SModelS & pyhf

Sabine Kraml
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for the SModelS collaboration

Gaël Alguero, Mohammad Altakach, SK, Andre Lessa, Sahana Narasimha*,
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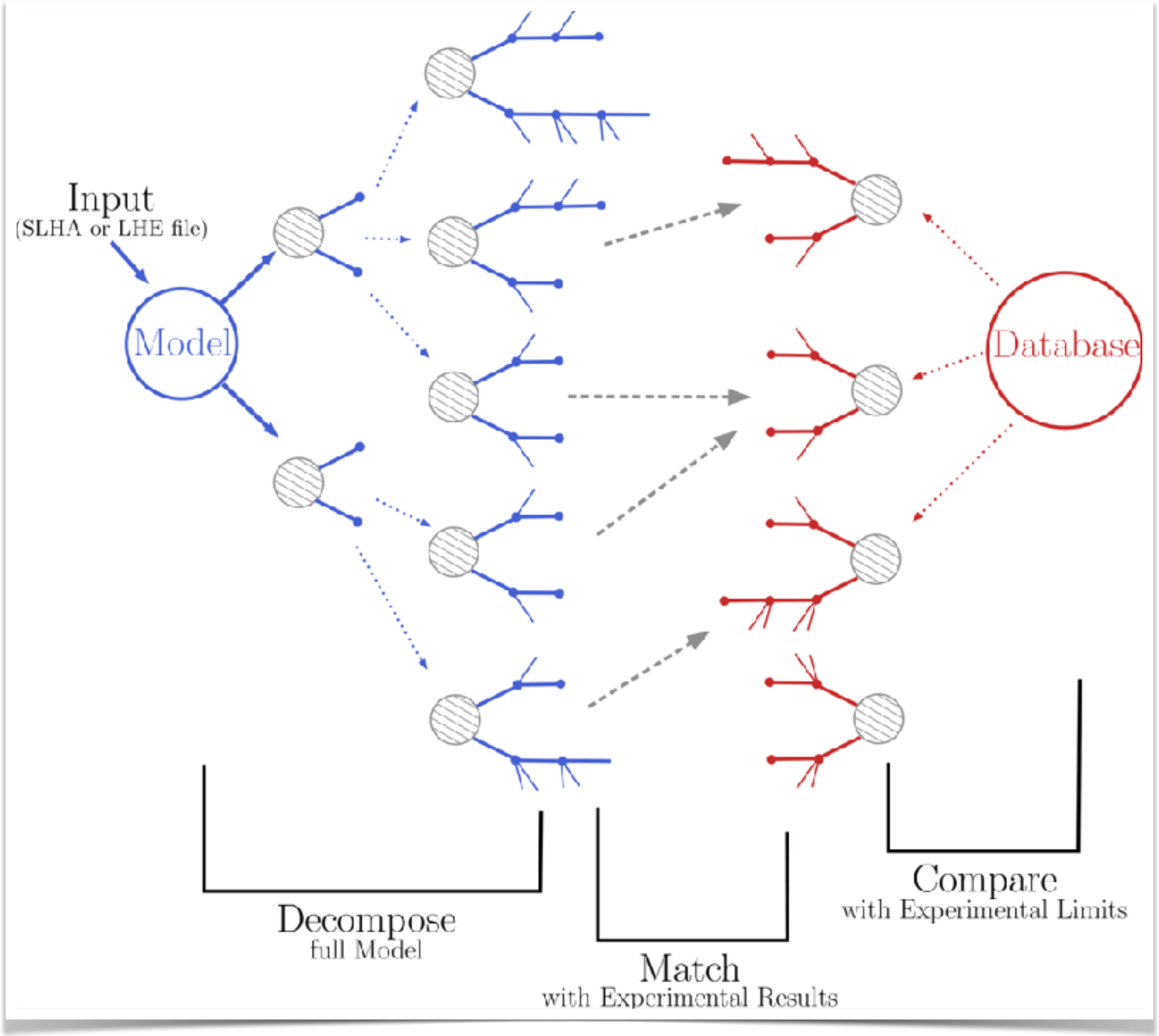
pyhf Users and Developers workshop, 4-8 Dec 2023, CERN & online

* current PhD students, thanks for plots.

What is SModelS ?

https://smodels.github.io

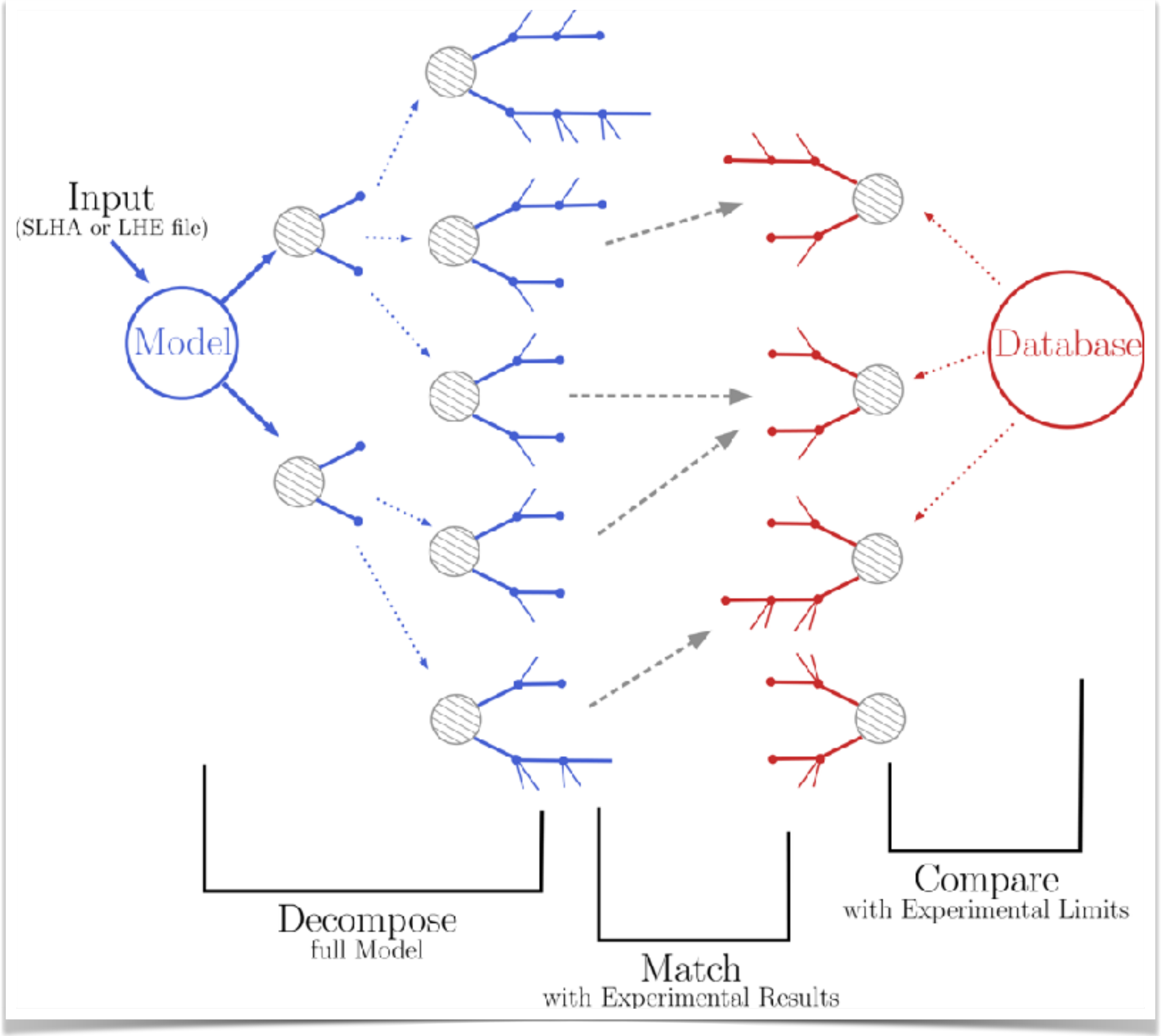
- Public tool for the fast reinterpretation of LHC searches on the basis of simplified-model results.
- Working principle: **decompose** the signatures of **full BSM scenarios into simplified model components**, which are then confronted against the experimental constraints from a **large database of results**.
- Input: SLHA files with mass spectrum, decay tables and cross sections.
- Mostly results from SUSY searches, but works for any BSM model with a Z_2-like symmetry!



What is SModelS ? -cont-

https://smodels.github.io

- Public tool for the fast reinterpretation of LHC searches on the basis of simplified-model results.
- Advantages are simplicity and **speed!**
  → **very fast** b/c no MC simulation needed
  → well suited for large scans and model surveys
- **Large database** of experimental results
- ATLAS and CMS, Run 1 and Run 2, **prompt and long-lived results** all **treated simultaneously**
- Easy **classification of** unconstrained cross section, **missing topologies**
- Limitation: **kind and variety of avilable simplified-model results.**



What is SModelS ? -cont-

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Special Article - Tools for Experiment and Theory

THE EUROPEAN PHYSICAL JOURNAL C

SModelS: a tool for interpreting simplified-model results from the LHC and its application to supersymmetry

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Abstract We present a general procedure to decompose Beyond the Standard Model (BSM) collider signatures presenting a Z_2 symmetry into Simplified Model Spectrum (SMS) topologies. Our method provides a way to cast BSM predictions for the LHC in a model independent framework, which can be directly confronted ... mental constraints. Our concrete ... focusses on supersymmetry searc... for which a large variety of SMS ... CMS are available. As show-case ... procedure to two scans of the minimal supersymmetric standard model. We discuss how the SMS limits constrain various particle masses and which regions of parameter space remain unchallenged by the current SMS interpretations of the LHC results.

1 Introduction

Searches at the ATLAS and CMS experiments at the LHC show no signs of physics beyond the Standard Model (BSM). After the first phase of LHC operation at centre-of-mass energies of 7–8 TeV in 2010–2012, the limits for the masses of supersymmetric particles, in particular of 1st/2nd generation squarks and gluinos, have been pushed well into the TeV range [1,2]. Likewise, precision measurements in the flavor sector, in particular in B-physics, are well consistent with Standard Model (SM) expectations [3,4] and show no sign, or need, of new physics. At the same time the recent discovery [5,6] of a Higgs-like particle with mass around 125 GeV makes the question of stability of the electroweak ...ge hierarchy problem—even more ...ymmetry (SUSY) is arguably the ...solve the gauge hierarchy problem ...like Higgs boson. So, the Higgs has ...ed—but where is supersymmetry?

Looking closely [7–12] one soon realizes that many of the current limits on SUSY particles are based on severe model assumptions, which impose particular relations between particle masses, decay branching ratios, etc. The prime example is the interpretation of the search results within the Constrained Minimal Supersymmetric Standard Model (CMSSM). The interpretation of the search results within a much more general realization of the MSSM is perfectly feasible, see [7,8,13], but computationally very demanding and certainly not suitable for a "quick" survey.

An approach which has therefore been adopted systematically by the ATLAS and CMS collab... pret the results within so-calle... tra [14,15]. Simplified Model S... are effective-Lagrangian descript... number of new particles. They we... for the characterization of new ph... large variety of results on searche... nels are available from both ATL... general cross section limits for SM... using these results to constrain con... BSM) scenarios is not straightforwa...

In this paper, we present a method ... decompose the signal of an arbitrary SUSY spectrum into simplified model topolo-

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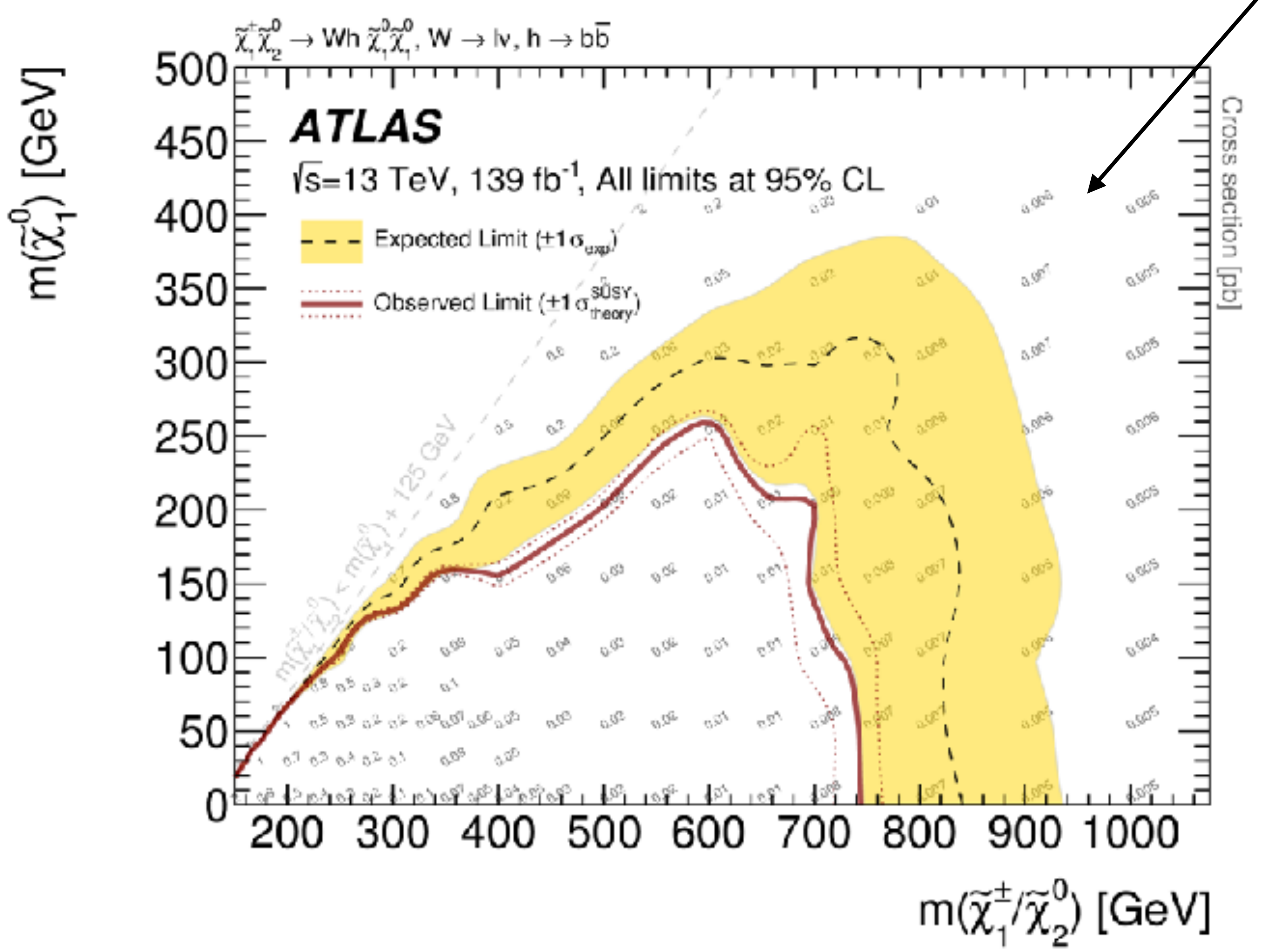
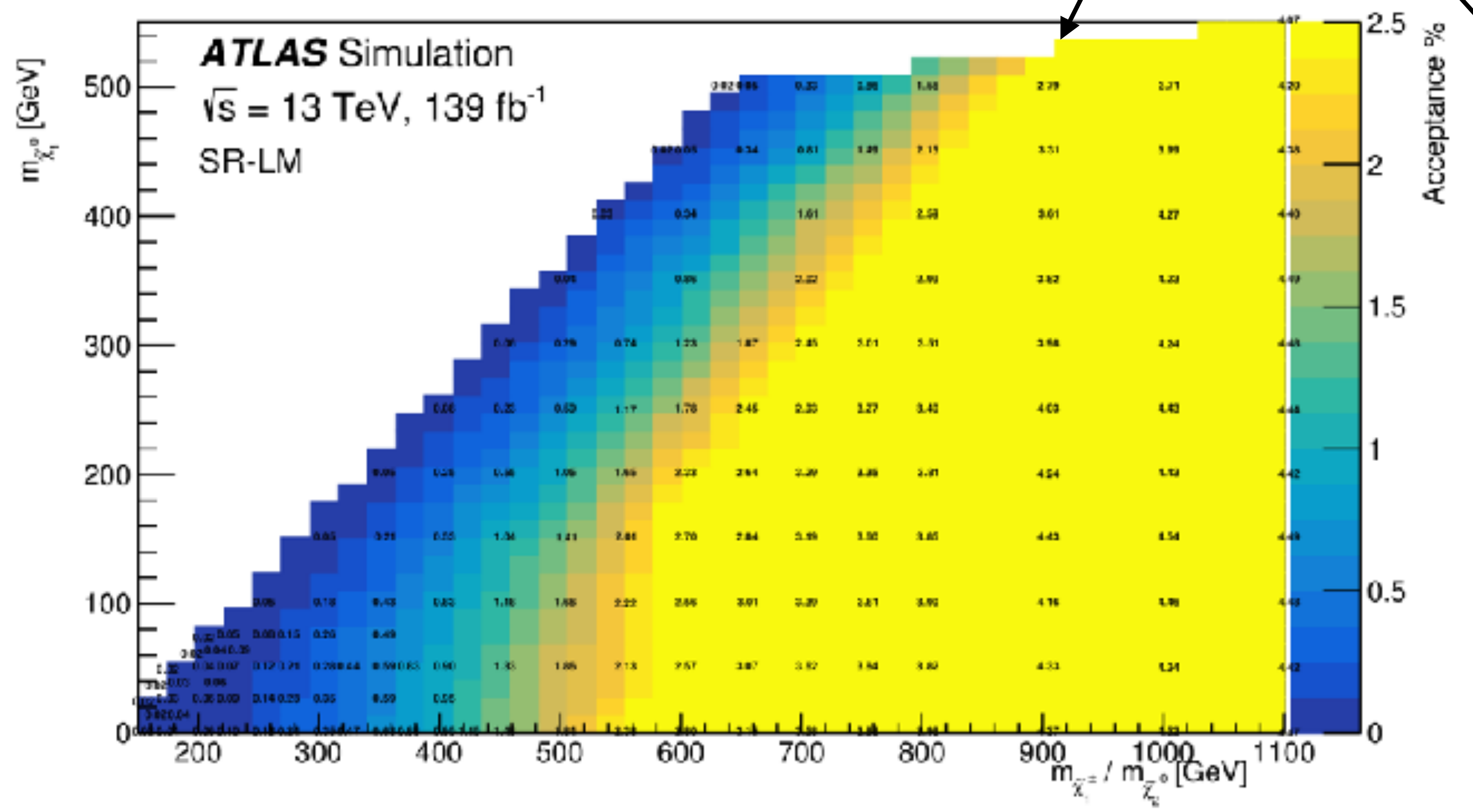
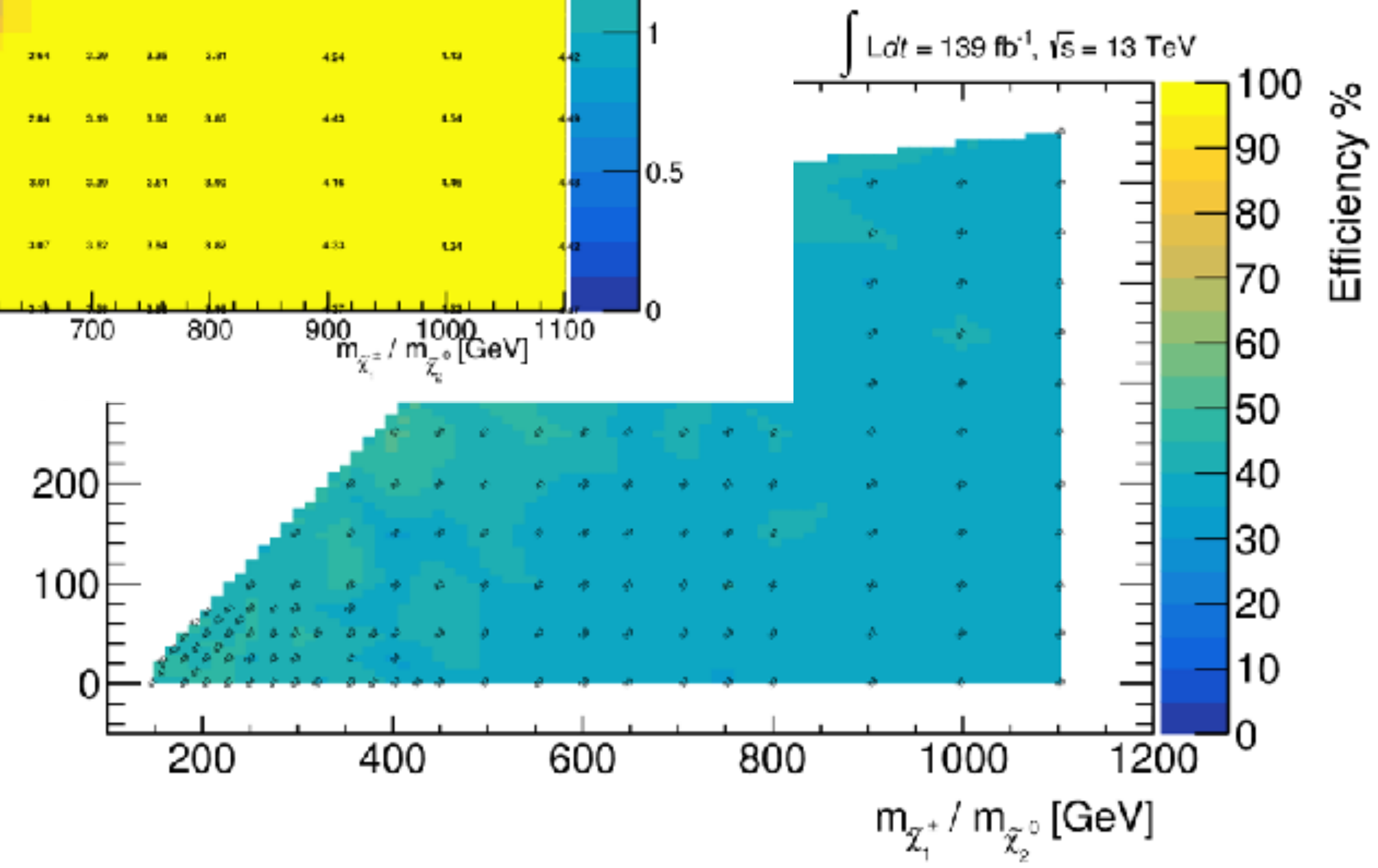
Experimental results in SModelS

upper limit (UL) maps and **A×ε 'efficiency' maps (EM)**







Experimental results in SModelS

Maps of Aε for the signal regions of an analysis allow us

- to **sum different contributions** to the same signal region

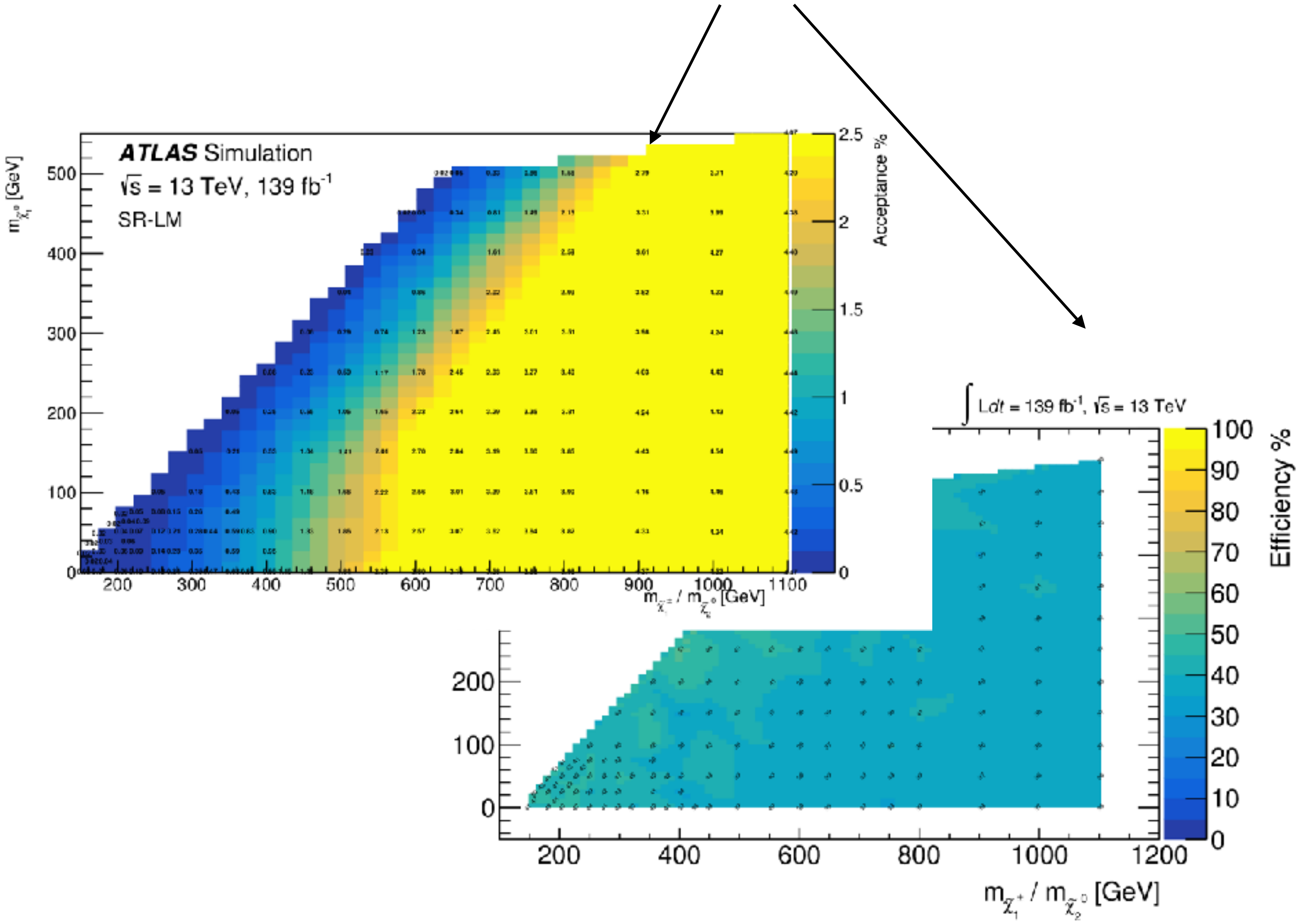
$$n_{\rm sig} = \sum A\epsilon\,[\sigma \times {\rm BR} \times {\rm BR}] \times \mathcal{L}$$

- given expected and observed numbers of events, **compute a likelihood** for the hypothesised signal *)

$$\mathcal{L}(\mu,\theta|D) = P(D|\mu s + b + \theta)\,p(\theta)$$

- do sophisticated statistical evaluations (likelihood ratio tests, confidence levels, p-values, etc.)

A×ε 'efficiency' maps (EM)



***) if information on correlations is available, SRs can be combined**

Interface to pyhf

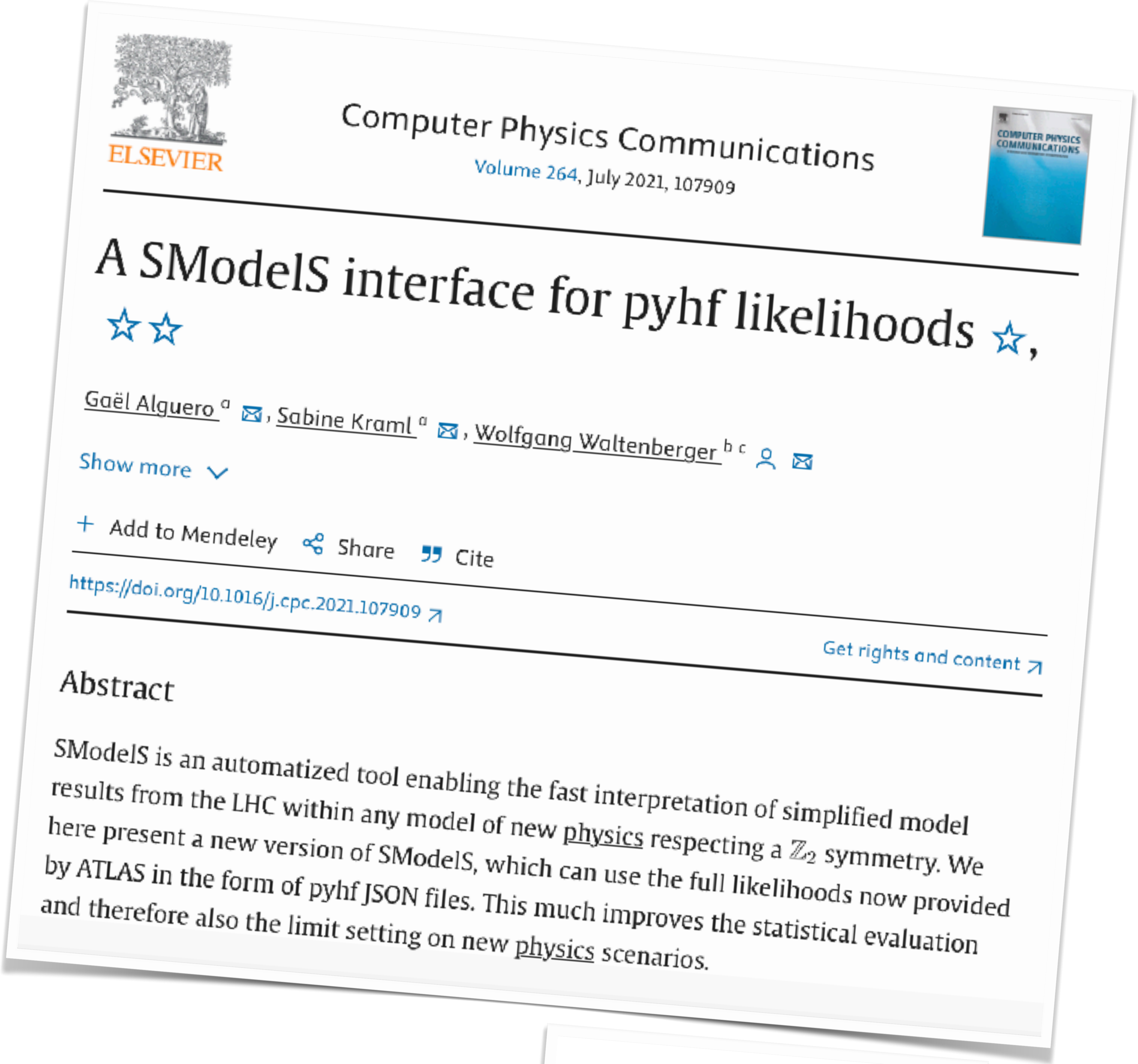
- Interface to pyhf established in 2020.
- Whenever a statistical model is available, we use it. A real boon for us!
- SModelS needs to be fast → we typically use `simplify`'ed JSONs *)

https://github.com/eschanet/simplify

- Usage of full llhds can be enforced through database add-on

```
path = latest+full_llhds
```

→ replaces simplify'ed HistFactory models by full ones;
available from SModelS v2.3 (June 2023) onwards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Computer Physics Communications
Volume 264, July 2021, 107909

A SModelS interface for pyhf likelihoods ☆, ☆☆

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

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Abstract

SModelS is an automatized tool enabling the fast interpretation of simplified model results from the LHC within any model of new physics respecting a $\mathbb{Z}_2$ symmetry. We here present a new version of SModelS, which can use the full likelihoods now provided by ATLAS in the form of pyhf JSON files. This much improves the statistical evaluation and therefore also the limit setting on new physics scenarios.

arXiv:2009.01809

*) subject to validation

The Database v2.3

- In total exp. results from **111 ATLAS and CMS publications**
- Run 1: 15 ATLAS + 18 CMS analyses
- **Run 2: 38 ATLAS + 40 CMS** analyses (17 ATLAS+13 CMS for full luminosity)
- **10 LLP** searches: HSCP, disappearing tracks, displaced vertices
- **7 ATLAS analyses with pyhf llhds**

→ bkg-only.json

ATLAS Run 2 analyses in SModelS v2.3 database

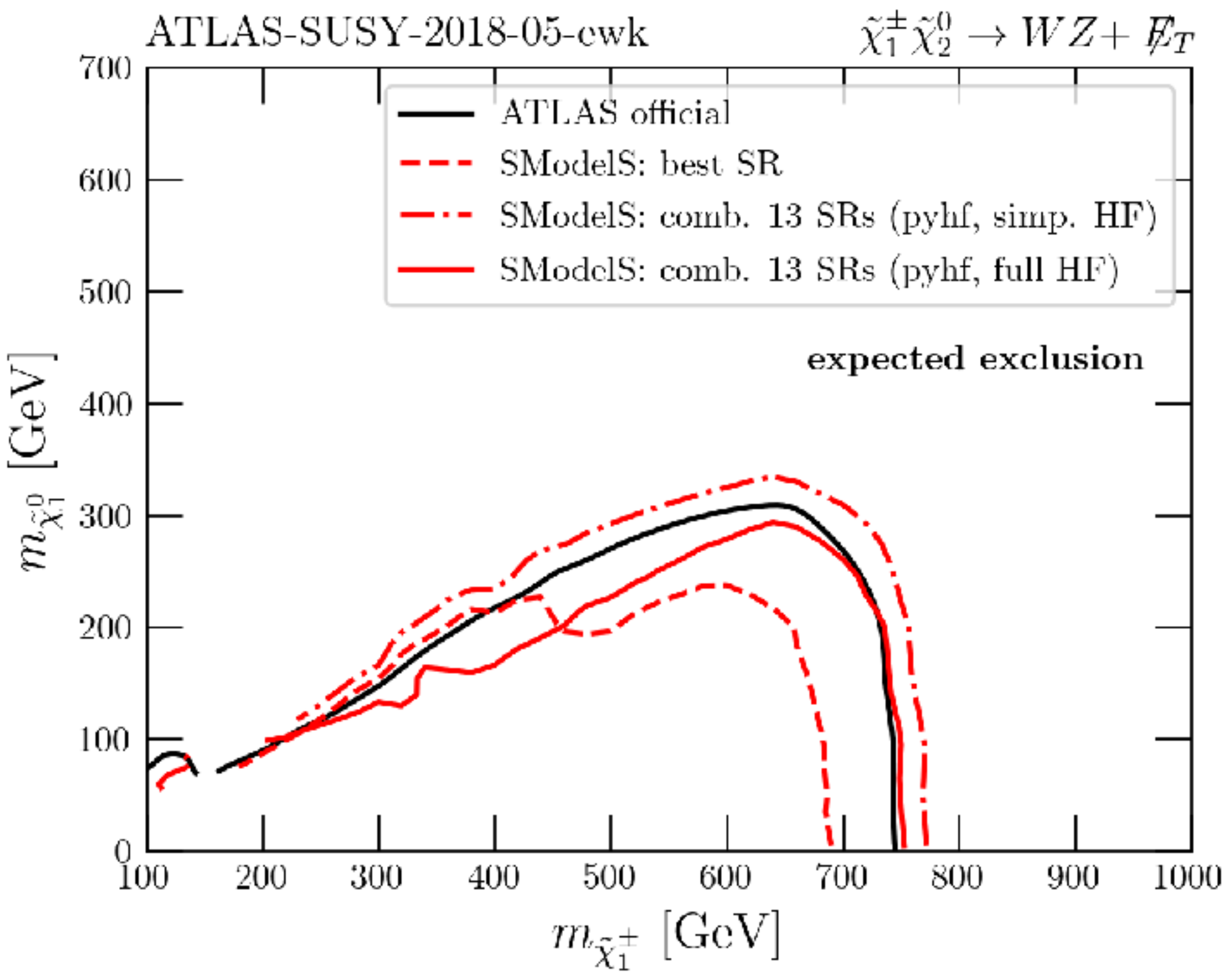
ID	Short Description	$\mathcal{L}$ [fb^{-1}]	UL$_{obs}$	UL$_{exp}$	EM	comb.
ATLAS-SUSY-2015-01	2 b-jets	3.2	✓			
ATLAS-SUSY-2015-02	1ℓ stop	3.2	✓		✓	
ATLAS-SUSY-2015-06	0ℓ + 2–6 jets	3.2			✓	
ATLAS-SUSY-2015-09	jets + 2 SS or $\geq 3\ell$	3.2	✓			
ATLAS-SUSY-2016-06	disappearing tracks	36.1			✓	
ATLAS-SUSY-2016-07	0ℓ + jets	36.1	✓		✓	
ATLAS-SUSY-2016-08	displaced vertices	32.8	✓			
ATLAS-SUSY-2016-14	2 SS or 3 ℓ's + jets	36.1	✓			
ATLAS-SUSY-2016-15	0ℓ stop	36.1	✓			
ATLAS-SUSY-2016-16	1ℓ stop	36.1	✓		✓	
ATLAS-SUSY-2016-17	2 OS ℓ	36.1	✓			
ATLAS-SUSY-2016-19	2 b-jets + τ's	36.1	✓			
ATLAS-SUSY-2016-24	2–3 ℓ's, EWK	36.1	✓		✓	
ATLAS-SUSY-2016-26	$\geq 2\,c$-jets	36.1	✓			
ATLAS-SUSY-2016-27	jets + γ	36.1	✓		✓	
ATLAS-SUSY-2016-28	2 b-jets	36.1	✓			
ATLAS-SUSY-2016-32	HSCP	31.6	✓	✓	✓	
ATLAS-SUSY-2016-33	2 SFOS ℓ's	36.1	✓			
ATLAS-SUSY-2017-01	$Wh(bb)$, EWK	36.1	✓			
ATLAS-SUSY-2017-02	0ℓ + jets	36.1	✓	✓		
ATLAS-SUSY-2017-03	multi-ℓ EWK	36.1	✓		✓	
ATLAS-SUSY-2018-04	2 hadronic taus	139.0	✓		✓	PYHF
ATLAS-SUSY-2018-05	2ℓ + jets, EWK	139.0	✓		✓	PYHF
ATLAS-SUSY-2018-05	2ℓ + jets, strong	139.0			✓	
ATLAS-SUSY-2018-06	3ℓ, EWK	139.0	✓	✓	✓	
ATLAS-SUSY-2018-08	2 OS ℓ	139.0	✓		✓	
ATLAS-SUSY-2018-10	1ℓ + jets	139.0	✓		✓	
ATLAS-SUSY-2018-12	0ℓ + jets	139.0	✓	✓	✓	
ATLAS-SUSY-2018-14	displaced vertices	139.0			✓	PYHF
ATLAS-SUSY-2018-22	multi-jets	139.0	✓		✓	
ATLAS-SUSY-2018-23	$Wh(\gamma\gamma)$, EWK	139.0	✓	✓		
ATLAS-SUSY-2018-31	$2b + 2h(bb)$	139.0	✓		✓	PYHF
ATLAS-SUSY-2018-32	2 OS ℓ	139.0	✓		✓	PYHF
ATLAS-SUSY-2018-40	$2b + 2h(\tau\tau)$	139.0	✓	✓	✓	
ATLAS-SUSY-2018-41	hadr. EWK search	139.0	✓	✓	✓	SLv1
ATLAS-SUSY-2018-42	charged LLPs, dE/dx	139.0	✓	✓	✓	
ATLAS-SUSY-2019-02	2 soft ℓ's, EWK	139.0	✓		✓	SLv1
ATLAS-SUSY-2019-08	$1\ell + h(bb)$, EWK	139.0	✓		✓	PYHF
ATLAS-SUSY-2019-09	3ℓ, EWK	139.0	✓	✓	✓	PYHF

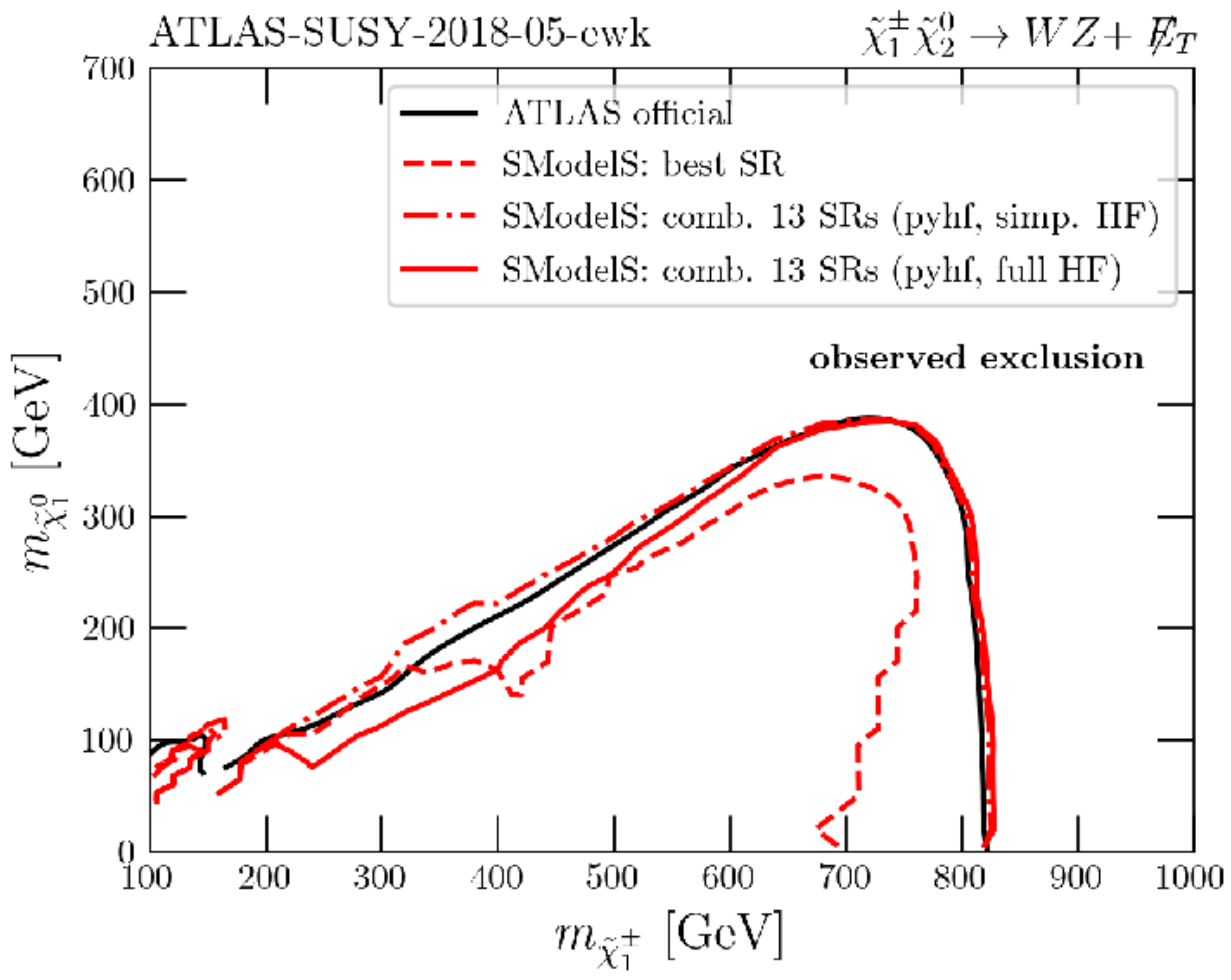
Best-SR vs. full vs. simplify'ed likelihoods

(database validation)

Best-SR vs. full vs. simplify'ed likelihoods

plots: Sahana Narasimha

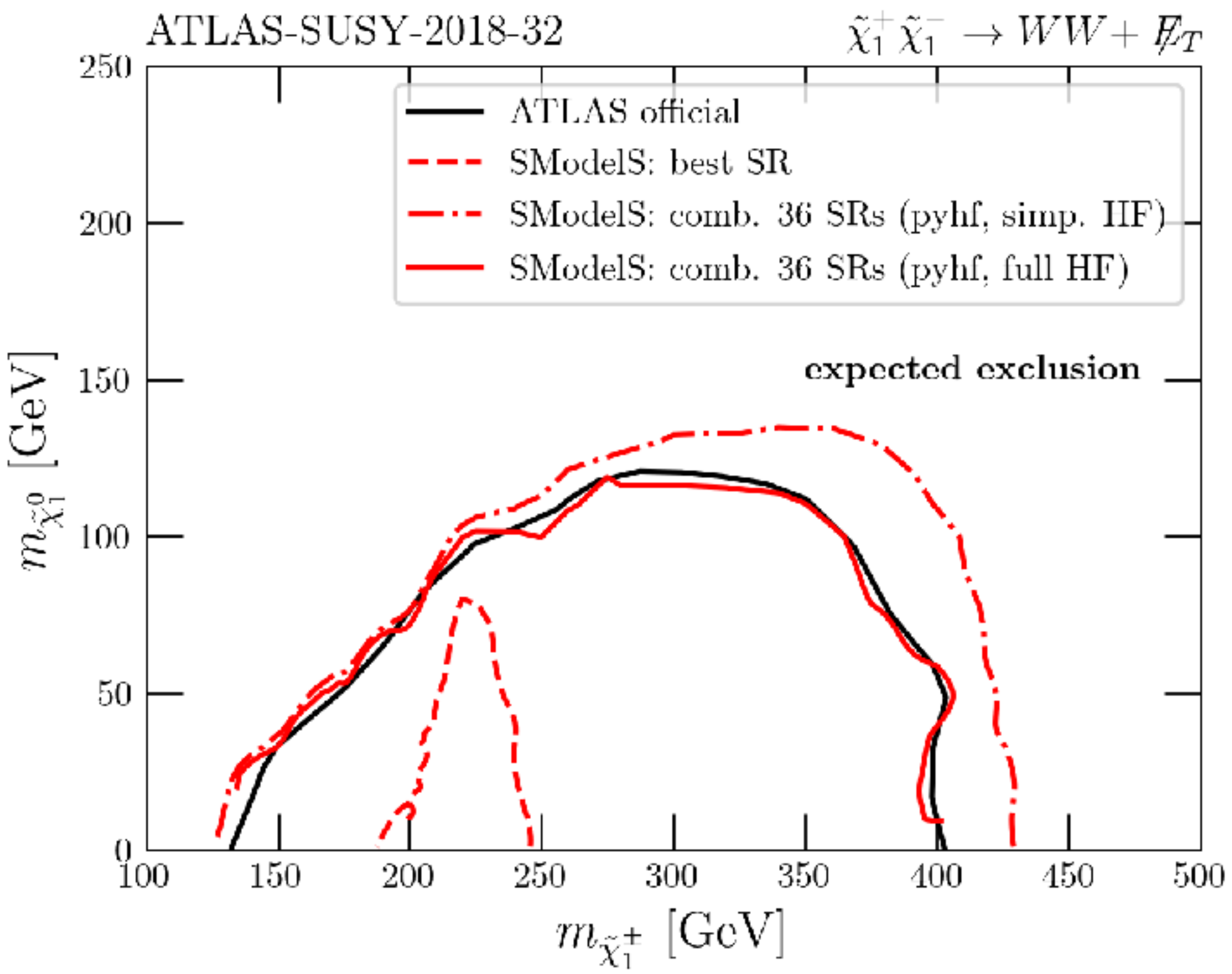


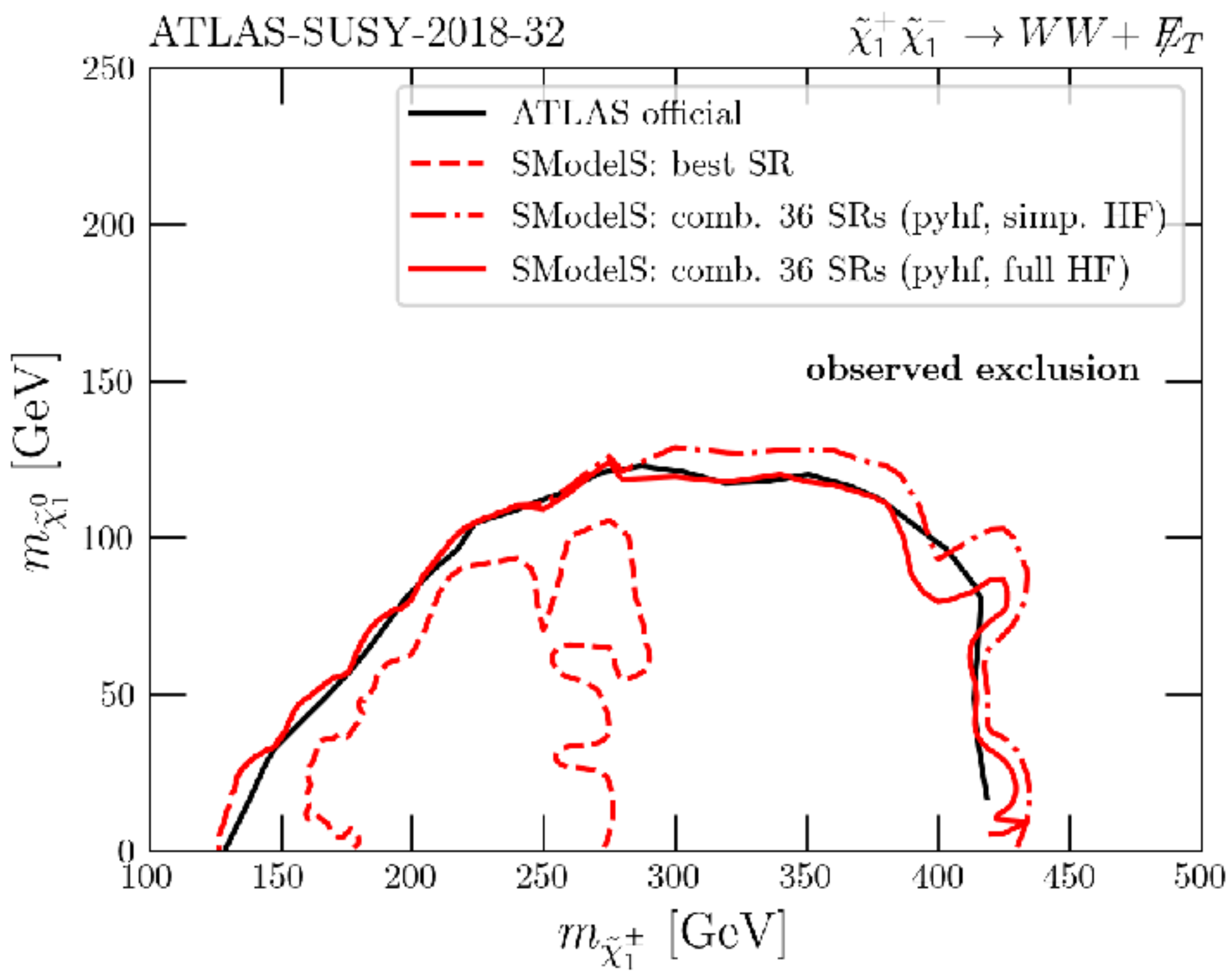


ATLAS-SUSY-2018-05: Searches for new phenomena in events with two leptons, jets, and missing transverse momentum

Best-SR vs. full vs. simplify'ed likelihoods

plots: Sahana Narasimha



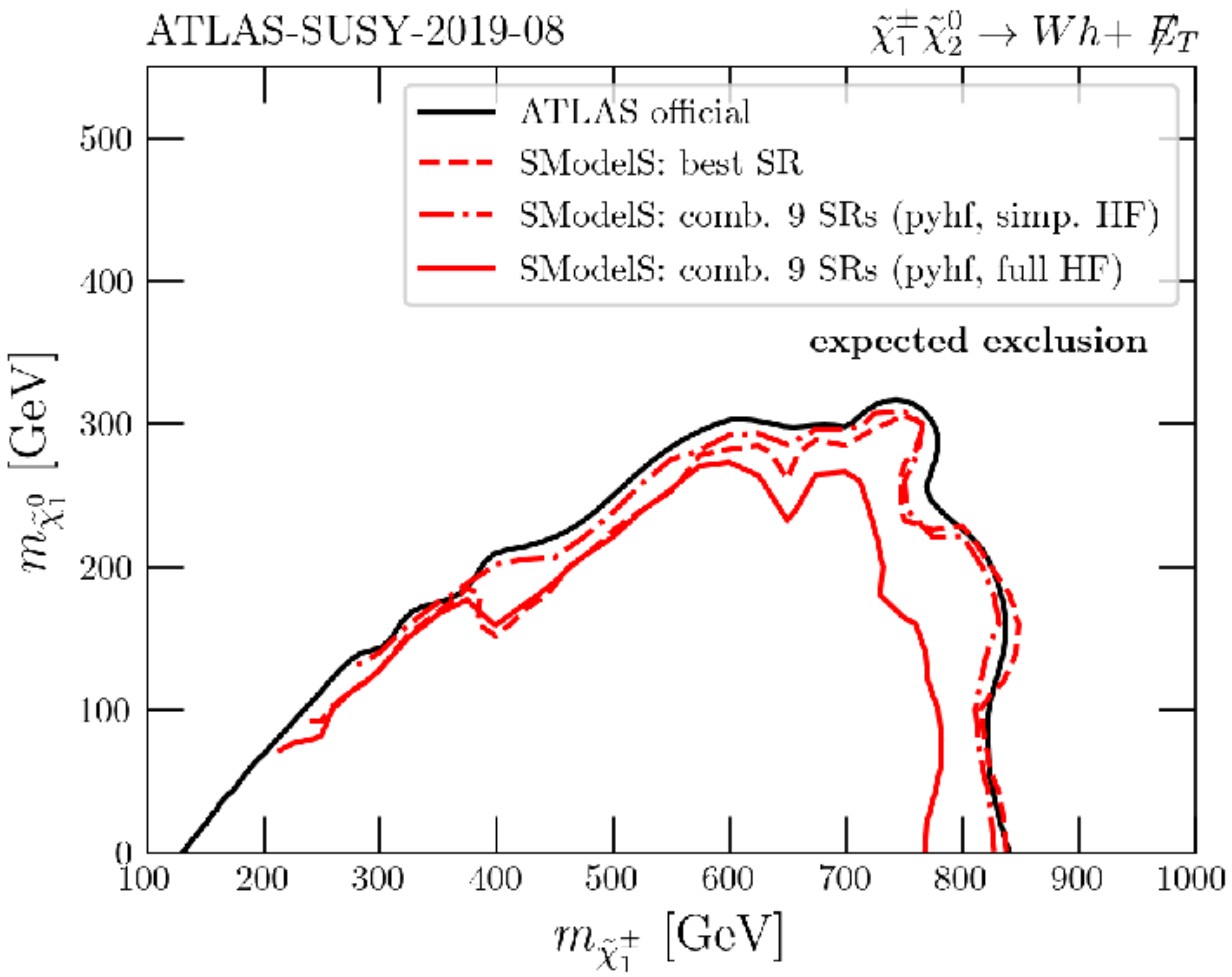


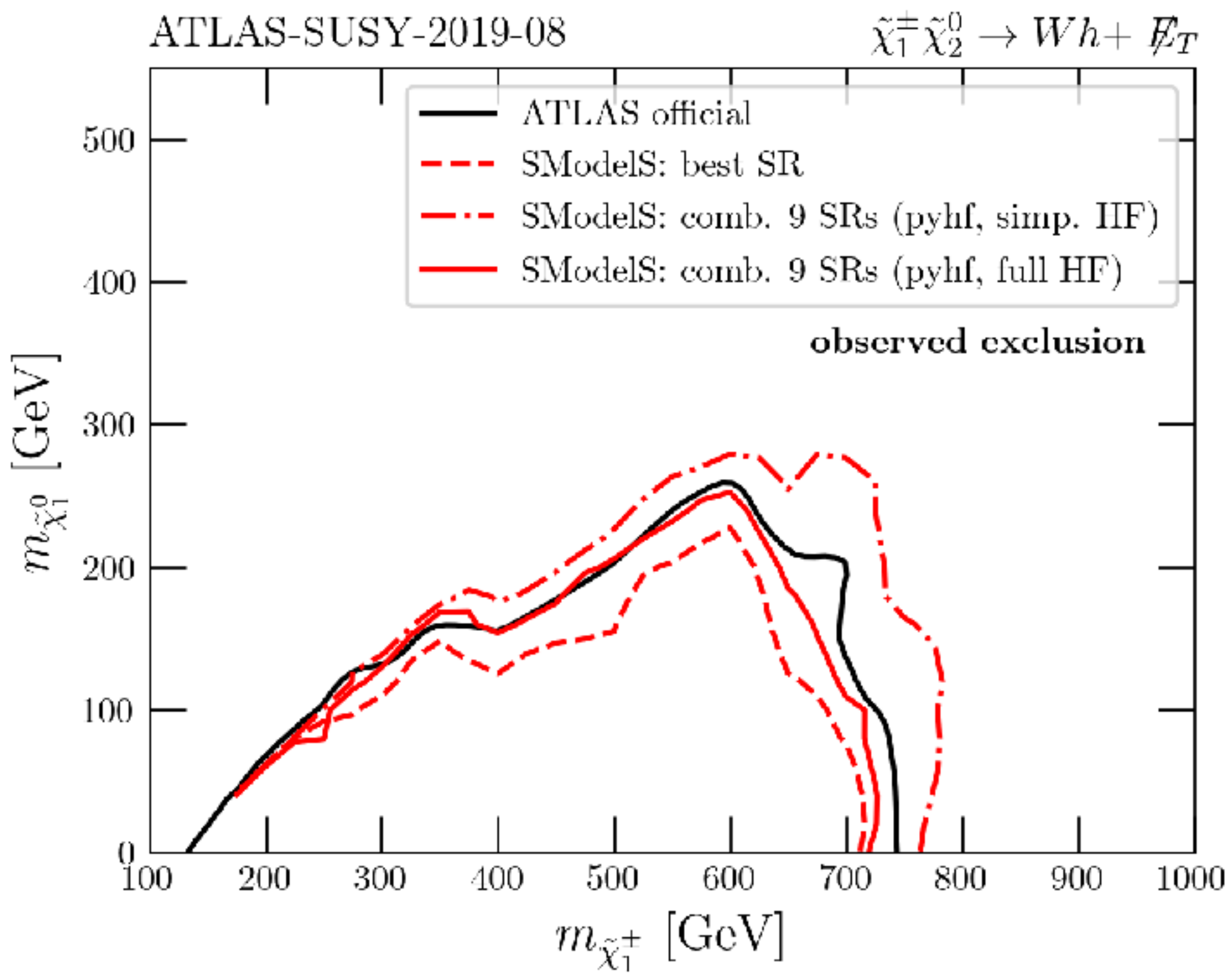
ATLAS-SUSY-2018-32: Charginos and sleptons decaying into final states with two leptons and missing transverse momentum

need to include CRs in fit

Best-SR vs. full vs. simplify'ed likelihoods

plots: Sahana Narasimha



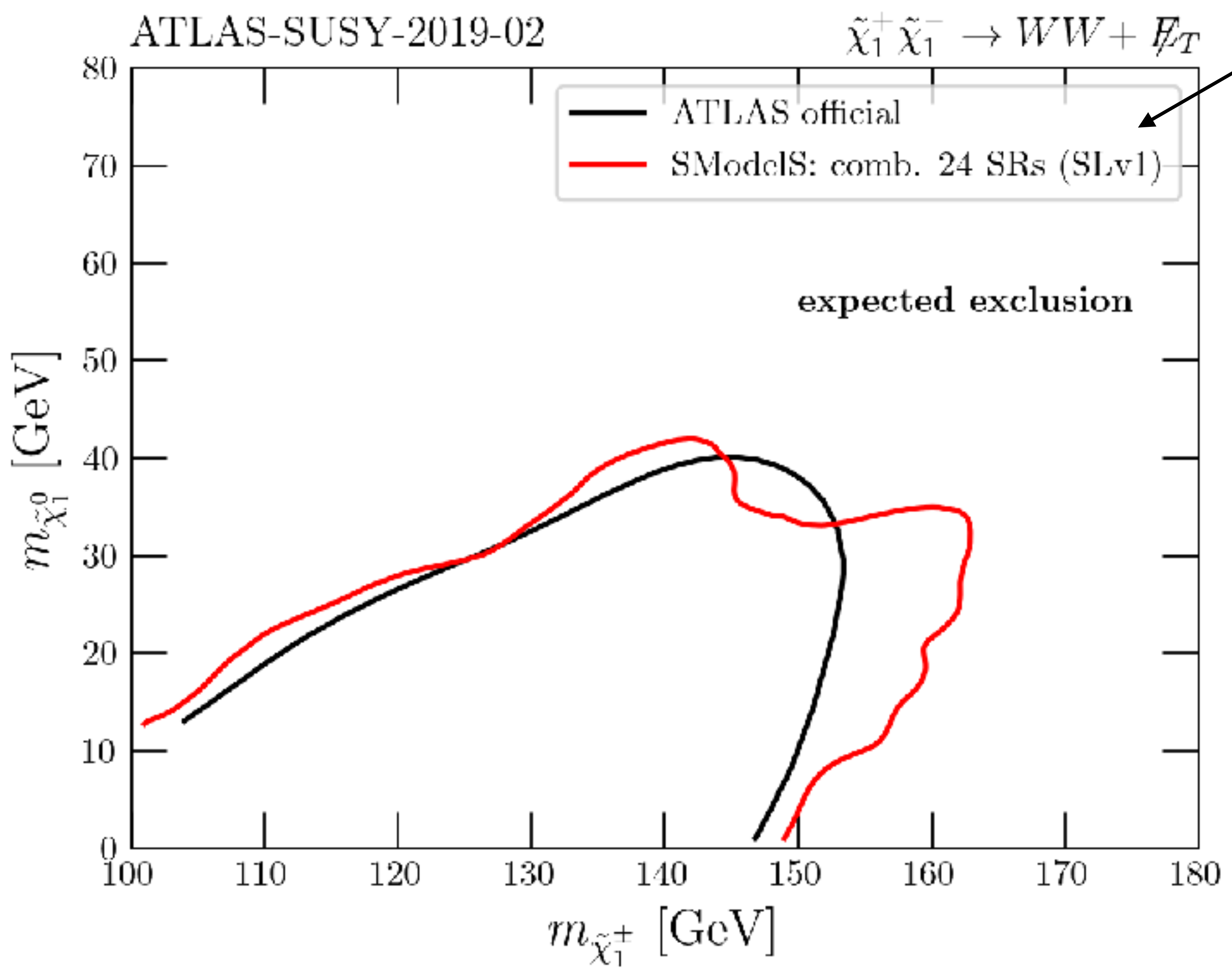


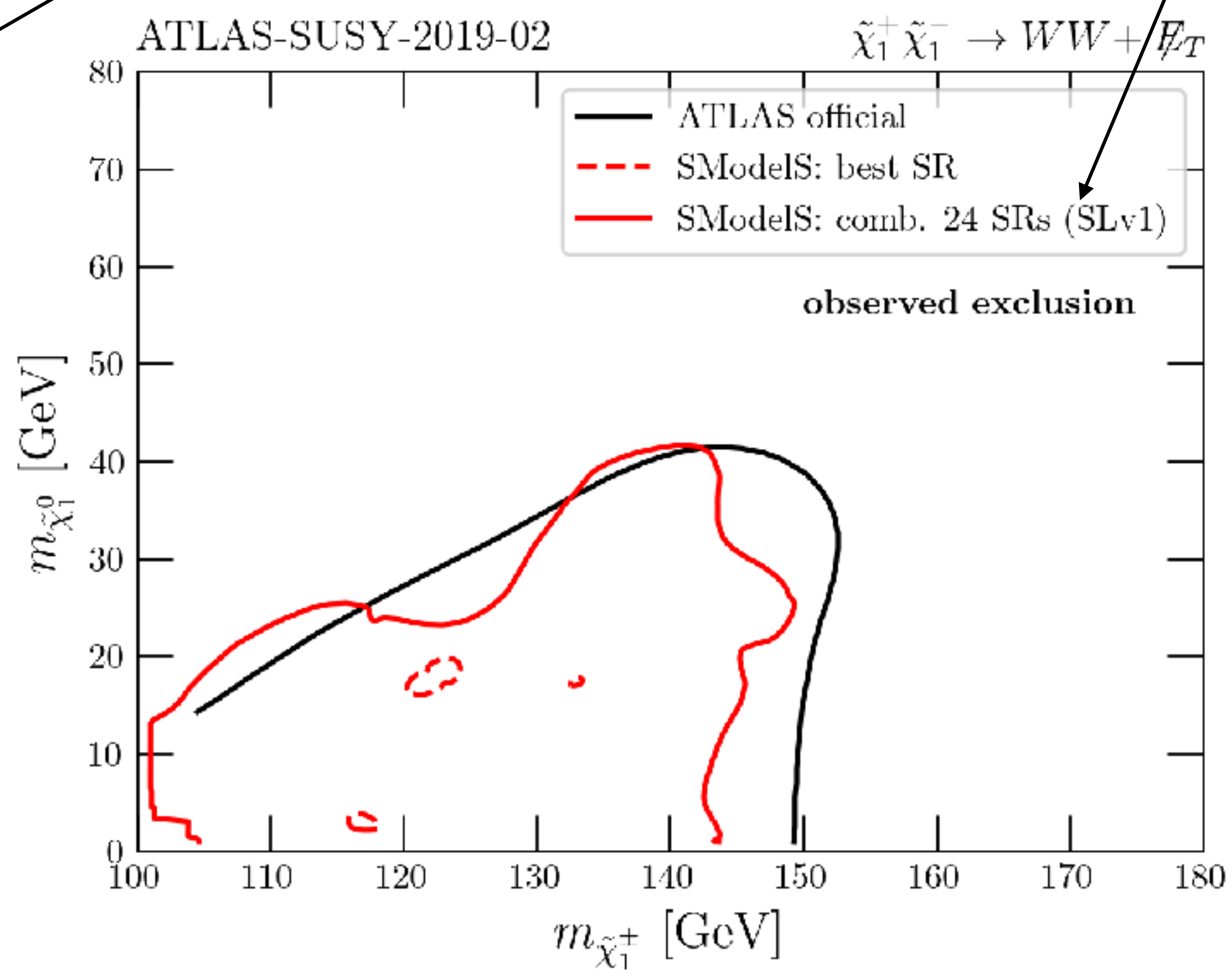
ATLAS-SUSY-2019-08: Electroweakinos in final states with one lepton, missing transverse momentum and a Higgs boson

full JSON file → good obs. limit; but why is exp. off?

HistFactory wanted

mock-up covariance matrix, assuming SF and DF SRs are independent
otherwise no sensitivity at all





plots: Sahana Narasimha

ATLAS-SUSY-2019-02: sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W-boson mass

Efficiency maps from patchsets

for pure simplified models
↓
pyhf signal patchsets shipped with the background-only JSON files
allow us to extract efficiency maps for all SRs (and the CRs)

provided we have also the exact cross sections as used in the analysis

ATLAS-SUSY-2018-41

Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum

- Analysis has 7 “exclusive” (WW, WZ, ZZ, Wh, Zh) and 3 “inclusive” (VV, VZ, Vh) signal regions

  wrt gauge bosons in the decays

- Originally published EMs only for 4Q-VV, 2B2Q-VZ, and 2B2Q-Vh SRs; supposedly independent

Region	CR0L-4Q	CR0L-2B2Q	SR-4Q-WW	SR-4Q-WZ	SR-4Q-ZZ	SR-4Q-VV
Observed	129	83	2	3	1	3
Post-fit	129 ± 11	83 ± 9	1.9 ± 0.4	3.4 ± 0.7	1.9 ± 0.5	3.9 ± 0.8
W+jets	24.2 ± 2.2	16.6 ± 2.0	0.37 ± 0.08	0.60 ± 0.13	0.26 ± 0.07	0.69 ± 0.15
Z+jets	78 ± 7	44 ± 5	1.0 ± 0.21	1.8 ± 0.4	1.26 ± 0.32	2.1 ± 0.4
VV	21.5 ± 1.9	7.1 ± 0.9	0.35 ± 0.11	0.73 ± 0.24	0.26 ± 0.09	0.79 ± 0.25
VVV	0.9 ± 0.4	0.10 ± 0.05	0.17 ± 0.09	0.19 ± 0.10	0.11 ± 0.07	0.23 ± 0.12
$t\bar{t}$	1.38 ± 0.12	7.8 ± 0.9	0.039 ± 0.009	0.060 ± 0.018	0.025 ± 0.010	0.063 ± 0.018
t+X	1.32 ± 0.12	2.87 ± 0.34	0.015 ± 0.006	0.039 ± 0.016	0.012 ± 0.005	0.039 ± 0.016
$t\bar{t}$+X	1.3 ± 0.9	3.7 ± 2.6	-	-	-	-
Other	< 0.1	0.95 ± 0.11	< 0.001	< 0.001	< 0.001	< 0.001

Region	SR-2B2Q-WZ	SR-2B2Q-Wh	SR-2B2Q-ZZ	SR-2B2Q-Zh	SR-2B2Q-VZ	SR-2B2Q-Vh
Observed	2	0	2	1	2	1
Post-fit	1.6 ± 0.4	1.9 ± 0.7	1.7 ± 0.5	1.6 ± 0.5	2.2 ± 0.6	2.5 ± 0.8
W+jets	0.11 ± 0.06	0.24 ± 0.09	0.23 ± 0.08	0.26 ± 0.10	0.26 ± 0.09	0.26 ± 0.09
Z+jets	0.84 ± 0.27	1.3 ± 0.5	0.78 ± 0.23	0.66 ± 0.24	1.15 ± 0.33	1.4 ± 0.5
VV	0.33 ± 0.11	0.09 ± 0.03	0.32 ± 0.10	0.085 ± 0.032	0.37 ± 0.11	0.085 ± 0.030
VVV	0.047 ± 0.027	< 0.01	0.051 ± 0.032	0.011 ± 0.007	0.06 ± 0.04	0.011 ± 0.007
$t\bar{t}$	0.016 ± 0.006	0.13 ± 0.04	0.064 ± 0.019	0.40 ± 0.16	0.072 ± 0.021	0.46 ± 0.18
t+X	0.11 ± 0.05	0.07 ± 0.04	0.11 ± 0.05	0.041 ± 0.022	0.11 ± 0.05	0.10 ± 0.05
$t\bar{t}$+X	0.10 ± 0.08	$0.07^{+0.10}_{-0.07}$	0.14 ± 0.12	$0.08^{+0.09}_{-0.08}$	0.18 ± 0.14	$0.10^{+0.11}_{-0.10}$
Other	< 0.01	0.03 ± 0.01	< 0.01	0.024 ± 0.008	< 0.01	0.037 ± 0.011

ATLAS-SUSY-2018-41

Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum

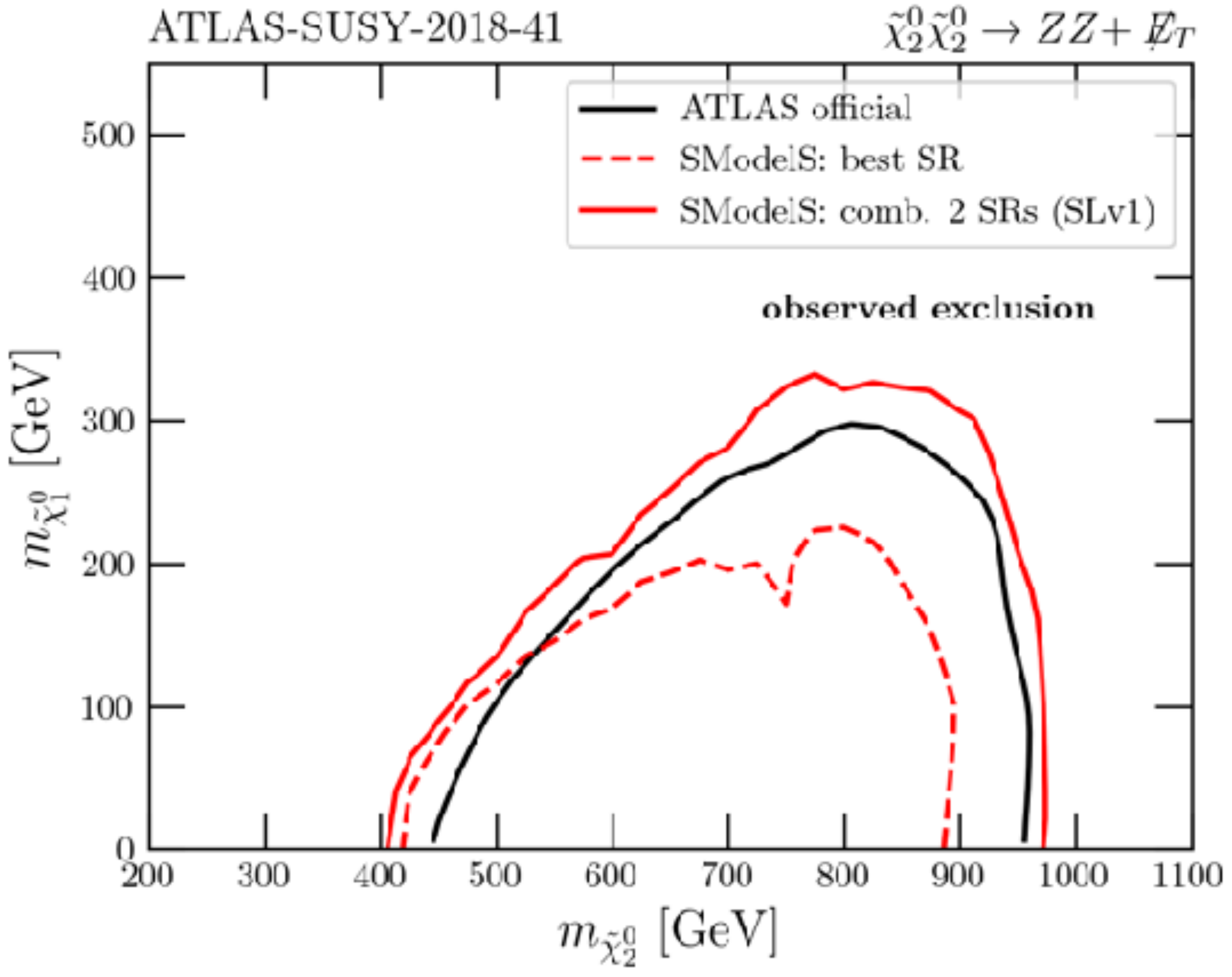
- Analysis has 7 “exclusive” (WW, WZ, ZZ, Wh, Zh) and 3 “inclusive” (VV, VZ, Vh) signal regions

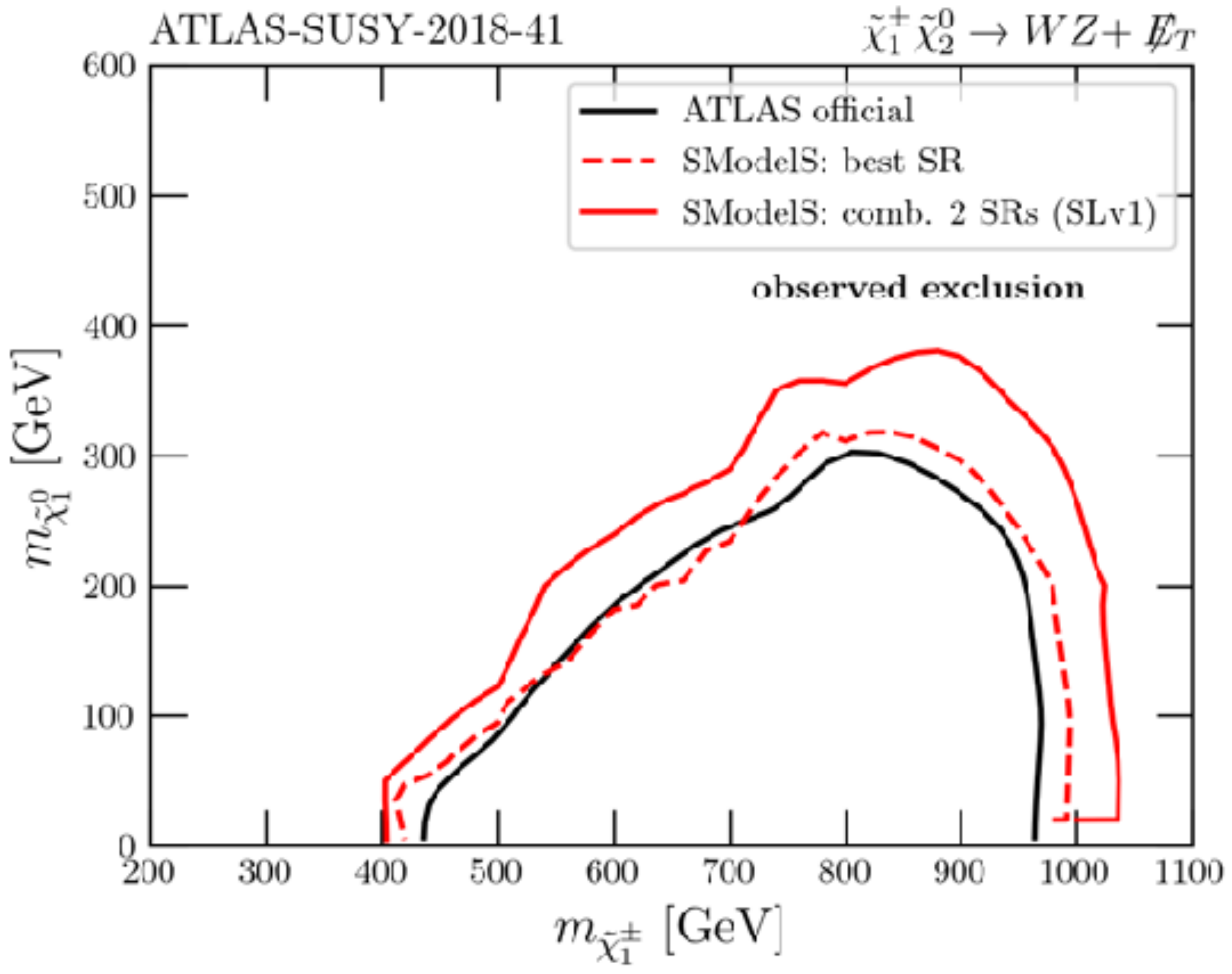
  wrt gauge bosons in the decays

- Originally published EMs only for 4Q-VV, 2B2Q-VZ, and 2B2Q-Vh SRs; supposedly independent

- Some validations worked well, others didn’t → ??

Examples:





with 4Q-VV, 2B2Q-VZ and 2B2Q-Vh EMs

ATLAS-SUSY-2018-41

Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum

- New HEPData record now contains
  - full BG-only JSON file (not only signal-specific llhds)
  - signal patchsets for “pure” simplified models
- We can extract EMs for *excl.* SRs from these
  - would be good to have also patchsets for pure ZZ, Zh and hh decay modes

```
patchset_hinoAxino_brN2H0.json → ZZ
patchset_hinoAxino_brN2H100.json → hh
patchset_hinoAxino_brN2H50.json → Zh,ZZ,hh ??
```

Version 3 modifications: Added CRs to likelihoods 2023-11-13

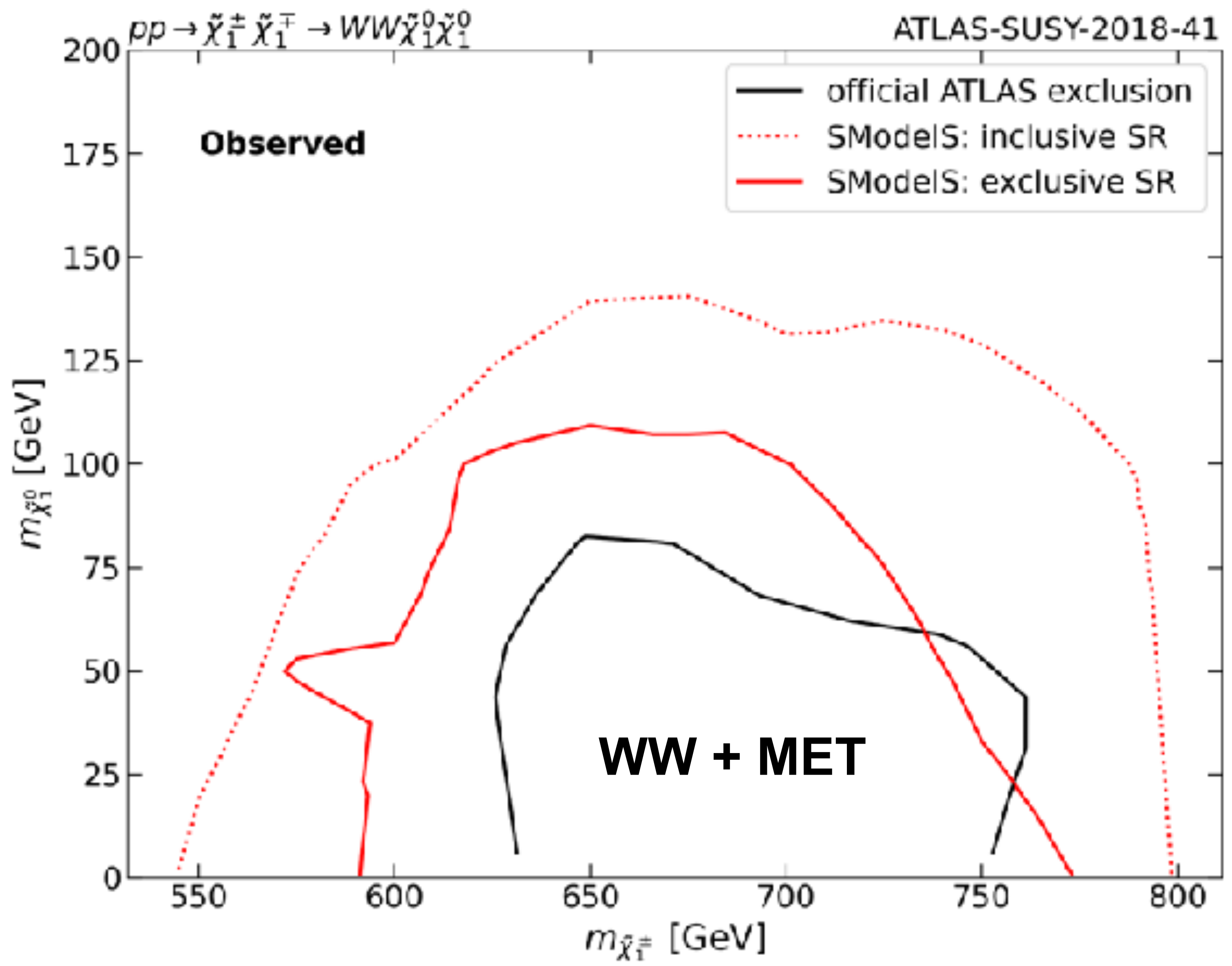
```
BGOnlyFit_fullLH.json

patchset_SM_C1C1_WW.json
patchset_SM_C1N2_Wh.json
patchset_SM_C1N2_WZ.json
```

many thanks to Shion Chen (et al.) !

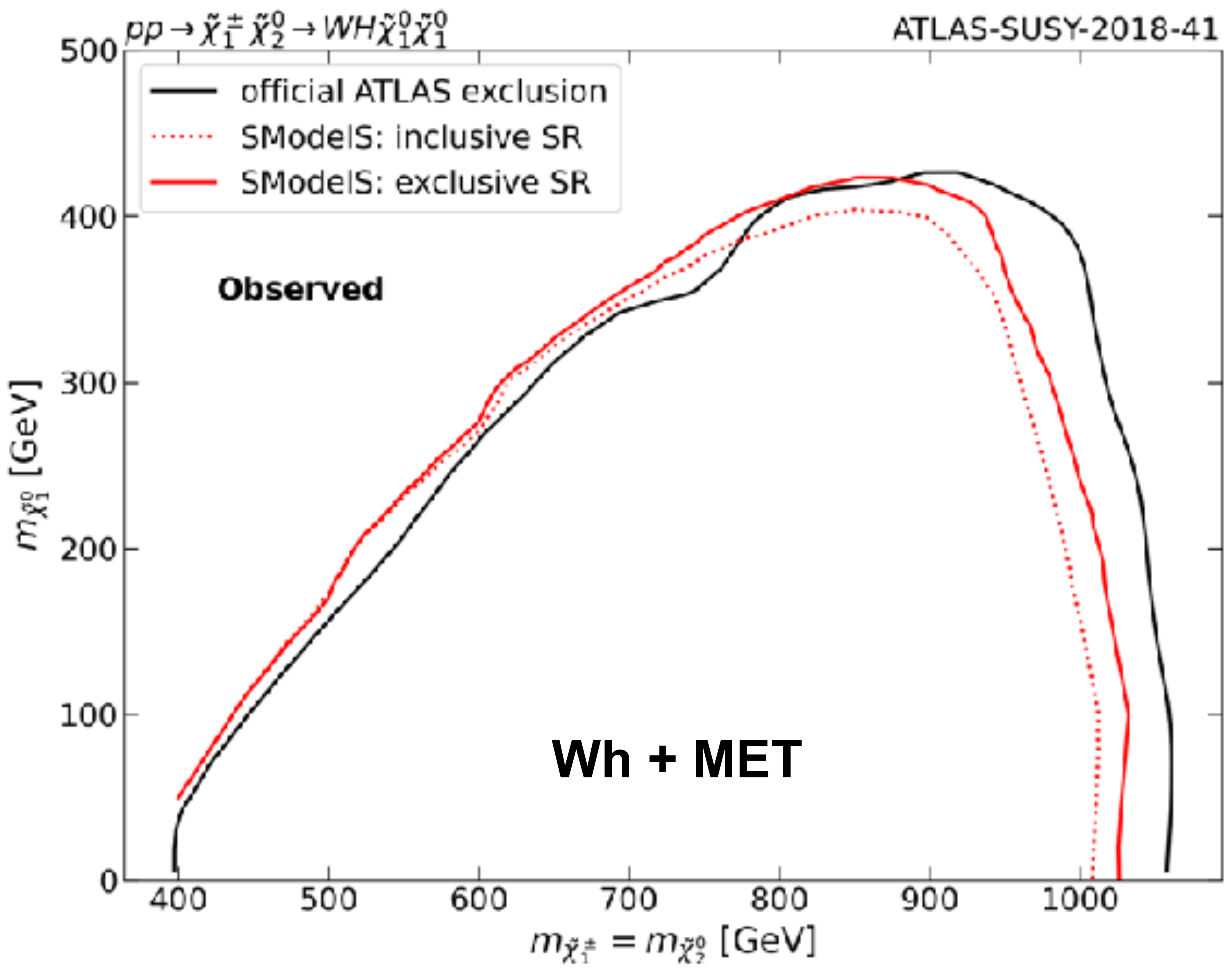
implementation and validation by Timothée Pascal

ATLAS-SUSY-2018-41 HistFactory & EMs from patchsets

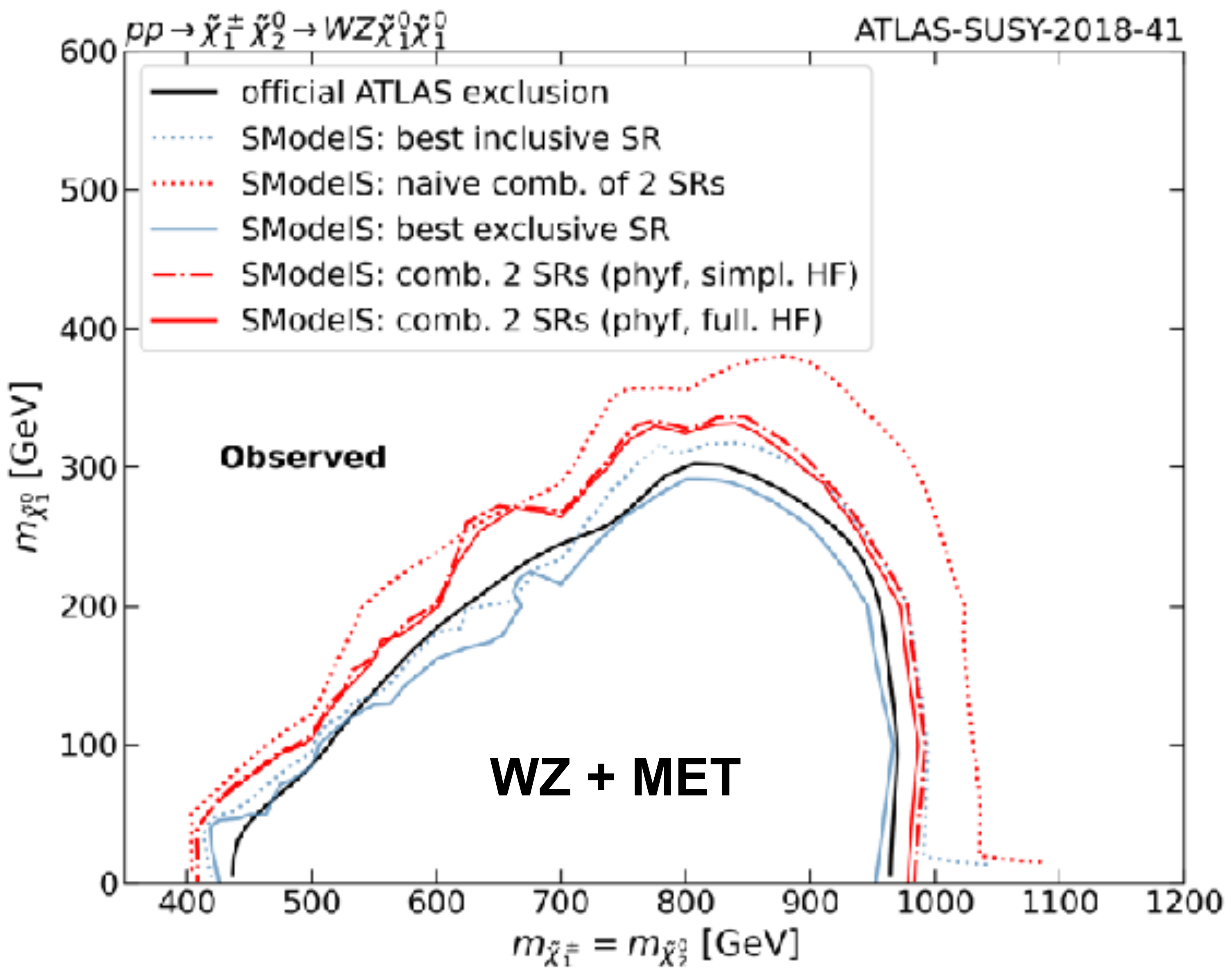
Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum



SR-4Q-WW (excl.) vs SR-4Q-VV (incl.)



SR-2B2Q-WH (excl.) vs SR-2B2Q-Vh (incl.)



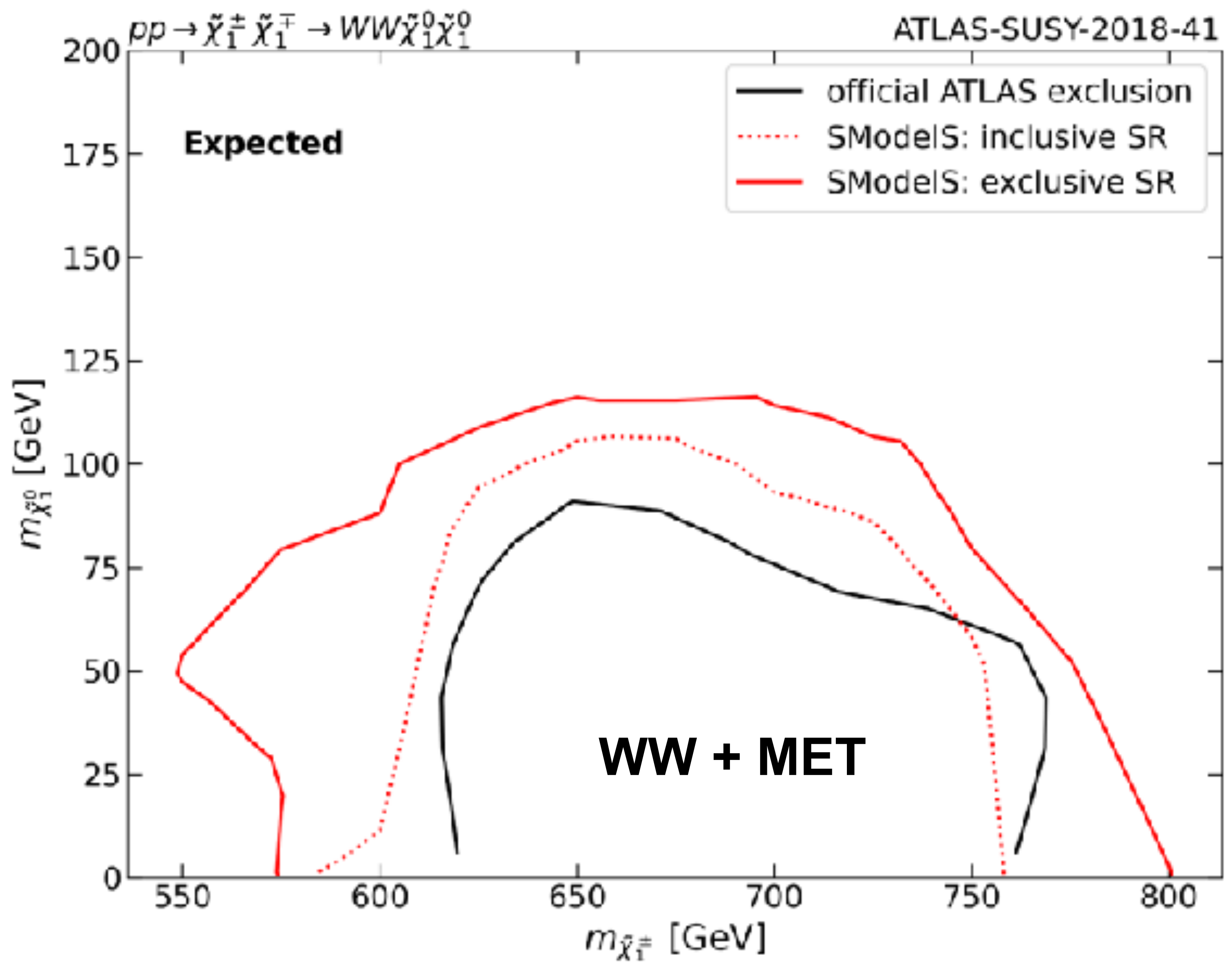
4Q-WZ + 2B2Q-WZ (excl.)
vs 4Q-VZ + 2B2Q-VZ (incl.)

Observed limits

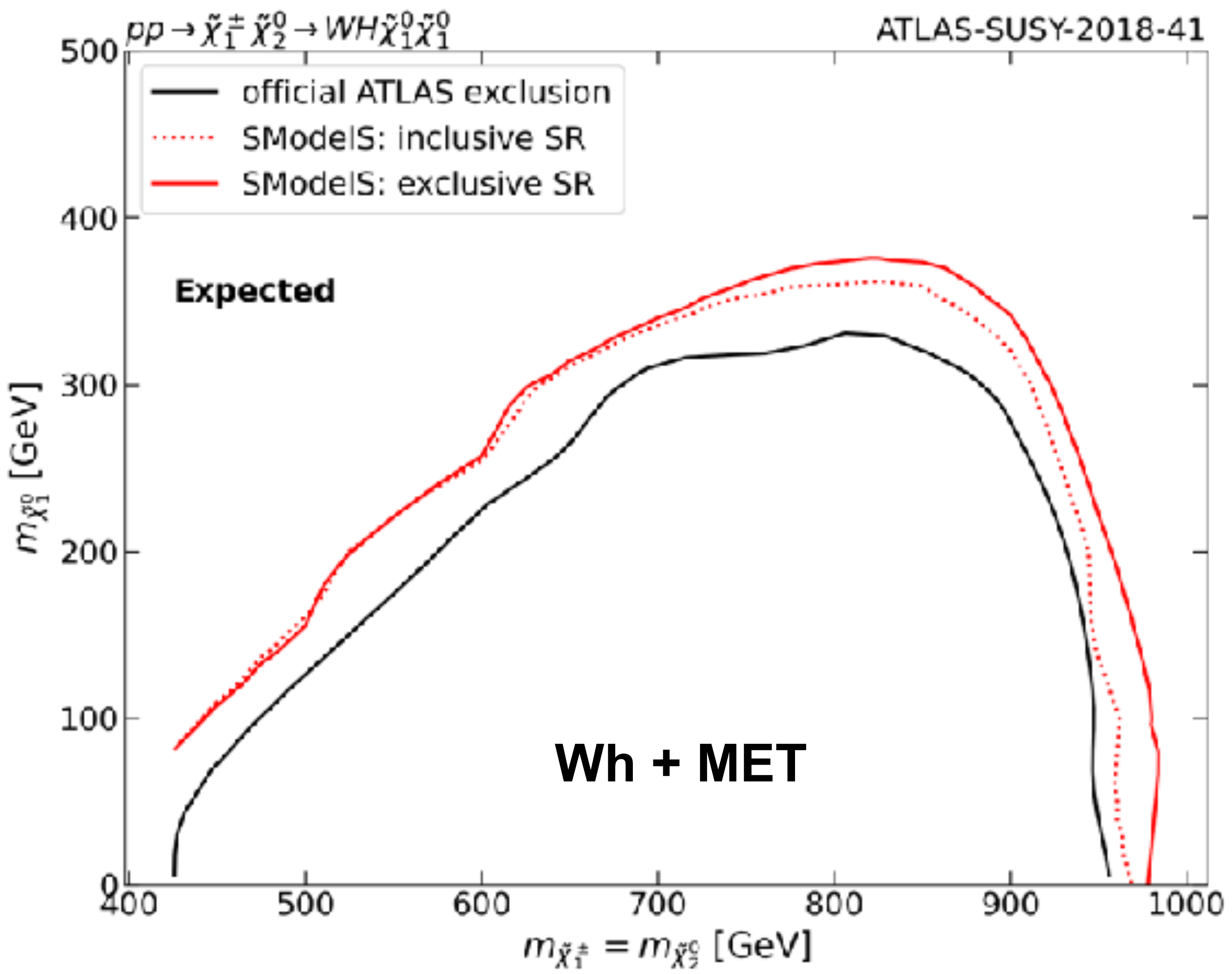
implementation and validation by Timothée Pascal

ATLAS-SUSY-2018-41 HistFactory & EMs from patchsets

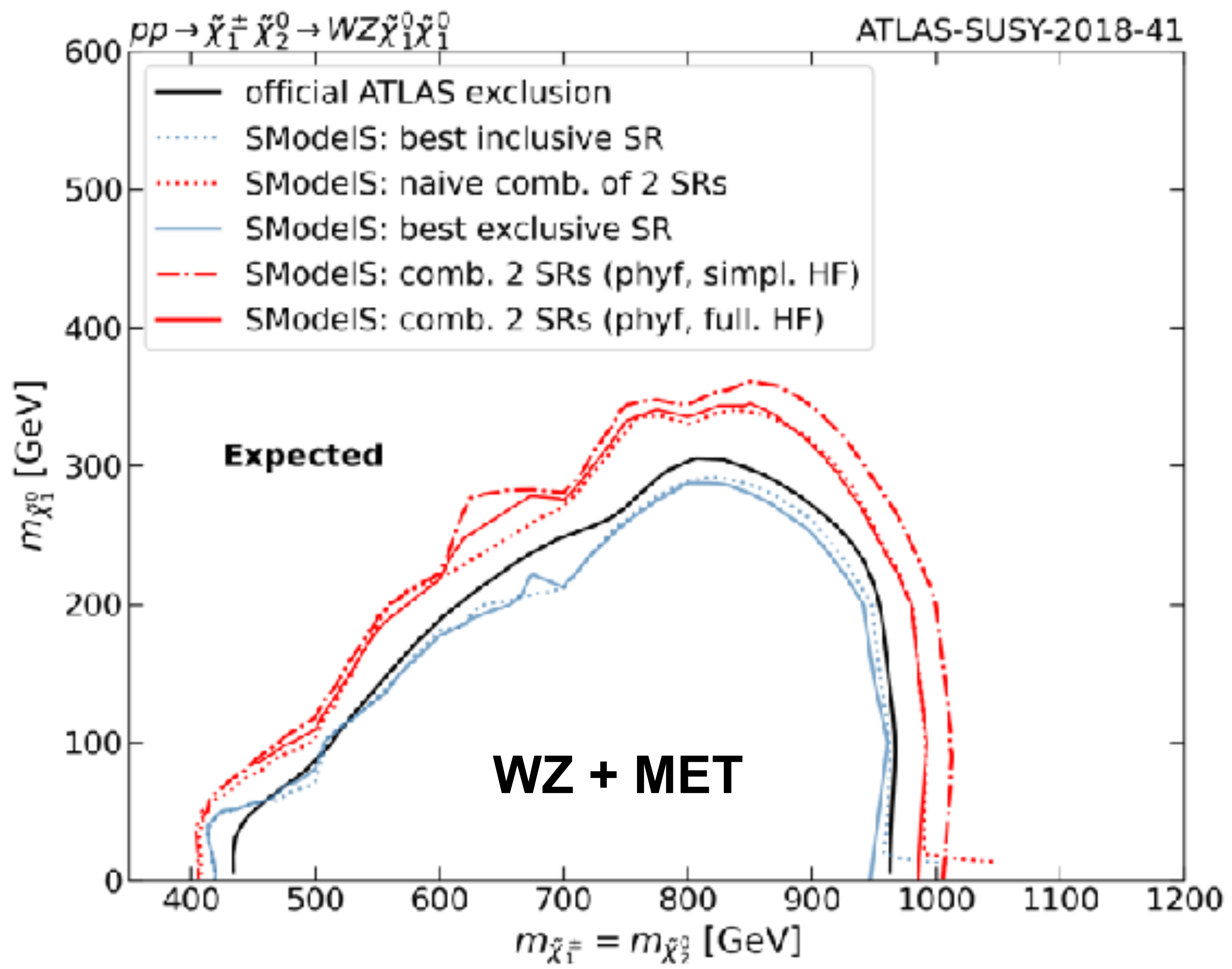
Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum



SR-4Q-WW (excl.) vs SR-4Q-VV (incl.)



SR-2B2Q-WH (excl.) vs SR-2B2Q-Vh (incl.)



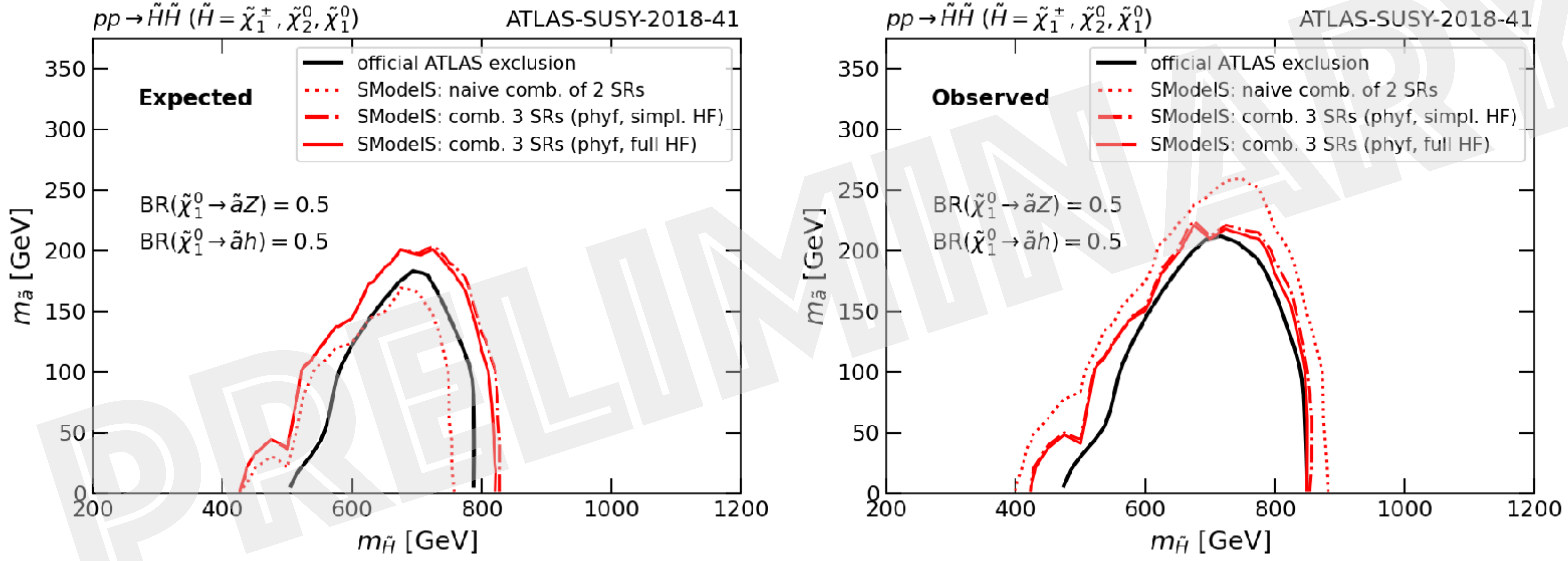
4Q-WZ + 2B2Q-WZ (excl.)
vs 4Q-VZ + 2B2Q-VZ (incl.)

Expected limits

implementation and validation by Timothée Pascal

ATLAS-SUSY-2018-41 HistFactory & EMs from patchsets

Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum



validating scenarios with mixed final states (from BRs)

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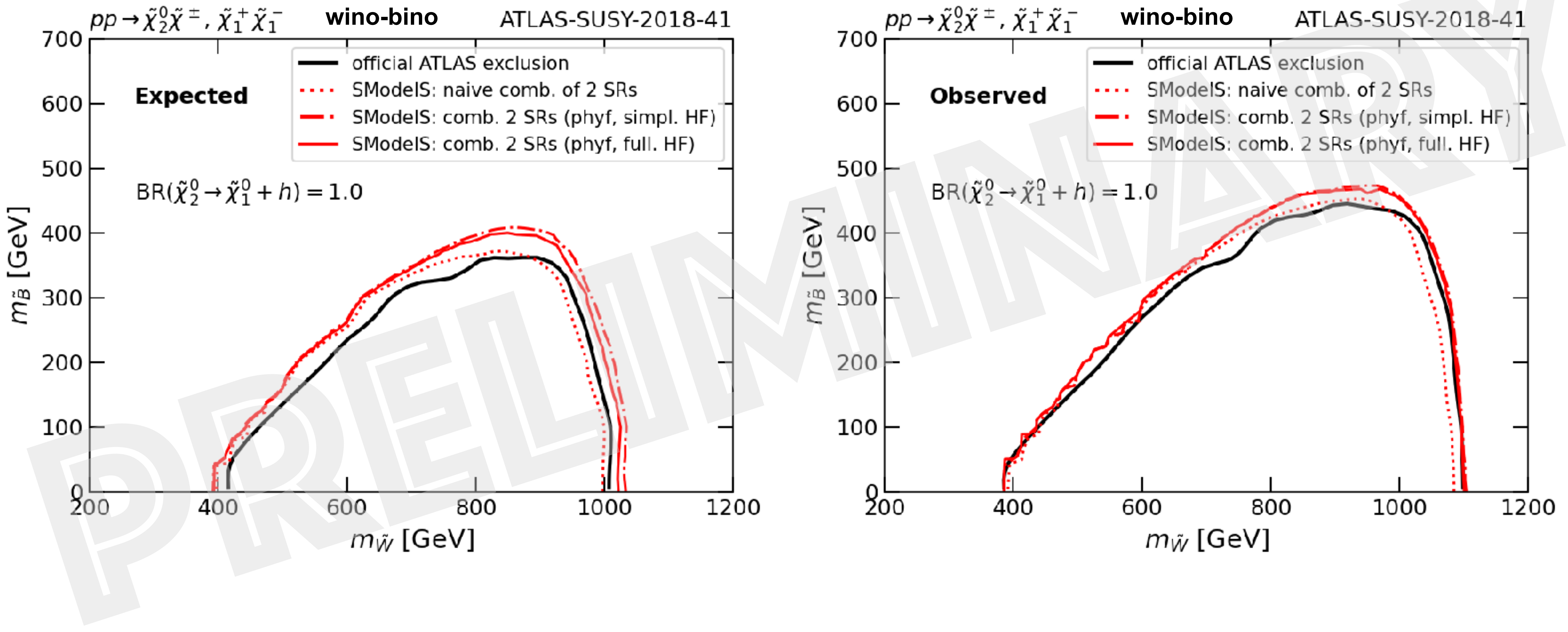
Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum



validating scenarios with mixed final states (from production)

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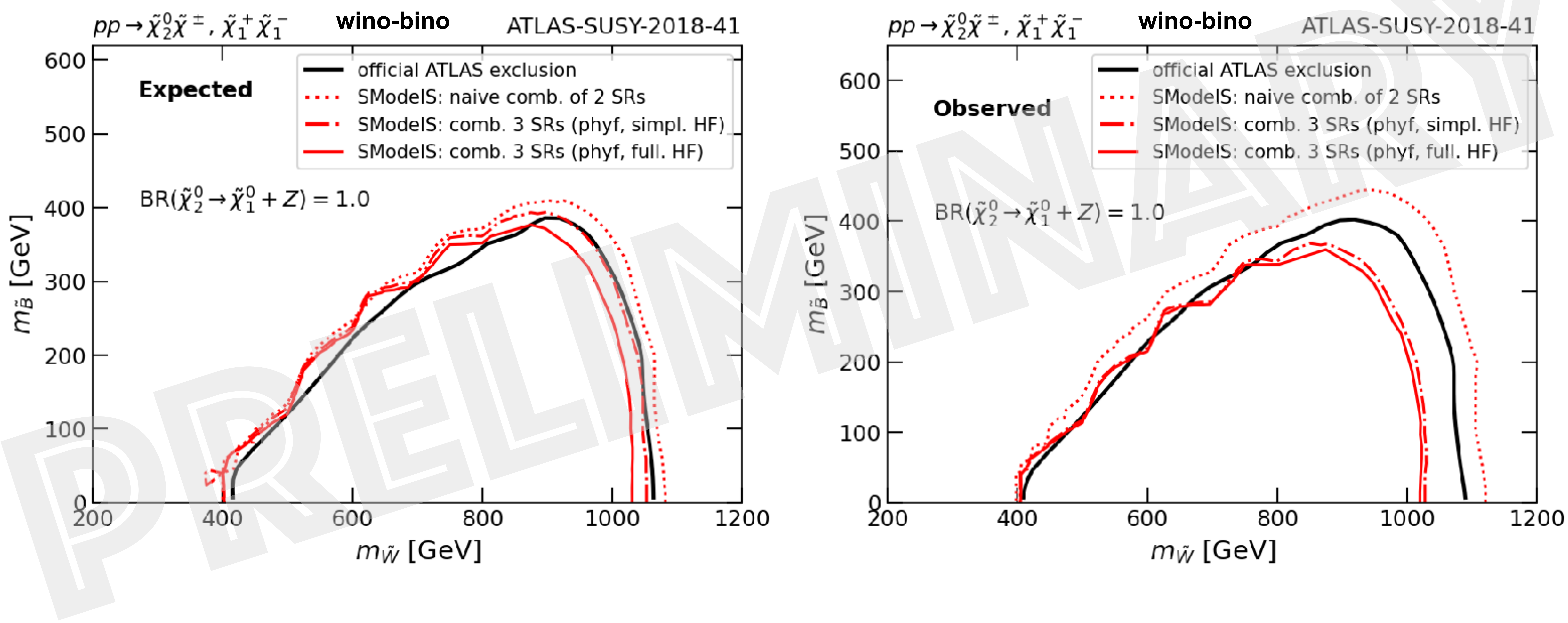


validating scenarios with mixed final states (from production)

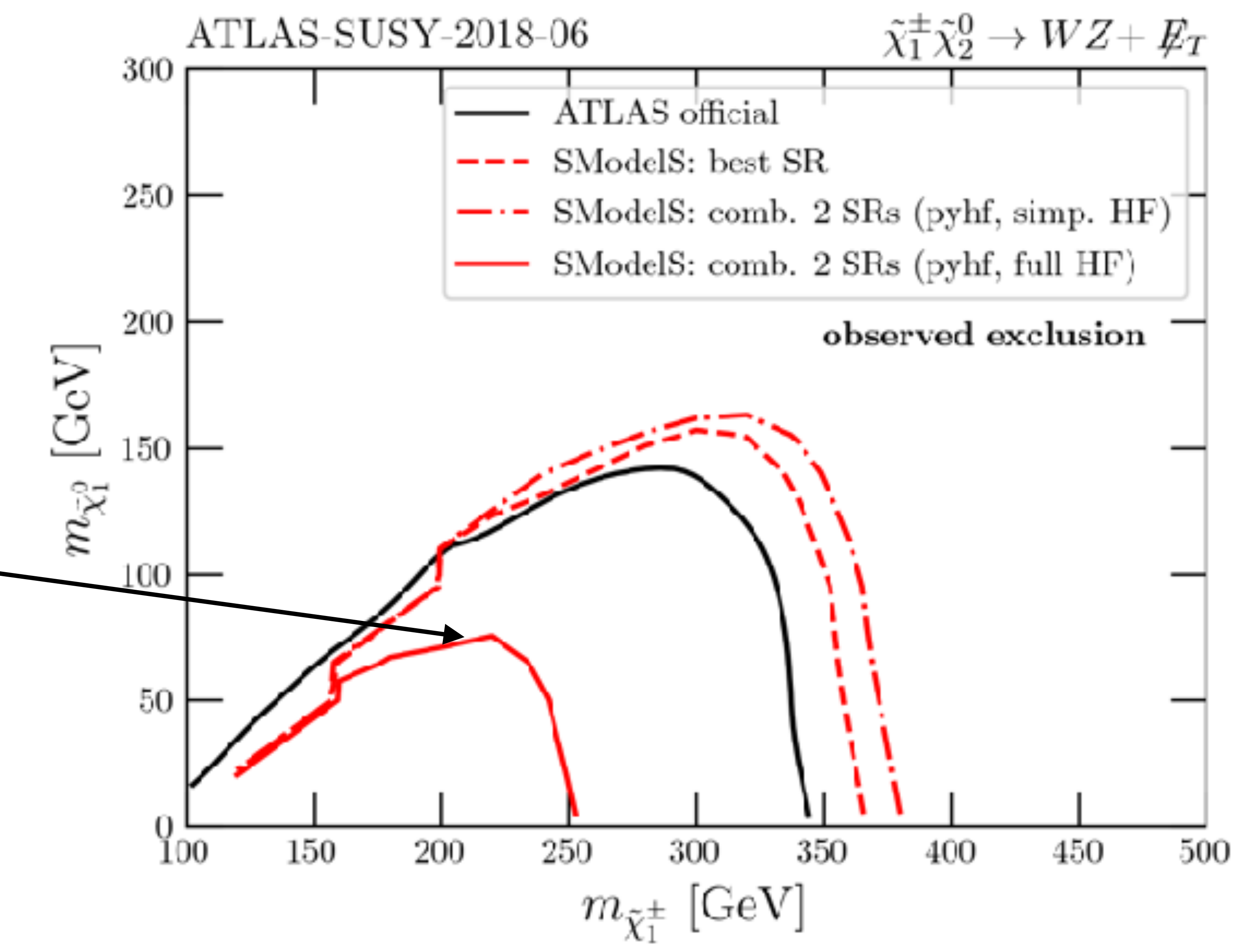
Conclusions

- [x] Full statistical models are extremely useful
- [x] In SModelS, we are mostly using `simplify`'ed ones for speed reasons
- [ ] Some differences wrt official ATLAS limits (exp vs obs limit) → ?
- [ ] Tools for different simplification schemes would be welcome,
  (e.g., simplified likelihood with linearised systematics, SLLS, by Nicolas Berger)
  but please **always** provide **the full BG-only model**
- [x] Patchsets for pure simplified models allow us to extract efficiency maps for the SModelS database (NB not possible for patchsets with mixed production/decay modes)

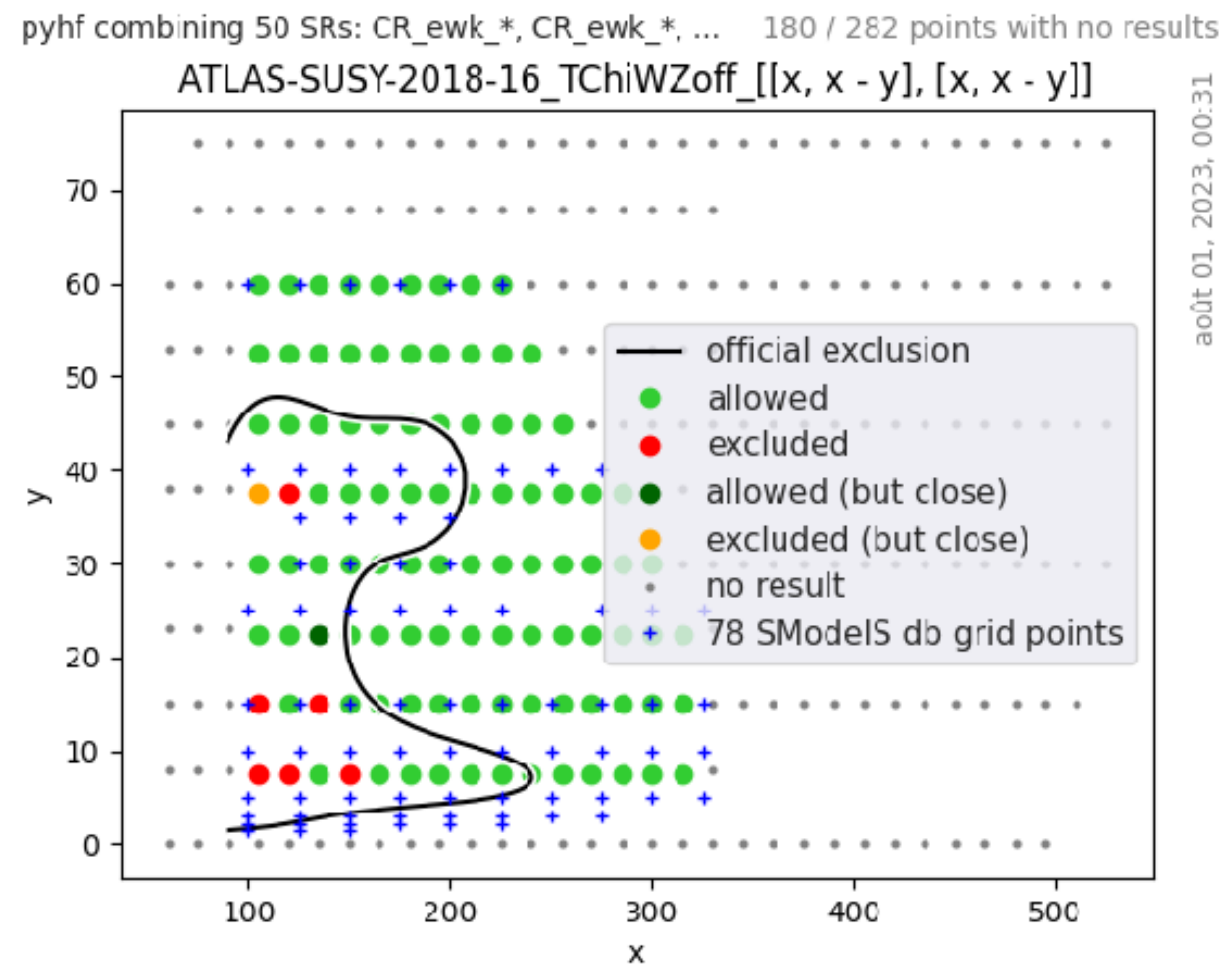
- thanks for pyhf

Open issues

- SUSY-2018-06 full llhd doesn't work properly



- SUSY-2018-16 provides full llhd, but so far we could not validate the EMs from this analysis in SModelS



- SUSY-2018-41 … questions, see above

- Backend dependence: PyTorch gives reliable results, but issues with numpy