New developments in SModelS

Timothée Pascal

on behalf of the SModelS collaboration:

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IRN Terascale at LPSC Grenoble, France - April 26, 2023

1. Inferring results from LHC Searches
   - Searching for new physics at the LHC
   - Reinterpreting Results with SModelS
2. Database updates
   - New analyses
   - Impacts on the EWino sector of the MSSM
3. Interface to Spey

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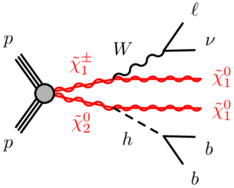
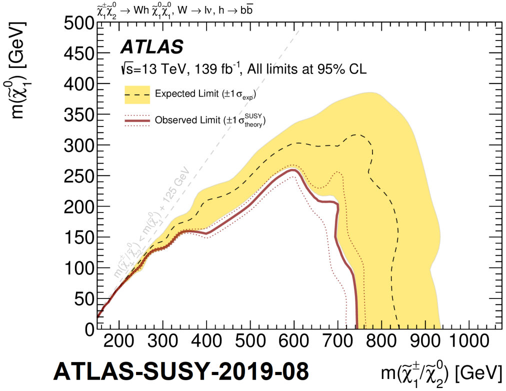
Data interpretation in LHC searches

arXiv:1105.2838

The ATLAS and CMS searches for supersymmerty (SUSY) interpret their data using simplified models (minimal set of parameters).





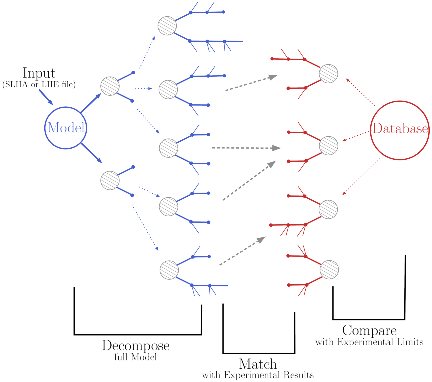
ATLAS-SUSY-2019-08

How would such results constrain a more complex model?

arXiv:2112.00769
arXiv:2009.01809
arXiv:1811.10624
arXiv:1312.4175

SModelS working principle

Public tool to confront BSM signals with a $\mathbb{Z}_2$-like symmetry against simplified model results from the LHC.



35 ATLAS and 39 CMS 13 TeV analyses in the database (v.2.2).
Code and documentation available online: https://smodels.github.io/

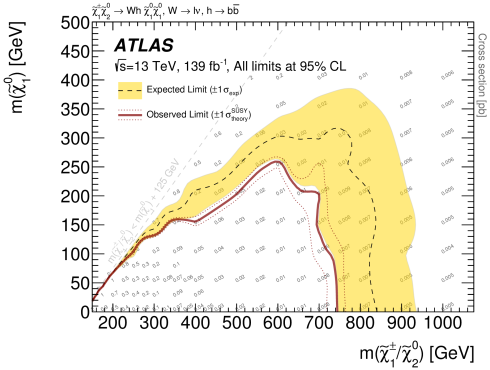
Two methods to reinterpret results

Test phase-space points and exclude it if $\boxed{r = \dfrac{\sigma^{\text{BSM}}}{\sigma^{\text{BSM}}_{\text{UL}}} \geqslant 1}$ using:

Cross-section upper limit maps:

$\sigma^{\text{BSM}} = \sum \sigma \prod \text{BR} \leftarrow$ input file.

$\sigma^{\text{BSM}}_{\text{UL}} = \sigma^{\text{BSM}}_{95\%} \leftarrow$ experimental publications.



Two methods to reinterpret results

Test phase-space points and exclude it if $\boxed{r = \frac{\sigma^{\text{BSM}}}{\sigma^{\text{BSM}}_{\text{UL}}} \geqslant 1}$ with:

Efficiency maps:

$\sigma^{\text{BSM}} = \epsilon \times \mathcal{A} \sum \sigma \prod \text{BR}$ per signal region $\leftarrow$ input file and exp. pub.

$\sigma^{\text{BSM}}_{\text{UL}} \leftarrow$ exp. pub. or computed through an hypothesis test:

$$\sigma^{\text{BSM}}_{\text{UL}} = \frac{s_{\text{UL}}}{\mathcal{L}} = \mu_{\text{UL}} \frac{s}{\mathcal{L}}, \quad s = n_{\text{signal}}.$$

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$$\sigma^{\text{BSM}}_{\text{UL}} = \frac{s_{\text{UL}}}{\mathcal{L}} = \mu_{\text{UL}} \frac{s}{\mathcal{L}}, \quad s = n_{\text{signal}}.$$

For 1 signal region:

$$L(\mu, \theta | D) = \frac{(\mu \times s + b + \theta)^{n^{obs}} e^{-(\mu \times s + b + \theta)}}{n^{obs}!} e^{-\frac{\theta^2}{2\delta^2}} .$$

Efficiency maps allow SModelS to compute likelihoods for the hypothesised signal $\rightarrow$ more than a binary information (excluded or not).

arXiv:2009.01809
arXiv:1811.10624

Using efficiency maps to reinterpret results

Signal region combination is possible using full statistical models (ATLAS), encoded in a json file and interfaced to SModelS with pyhf.

HistFactory likelihood:

$$L(\mu, \theta|D) = \prod_{i=1}^{N} \frac{(\mu s_i + b_i + \theta_i)^{n_i^{obs}} e^{-(\mu s_i + b_i + \theta_i)}}{n_i^{obs}!} \prod_{\theta \in \{\theta\}} c_\theta(a_\theta|\theta).$$

The correlations can otherwise be encoded in a covariance matrix (CMS).

Simplified likelihood:

$$L(\mu, \theta|D) = \prod_{i=1}^{N} \frac{(\mu s_i + b_i + \theta_i)^{n_i^{obs}} e^{-(\mu s_i + b_i + \theta_i)}}{n_i^{obs}!} e^{-\frac{1}{2}\overrightarrow{\theta}^T V^{-1} \overrightarrow{\theta}}.$$

1. Inferring results from LHC Searches
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Newcomers with database v.2.3

ID	Short Description	$\mathcal{L}$ [fb^{-1}]	UL$_{\text{obs}}$	UL$_{\text{exp}}$	EM	comb.
CMS-SUS-19-009	$\tilde{t}\tilde{t}$ into 1ℓ + jets + $\not\!\!E_T$	137.0	$\checkmark$	$\checkmark$		
CMS-SUS-19-010	Hadronic search for $\tilde{t}\tilde{t}$	137.0	$\checkmark$	$\checkmark$		
CMS-SUS-20-004	$\tilde{H}\tilde{H}$ into $2h$ + $\not\!\!E_T$	137.0	$\checkmark$	$\checkmark$	($\checkmark$)	Cov.
CMS-SUS-21-002	Hadronic search for $\tilde{\chi}^{\pm}_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$	137.0	$\checkmark$	$\checkmark$	($\checkmark$)	Cov.
CMS-SUS-21-007	$\tilde{g}\tilde{g}$ into 1ℓ + jets + $\not\!\!E_T$	138.0	$\checkmark$			
ATLAS-SUSY-2013-12	$\tilde{\chi}^0_2\tilde{\chi}^{\pm}_1$ into 3ℓ + $\not\!\!E_T$	20.3	$\checkmark$		$\checkmark$	
ATLAS-SUSY-2018-05	$\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$, $\tilde{\chi}\tilde{\chi}$ into 2ℓ + jets + $\not\!\!E_T$	139.0	$\checkmark$		$\checkmark$	JSON
ATLAS-SUSY-2018-32	$\tilde{\ell}\tilde{\ell}$, $\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ into 2ℓ + $\not\!\!E_T$	139.0	$\checkmark$		$\checkmark$	JSON
ATLAS-SUSY-2018-41	Hadronic search for $\tilde{\chi}^{\pm}$, $\tilde{\chi}^0$	139.0	$\checkmark$	$\checkmark$	($\checkmark$)	Cov.
ATLAS-SUSY-2018-42	Charged LLPs ($\tilde{\ell}\tilde{\ell}$ into 2ℓ)	139.0	$\checkmark$	$\checkmark$		
ATLAS-SUSY-2018-42	Charged LLPs ($\tilde{g}\tilde{g}$ into jets)	139.0	$\checkmark$	$\checkmark$	($\checkmark$)	Cov.
ATLAS-SUSY-2019-02	$\tilde{\ell}\tilde{\ell}$, $\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ into 2ℓ + $\not\!\!E_T$	139.0	$\checkmark$		($\checkmark$)	Cov.

$\checkmark$: already in v.2.2 $\checkmark$: new in v.2.3

Newcomers with database v.2.3

ID	Short Description	$\mathcal{L}$ [fb^{-1}]	UL$_{obs}$	UL$_{exp}$	EM	comb.
CMS-SUS-19-009	$\tilde{t}\tilde{t}$ into 1ℓ + jets + $\not{E}_T$	137.0	✓	✓		
CMS-SUS-19-010	Hadronic search for $\tilde{t}\tilde{t}$	137.0	✓	✓		
CMS-SUS-20-004	$\tilde{H}\tilde{H}$ into $2h$ + $\not{E}_T$	137.0	✓	✓	(✓)	Cov.
CMS-SUS-21-002	Hadronic search for $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$	137.0	✓	✓	(✓)	Cov.
CMS-SUS-21-007	$\tilde{g}\tilde{g}$ into 1ℓ + jets + $\not{E}_T$	138.0	✓			
ATLAS-SUSY-2013-12	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ into 3ℓ + $\not{E}_T$	20.3	✓		✓	
ATLAS-SUSY-2018-05	$\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$, $\tilde{\chi}\tilde{\chi}$ into 2ℓ + jets + $\not{E}_T$	139.0	✓		✓	JSON
ATLAS-SUSY-2018-32	$\tilde{\ell}\tilde{\ell}$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ into 2ℓ + $\not{E}_T$	139.0	✓		✓	JSON
ATLAS-SUSY-2018-41	Hadronic search for $\tilde{\chi}^\pm$, $\tilde{\chi}^0$	139.0	✓	✓	(✓)	Cov.
ATLAS-SUSY-2018-42	Charged LLPs ($\tilde{\ell}\tilde{\ell}$ into 2ℓ)	139.0	✓	✓		
ATLAS-SUSY-2018-42	Charged LLPs ($\tilde{g}\tilde{g}$ into jets)	139.0	✓	✓	(✓)	Cov.
ATLAS-SUSY-2019-02	$\tilde{\ell}\tilde{\ell}$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ into 2ℓ + $\not{E}_T$	139.0	✓		(✓)	Cov.

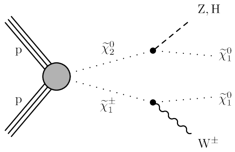
✓: already in v.2.2 ✓: new in v.2.3

best SR simplified likelihood HistFactory model

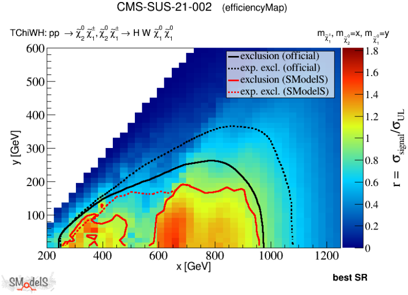
CMS-SUS-21-002

arXiv:2205.09597

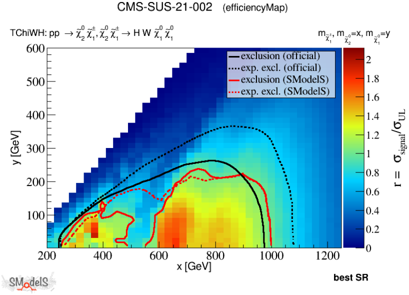
13 TeV search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to$ jets + MET.
Implementation of efficiency maps + cov. matrix:



Without combination of signal regions:



Fiducial σ_{UL}^{BSM} from published tables

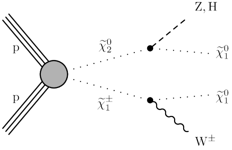


Fiducial σ_{UL}^{BSM} computed with SModelS

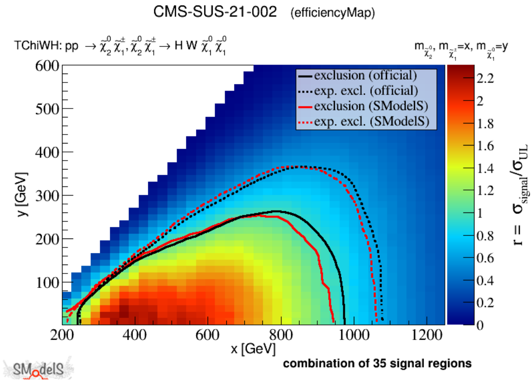
CMS-SUS-21-002

arXiv:2205.09597

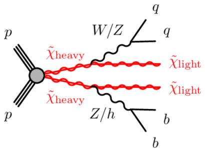
13 TeV search for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow$ jets + MET.
Implementation of efficiency maps + cov. matrix:



Combination of 35 signal regions:



ATLAS-SUSY-2018-41

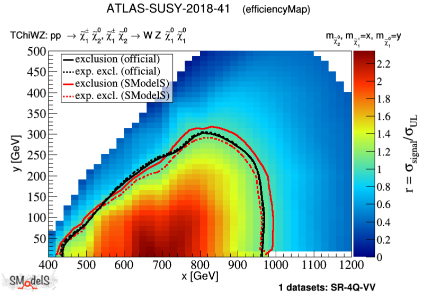


arXiv:2108.07586

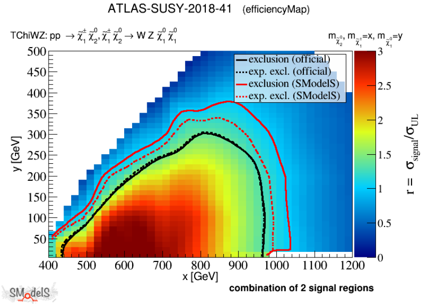
13 TeV search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to$ jets + MET.
Corrected previous implementation for:

	$n(W_{qq})$	$n(Z_{qq})$	$n(V_{qq})$	$n(Z_{bb})$	$n(H_{bb})$
4Q-WW	$= 2$	-	$= 2$	$= 0$	$= 0$
4Q-WZ	≥ 1	≥ 1	$= 2$	$= 0$	$= 0$
4Q-ZZ	-	$= 2$	$= 2$	$= 0$	$= 0$
4Q-VV	-	-	$= 2$	$= 0$	$= 0$

	$n(W_{qq})$	$n(Z_{qq})$	$n(V_{qq})$	$n(Z_{bb})$	$n(H_{bb})$
2B2Q-WZ	$= 1$	-	$= 1$	$= 1$	$= 0$
2B2Q-ZZ	-	$= 1$	$= 1$	$= 1$	$= 0$
2B2Q-Wh	$= 1$	-	$= 1$	$= 0$	$= 1$
2B2Q-Zh	-	$= 1$	$= 1$	$= 0$	$= 1$
2B2Q-VZ	-	-	$= 1$	$= 1$	$= 0$
2B2Q-Vh	-	-	$= 1$	$= 0$	$= 1$

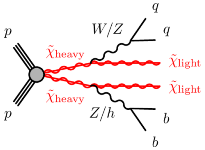


1 signal region



Combination of 2 signal regions

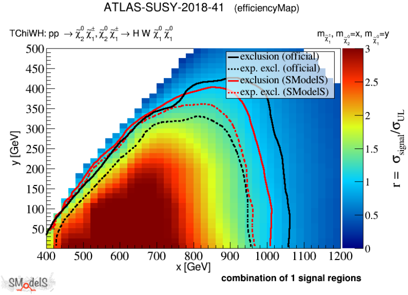
ATLAS-SUSY-2018-41



arXiv:2108.07586

13 TeV search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow$ jets + MET.
Reasonably good implementation for:

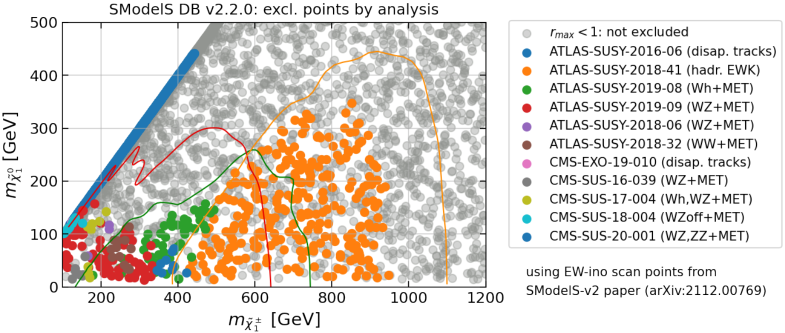
	$n(W_{qq})$	$n(Z_{qq})$	$n(V_{qq})$	$n(Z_{bb})$	$n(H_{bb})$
2B2Q-WZ	$= 1$	-	$= 1$	$= 1$	$= 0$
2B2Q-ZZ	-	$= 1$	$= 1$	$= 1$	$= 0$
2B2Q-Wh	$= 1$	-	$= 1$	$= 0$	$= 1$
2B2Q-Zh	-	$= 1$	$= 1$	$= 0$	$= 1$
2B2Q-VZ	-	-	$= 1$	$= 1$	$= 0$
2B2Q-Vh	-	-	$= 1$	$= 0$	$= 1$



1 signal region

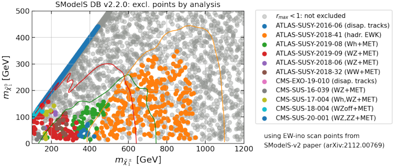
Impacts on the EWino sector of the MSSM

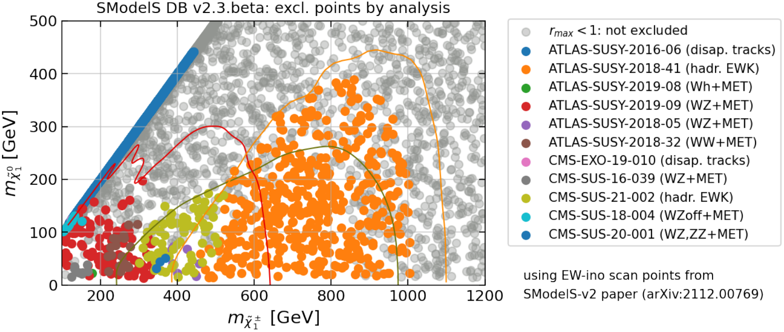
$$
\begin{aligned}
10\text{ GeV} < \quad & M_1 \approx M_{\tilde{B}} & < 3\text{ TeV}, \\
100\text{ GeV} < \quad & M_2 \approx M_{\tilde{W}} & < 3\text{ TeV}, \\
100\text{ GeV} < \quad & \mu \approx M_{\tilde{H}} & < 3\text{ TeV}, \\
5 < \quad & \tan\beta = \frac{v_2}{v_1} & < 50.
\end{aligned}
$$



using EW-ino scan points from SModelS-v2 paper (arXiv:2112.00769)

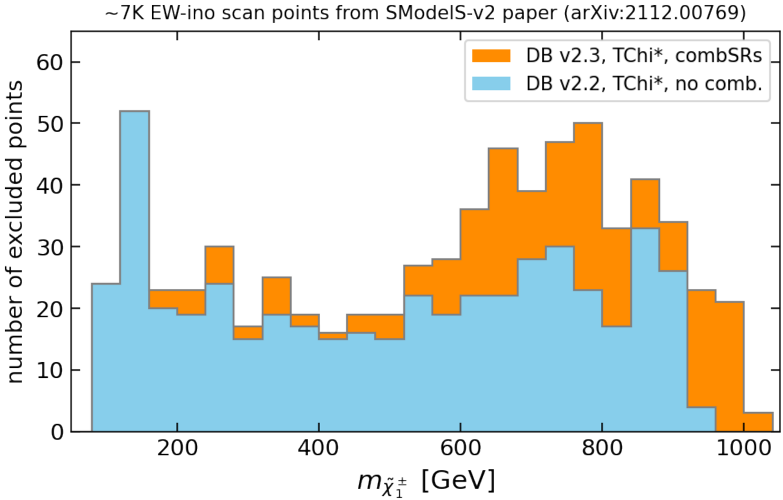
Impacts on the EWino sector of the MSSM





using EW-ino scan points from
SModelS-v2 paper (arXiv:2112.00769)

Impacts on the MSSM EWino sector



What is Spey?

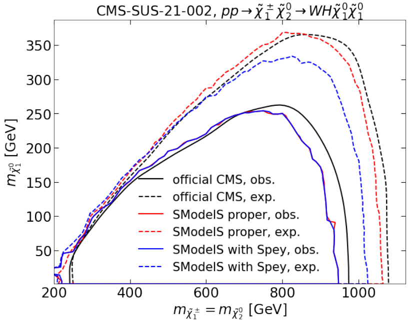
- Spey: Statistical analysis for Phenomenology from Experimental Yields.
- Under development by Jack Araz (IPPP Durham).
- A new statistics tool which can simultaneously use various backends and efficiently combine them within one statistical model.
- For the moment, implemented backends are: pyhf and simplified likelihood framework.

Why switch to Spey?

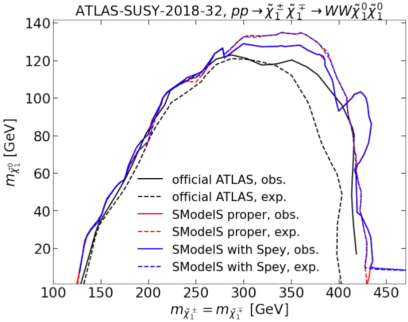
- Clearer code/centralize the statistical computations.
- Reinterpretation tools can all interface to the same, well-tested framework.
- Proper way to combine statistical models from different backends.
- Easy way to implement new backends (e.g. linearized systematic uncertainties, see Nicolas Berger's talk right after).

Work in progress

- Substitution of SModelS statistical computations by Spey.
  ↳ L_{BSM}, L_{SM}, L_{max}, $\mu^{\text{exp}}_{\text{UL}}$, $\mu^{\text{obs}}_{\text{UL}}$
- Consistency checks and revalidation of all experimental results in the database.



Combination of 35 signal regions



Combination of 39 regions (36 SR + 3 CR)

Spey for the combination of analyses

From SModelS v.2.2 on, it is possible to combine uncorrelated analyses.

$$L_{\text{combined}}(\mu) = \prod_i L_i(\mu, \theta_i | D_i)$$

Will fix some issues when combining analyses with different backends.

```
#Select running mode
[options]
checkInput = True ;Set True to check the input file for possible errors
doInvisible = True ;Set True if invisible compression should be performed, False elsewise
doCompress = True ;Set True if mass compression should be performed, False elsewise
computeStatistics = True ;Set True to compute the likelihoods L_BSM, L_SM and L_max for EM-type
testCoverage = True ;Set True if topologies not covered by experiments (missing topologies) shou
combineSRs = True ;Set True to combine signal regions when covariance matrix or pyhf JSON likeli
(faster).
combineAnas = ATLAS-SUSY-2018-41,ATLAS-SUSY-2019-08,ATLAS-SUSY-2019-09,CMS-SUS-20-001 ; list of
only. Use with care! (Also, for the time being, it is advisable to use only if combineSRs=False)

reportAllSRs = False ;Set True to report all signal regions, instead of best signal region only.
```

SModelS parameters.ini file.

Conclusion

→ SModelS v.2.3 (to be realesed soon):

- 11 new or upgraded analyses (5 CMS and 6 ATLAS) in the database.
  ↳ CMS: 2 simplified likelihoods
  ↳ ATLAS: 2 full likelihoods
  2 simplified likelihoods
  1 best SR likelihood
- Delegation of statistical computations to Spey.
  ↳ likelihoods, observed and expected upper limits on μ
- Full set of EWino searches and improved statistics tool.
  ↳ Robust combination of EWino searches

→ Future:

- SModelS v.3.0: constrain models without a $\mathbb{Z}_2$-like symmetry.

Acknowledgments

Many thanks to the IRN Terascale organizers and to the coordinators of the methods and tools session.

This work was funded thanks to the ANR-15-IDEX-02 (APM@LHC), ANR-21-CE31-0023 (PRCI SLDNP) and IN2P3 master project "Théorie – BSMGA".

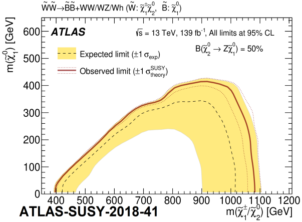
Backup Slides

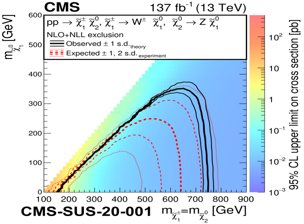
ATLAS-SUSY-2018-41

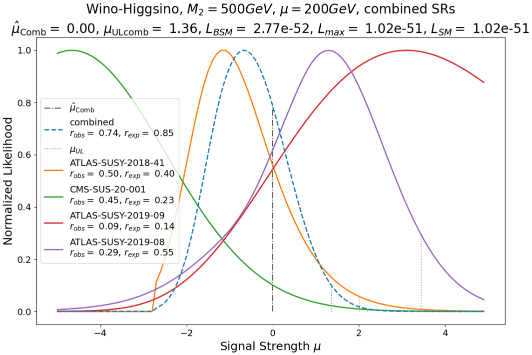
Region	CR0L-4Q	CR0L-2B2Q	SR-4Q-WW	SR-4Q-WZ	SR-4Q-ZZ	SR-4Q-VV
Observed	129	83	2	3	1	3
Post-fit	129 ± 11	83 ± 9	1.9 ± 0.4	3.4 ± 0.7	1.9 ± 0.5	3.9 ± 0.8
W+jets	24.2 ± 2.2	16.6 ± 2.0	0.37 ± 0.08	0.60 ± 0.13	0.26 ± 0.07	0.69 ± 0.15
Z+jets	78 ± 7	44 ± 5	1.0 ± 0.21	1.8 ± 0.4	1.26 ± 0.32	2.1 ± 0.4
VV	21.5 ± 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

$$L_{\text{combined}}(\mu) = \prod_i L_i(\mu, \theta_i | D_i)$$

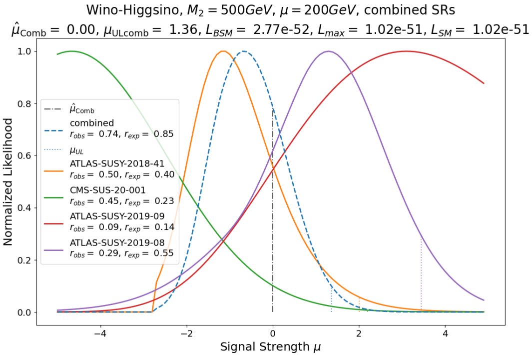


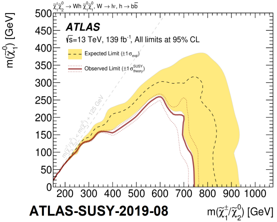


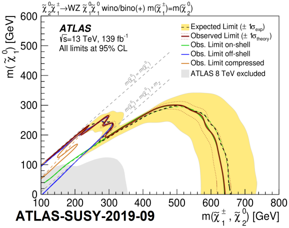


Under-fluctuation in the background leads to negative $\hat{\mu}$.

$$L_{\text{combined}}(\mu) = \prod_i L_i(\mu, \theta_i | D_i)$$







Excess in the data leads to positive $\hat{\mu}$.

Database v.2.2.0:

Run 2 - 13 TeV

In total, we have results from 35 ATLAS and 39 CMS 13 TeV searches.

- ATLAS upper limits: 32 analyses, 80 (of which 4 LLP) results
- ATLAS efficiency maps: 21 analyses, 65 (of which 11 LLP) results, 599 individual maps
- CMS upper limits: 36 analyses, 143 (of which 3 LLP) results
- CMS efficiency maps: 8 analyses, 53 results, 3186 individual maps

Run 1 - 8 TeV

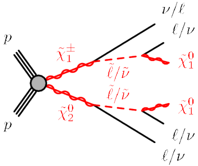
In total, we have results from 15 ATLAS and 18 CMS 8 TeV searches.

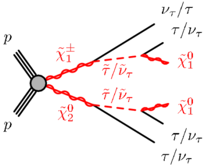
- ATLAS upper limits: 13 analyses, 34 results
- ATLAS efficiency maps: 10 analyses, 31 results, 269 individual maps
- CMS upper limits: 16 analyses, 56 (of which 3 LLP) results
- CMS efficiency maps: 9 analyses, 47 (of which 9 LLP) results, 980 individual maps

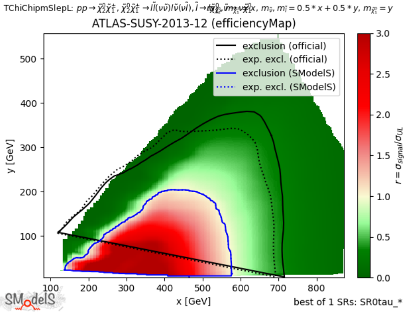
ATLAS-SUSY-2013-12

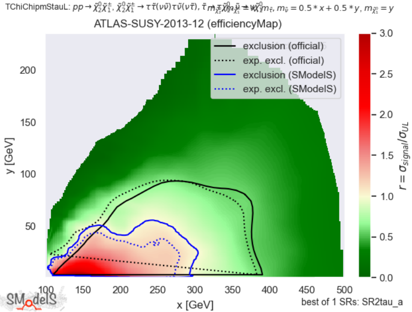
arXiv:1402.7029

8 TeV search for $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow 3$ leptons + MET.
Implementation of efficiency maps:





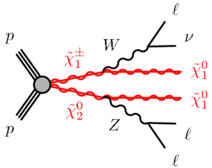


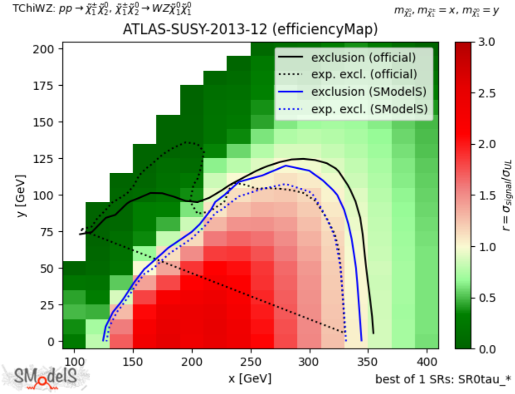


ATLAS-SUSY-2013-12

arXiv:1402.7029

8 TeV search for $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to$ 3 leptons + MET.
Implementation of efficiency maps:





ATLAS-SUSY-2019-02

arXiv:2209.13935

13 TeV search for $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp} \to W^{\pm}W^{\mp}$ + MET.