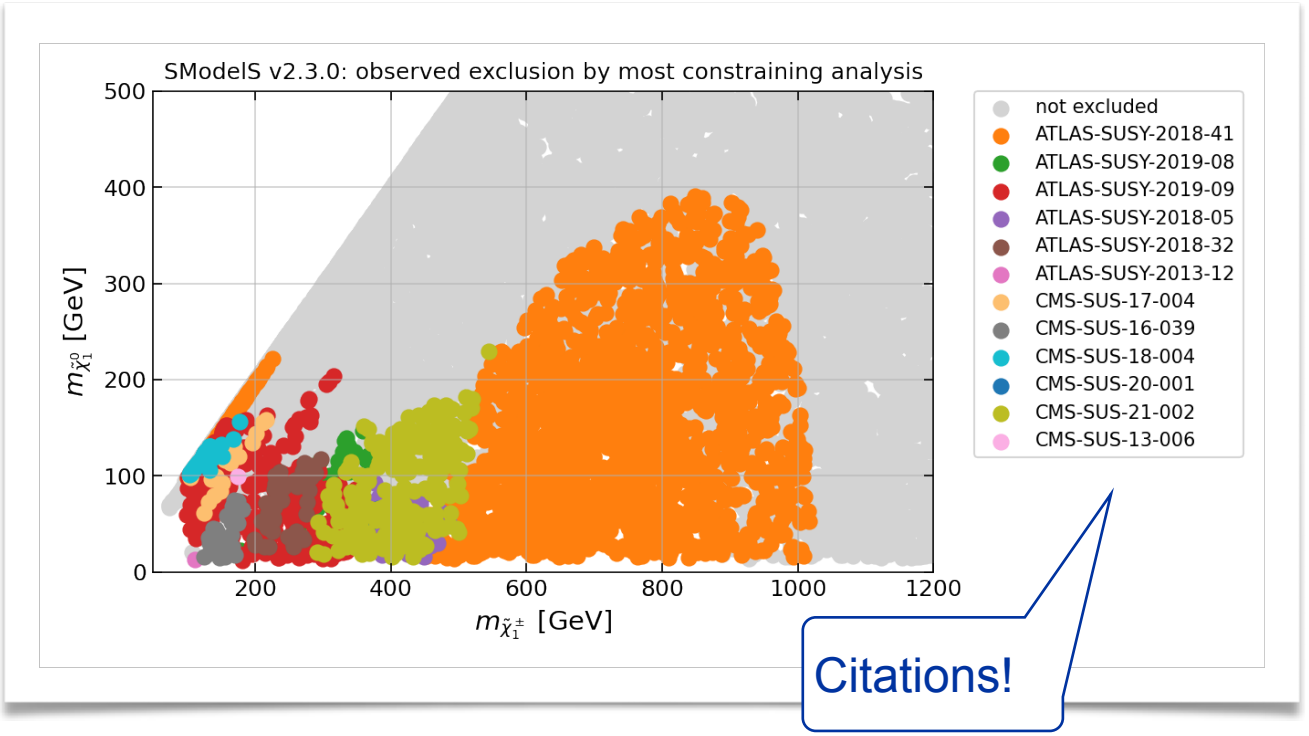
A few examples of nice recasted results!

Simplified model results

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



Citations!

A few examples of nice recasted results!

Simplified model results

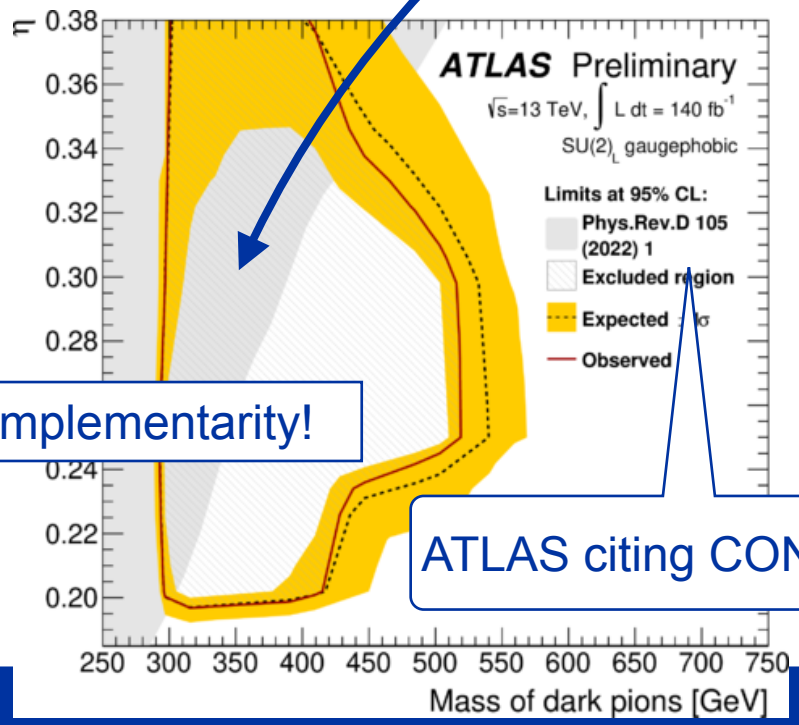
Measurement-based pipeline

2105.08494 -> CONTUR exploiting Rivet of SM measurements, control-region mesurements (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!

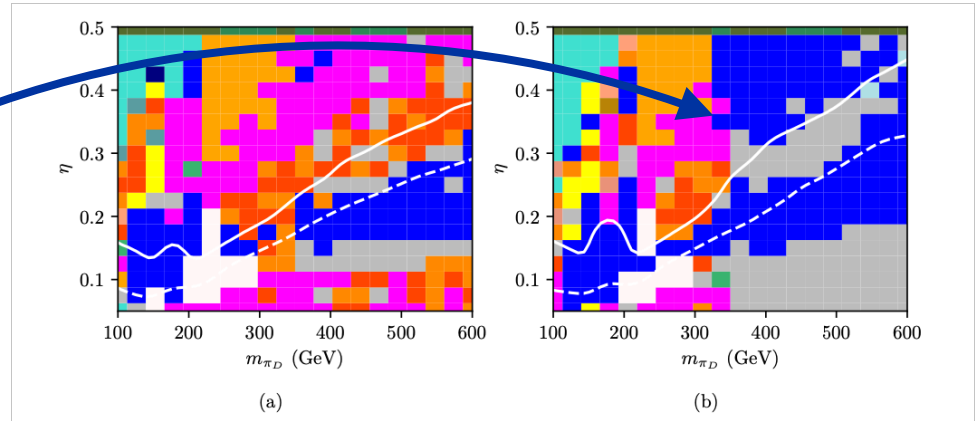


FIG. 5: Scans in $\eta - m_{\pi_D}$ for two sub-models, focussing on the $\eta < 0.5$ region and excluding the ATLAS dilepton search. (a) Gaugephilic $SU(2)_L$, (b) Gaugephobic $SU(2)_L$ The colours indicate the dominant signature pool giving the sensitivity. The white solid line is the 95% exclusion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

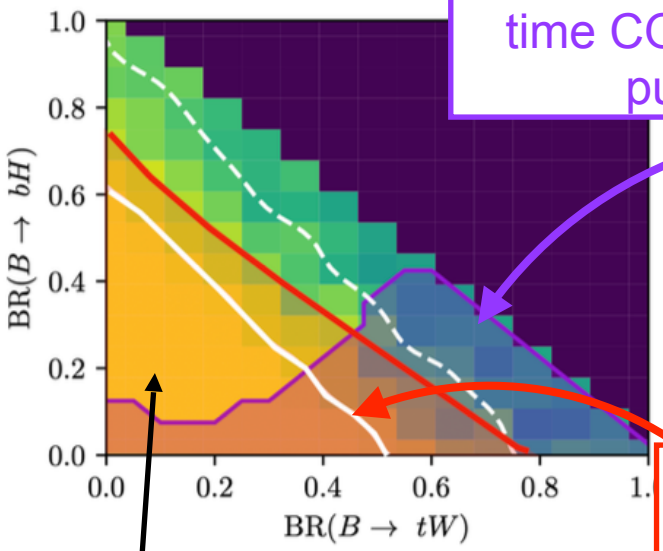
Measurement-based pipeline

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

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

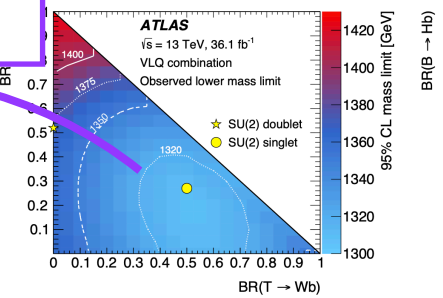
Makes use of:
- Truth-level rivet routines (runnable code snippets)
- Published differential cross-sections
- Published MC predictions for those cross-sections (important!)

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



ATLAS exclusion at the time CONTUR paper published

1808.02343

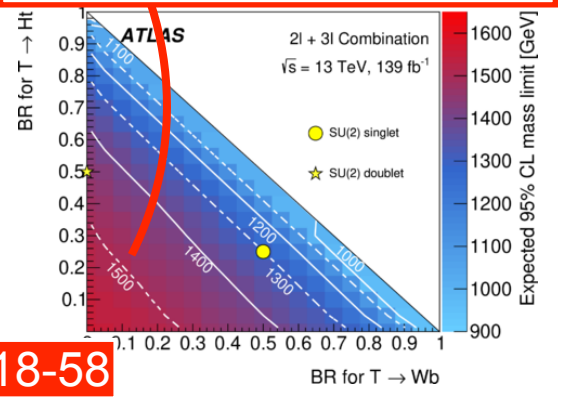


(a)

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

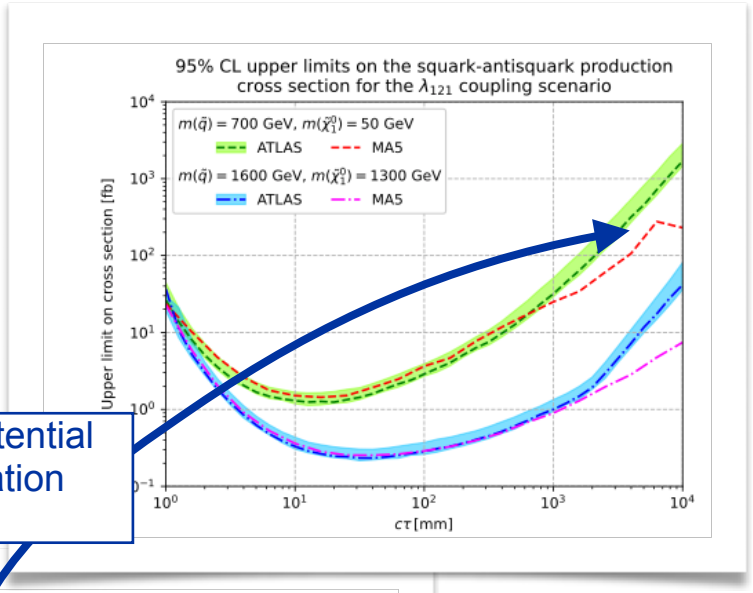
Measurement-based pipeline

Reco-level smearing pipeline

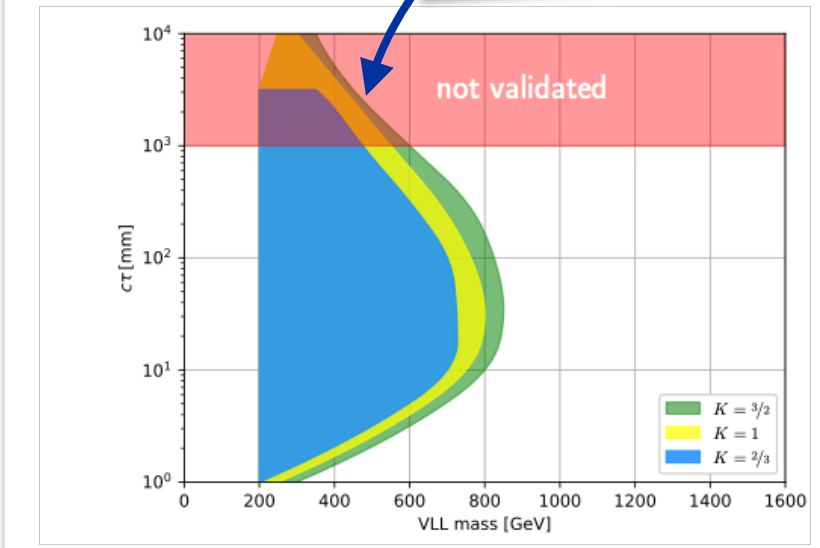
2112.05163 -> MadAnalysis 5 uses SUSY-2017-04 to set limits on long-lived vector-like leptons

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?)



A few examples of nice recasted results!

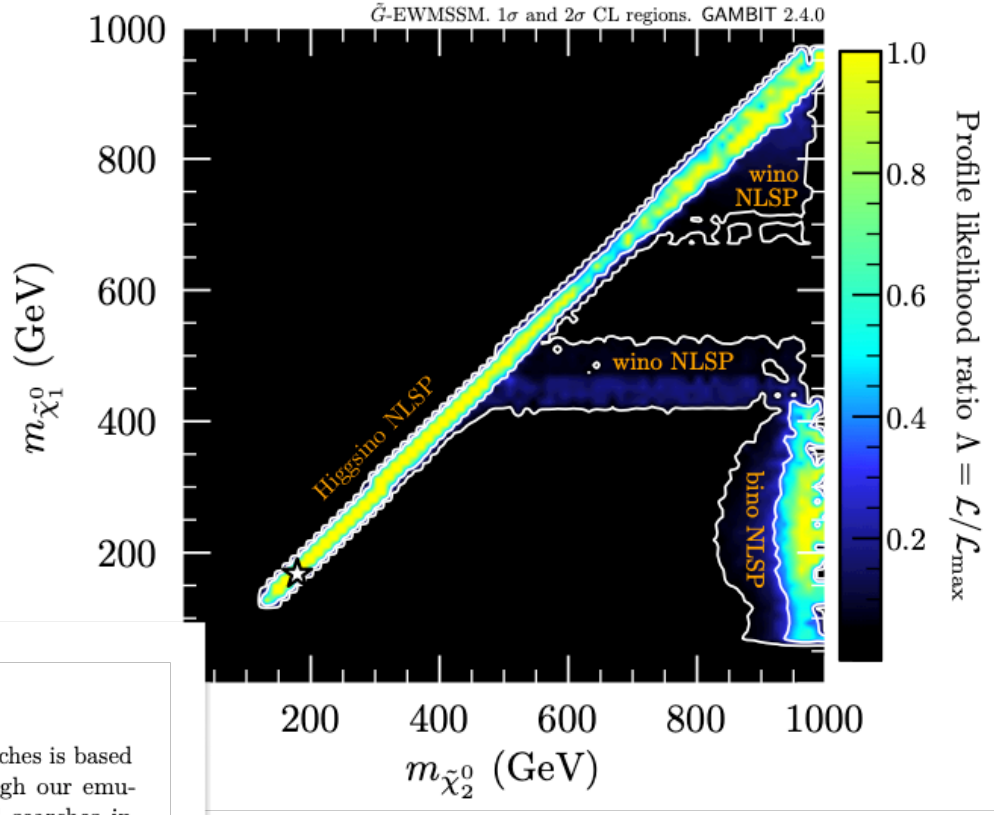
Simplified model results

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

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- Per-object efficiency maps

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...)