Global constraints of the electroweak-ino sector of the MSSM with SModelS 2.3

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LHC Reinterpretation Forum 2023

1. Introduction to SModelS
2. The combination of electroweak-ino LHC searches
3. Results to the electroweak-ino sector of the MSSM

1 Introduction to SModelS

2 The combination of electroweak-ino LHC searches

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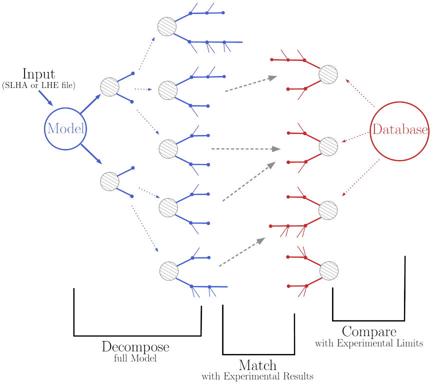
SModelS working principle

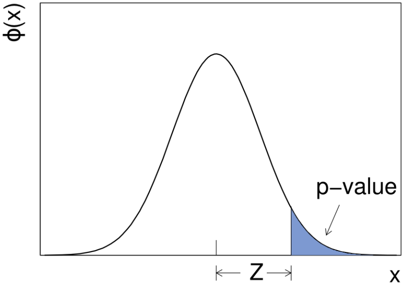
Public tool to confront BSM signals with a $\mathbb{Z}_2$-like symmetry against simplified model results from the LHC.
No MC generator is required, making it a good tool for large scans.



Code and documentation available online: https://smodels.github.io/

Building a global likelihood through SModelS

$$L_{\mathsf{C}}(\mu) = \prod_i L_i(\mu)$$



arXiv:1007.172

$$\mu_{\mathsf{UL}} = \mu_{95} \text{ when p-value} \approx 0.05$$

A model point is excluded if $\boxed{r = \frac{\sigma^{\mathsf{BSM}}}{\sigma^{\mathsf{BSM}}_{\mathsf{UL}}} = \frac{1}{\mu_{\mathsf{UL}}} \geqslant 1}$

Building a global likelihood through SModelS

$$L_{\mathsf{C}}(\mu) = \prod_i L_i(\mu)$$

For each individual likelihood (analysis), signal regions combination is possible using a full HistFactory models (ATLAS), encoded in a json file:

$$L_i(\mu) = \prod_{j=1}^{N} \mathrm{Pois}(n_j^{obs}|\mu s_j + b_j + \theta_j) \prod_{\theta \in \{\theta\}} c_\theta(a_\theta|\theta)$$

where $s_j = \epsilon_j \mathcal{A}_j \sum \sigma \prod BR * \mathcal{L}$ | $b_j =$ bkg | $\theta_j =$ nuisance parameters

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Simplified likelihood encoded in a covariance matrix (CMS):

$$L_i(\mu) = \prod_{j=1}^{N} \mathrm{Pois}(n_j^{obs} | \mu s_j + b_j + \theta_j) \prod_{\theta \in \{\theta\}} e^{-\frac{1}{2} \overrightarrow{\theta}^T V^{-1} \overrightarrow{\theta}}$$

Building a global likelihood through SModelS

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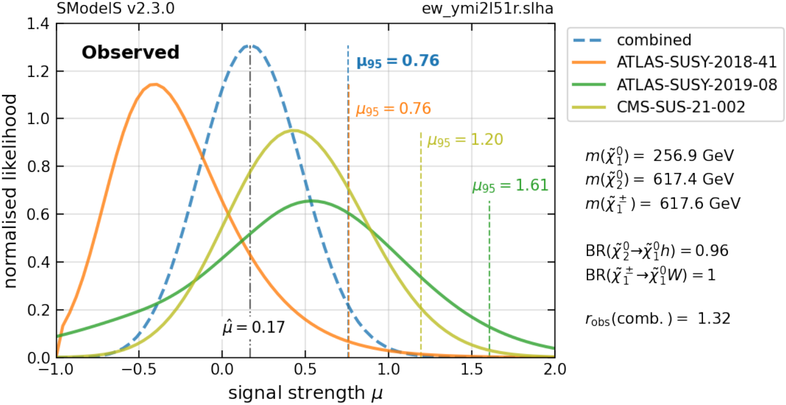
If the combination of signal regions (SRs) is not possible, use the most sensitive one (" best SR "), i.e. lowest μ_{UL} obtained with $n_j^{obs} = b_j$

Building a global likelihood through SModelS

$\hat{\mu} < 0$
under-fluctuation
$\longleftarrow$

$\hat{\mu} > 0$
excess
$\longrightarrow$



$m(\tilde{\chi}^0_1) =$ 256.9 GeV
$m(\tilde{\chi}^0_2) =$ 617.4 GeV
$m(\tilde{\chi}^\pm_1) =$ 617.6 GeV

$\mathrm{BR}(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h) = 0.96$
$\mathrm{BR}(\tilde{\chi}^\pm_1 \to \tilde{\chi}^0_1 W) = 1$

$r_{\mathrm{obs}}(\mathrm{comb.}) =$ 1.32

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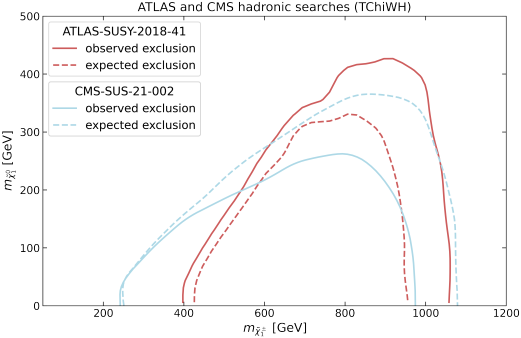
EW-ino searches in SModelS database v2.3

ID	Short Description	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	arXiv	TxName	comb.
CMS-SUS-13-012	Multijet search for $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$	8	19.5	1402.4770	TChiWW TChiWZ TChiZZ	
CMS-SUS-16-039	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0\tilde{\chi}_1^0$ into 2 or more $\ell + \not{E}_T$	13	35.9	1709.05406	TChiWZ TChiWZoff	Cov. Cov.
CMS-SUS-16-048	$\tilde{t}\tilde{t}$, $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ into 2 soft OS $\ell + \not{E}_T$	13	35.9	1801.01846	TChiWWoff	Cov.
CMS-SUS-20-004	$\tilde{H}\tilde{H}$ into $2h + \not{E}_T$	13	137	2201.04206	TChiHH	Cov.
CMS-SUS-21-002	Hadronic search for $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$	13	137	2205.09597	TChiWV	Cov.
ATLAS-SUSY-2013-11	$\tilde{\ell}\tilde{\ell}$, $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ into $2\ell + \not{E}_T$	8	20.3	1403.5294	TChiWW	
ATLAS-SUSY-2013-12	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ into $3\ell + \not{E}_T$	8	20.3	1402.7029	TChiWH TChiWZ TChiWZoff	
ATLAS-SUSY-2016-24	$\tilde{\ell}\tilde{\ell}$, $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ into 2 or $3\ell + \not{E}_T$	13	36.1	1803.02762	TChiWZ	
ATLAS-SUSY-2017-03	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ into 2 or $3\ell + \not{E}_T$	13	36.1	1806.02293	TChiWZ	
ATLAS-SUSY-2018-05	$\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$, $\tilde{\chi}\tilde{\chi}$ into 2ℓ + jets + $\not{E}_T$	13	139	2204.13072	TChiWZ TChiWZoff	JSON (s) JSON (s)
ATLAS-SUSY-2018-06	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ into $3\ell + \not{E}_T$	13	139	1912.08479	TChiWZ TChiWZoff	
ATLAS-SUSY-2018-32	$\tilde{\ell}\tilde{\ell}$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ into $2\ell + \not{E}_T$	13	139	1908.08215	TChiWW	JSON (s)
ATLAS-SUSY-2018-41	Hadronic search for $\tilde{\chi}^\pm$, $\tilde{\chi}^0$	13	139	2108.07586	TChiVV	Cov.
ATLAS-SUSY-2019-02	$\tilde{\ell}\tilde{\ell}$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ into $2\ell + \not{E}_T$	13	139	2209.13935	TChiWW	Cov.
ATLAS-SUSY-2019-08	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ into 1ℓ + 2 b-jets + $\not{E}_T$	13	139	1909.09226	TChiWH	JSON
ATLAS-SUSY-2019-09	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ into $3\ell + \not{E}_T$	13	139	2106.01676	TChiWZ TChiWZoff	JSON (s) JSON (s)

best SR   simplified likelihood   HistFactory model

V = W,Z,H   (s) = simplified JSON

EW-ino searches in SModelS database v2.3



The two most sensitive and constraining analyses are the ATLAS and CMS hadronic searches

ATLAS sees an under-fluctuation, while CMS sees an excess;

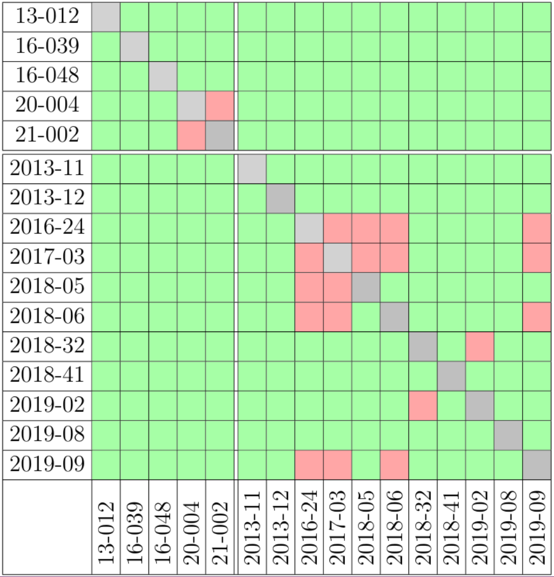
Disclaimer

What will follow is not a SModels feature and should not be mistaken with the SModelS *combineAnas* option.

Trivial combination

CMS-SUS-XX-XXX

ATLAS-SUSY-XXXX-XX



Approximation:

We assume two analyses can be combined if they do not share any event in their SRs

Which combination to choose?

Many combinations are possible, which one to choose?

- List of all the analyses that give $\mu_{\mathrm{UL}}^{exp} \leqslant 10$ for the tested model point:

  e.g.: "CMS-SUS-20-004", "CMS-SUS-21-002", "ATLAS-SUSY-2018-05"

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- Build all the possible combinations:

  ↳ If two analysis belong to a different experiment or a different run, they are combinable, otherwise need to check with the combination matrix

  e.g.:
  - ["CMS-SUS-20-004"]
  - ["CMS-SUS-21-002"]
  - ["ATLAS-SUSY-2018-05"]
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- Remove the subsets, e.g.:
  - ["CMS-SUS-20-004", "ATLAS-SUSY-2018-05"]
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- For each remaining combination, compute $\dfrac{L_{\mathsf{BSM}}^{\mathsf{exp}}}{L_{\mathsf{SM}}^{\mathsf{exp}}}$

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- The combination with the lowest ratio is chosen (most likely to be the most sensitive)

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Selected points

Random scan over:
(all other scales decoupled)

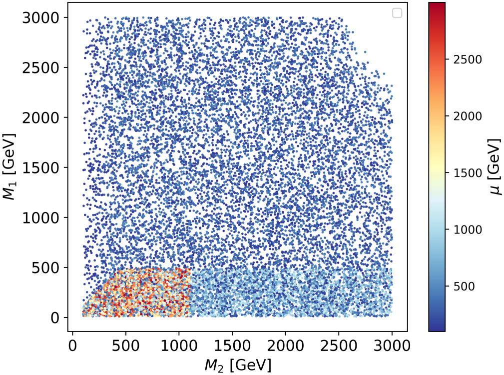
$$\begin{aligned} 10\text{ GeV} < & \quad M_1 \quad < 3\text{ TeV} \\ 100\text{ GeV} < & \quad M_2 \quad < 3\text{ TeV} \\ 100\text{ GeV} < & \quad \mu \quad < 3\text{ TeV} \\ 5 < & \quad \tan\beta \quad < 50 \end{aligned}$$

SUSY spectrum: SoftSUSY 4.1.11

NLO x-sec: Resummino 3.1.2

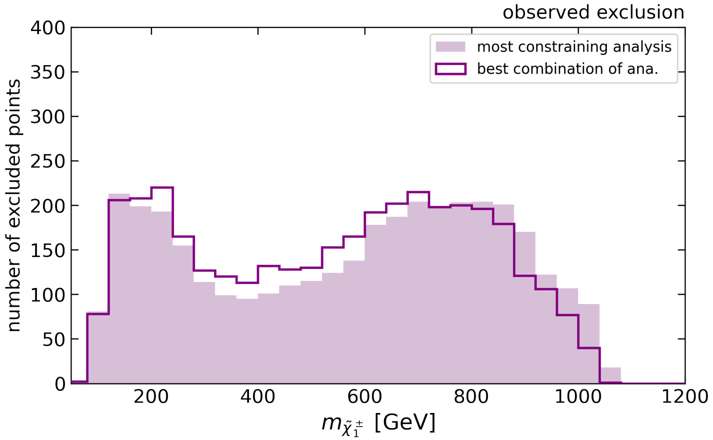
$$m_{\tilde{\chi}_1^0} < 500\text{ GeV}$$
$$m_{\tilde{\chi}_1^\pm} < 1200\text{ GeV}$$
$$\Gamma_{\tilde{\chi}_1^\pm} > 10^{-11}\text{ GeV}$$

In the end: 18305 points



Most constraining analysis

excluded $\Leftrightarrow r = \frac{\sigma^{\text{BSM}}}{\sigma^{\text{BSM}}_{\text{UL}}} = \frac{1}{\mu_{\text{UL}}} \geqslant 1$



The exclusion power is enhanced by the combination for mid range $m_{\tilde{\chi}_1^\pm}$ and decreased for high $m_{\tilde{\chi}_1^\pm}$

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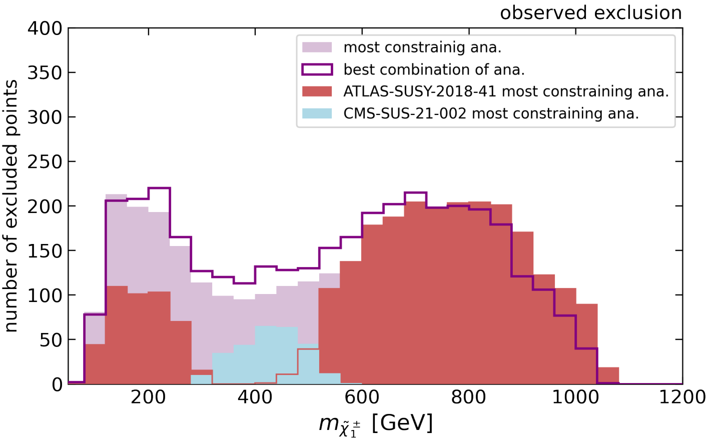


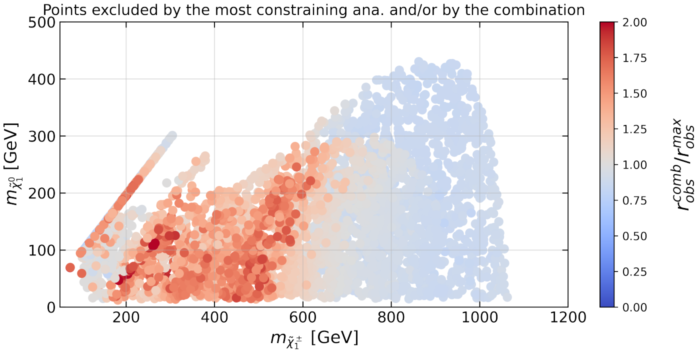
The most constraining analysis is the ATLAS hadronic search

Red bars below 300 GeV: mainly higgsino LSP (some wino LSP too)

Variation of the exclusion power

excluded $\Leftrightarrow r = \frac{\sigma^{\text{BSM}}}{\sigma^{\text{BSM}}_{\text{UL}}} = \frac{1}{\mu_{\text{UL}}} \geqslant 1$

Select the points excluded by the most constraining analysis and/or by the combination: 3965 points



For $m_{\tilde{\chi}_1^\pm} < 200$ GeV (compressed region): see later

For $m_{\tilde{\chi}_1^\pm} < 200$ GeV (offshell): mainly TChiWZoff, dominated by the ATLAS 3 ℓ + MET search

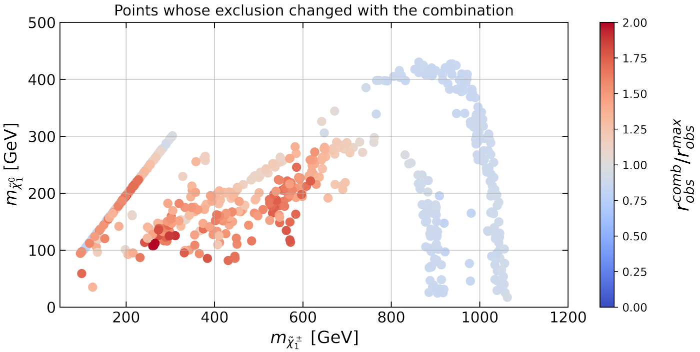
For 200 GeV $< m_{\tilde{\chi}_1^\pm} <$ 600 GeV: CMS hadronic search is combined with analyses which have recorded under-fluctuations (except for ATLAS 1 ℓ + 1 b-jet + MET search)

For 600 GeV $< m_{\tilde{\chi}_1^\pm}$: the CMS hadronic search decreases the exclusion power

Variation of the exclusion power

excluded $\Leftrightarrow r = \frac{\sigma^{\text{BSM}}}{\sigma^{\text{BSM}}_{\text{UL}}} = \frac{1}{\mu_{\text{UL}}} \geqslant 1$

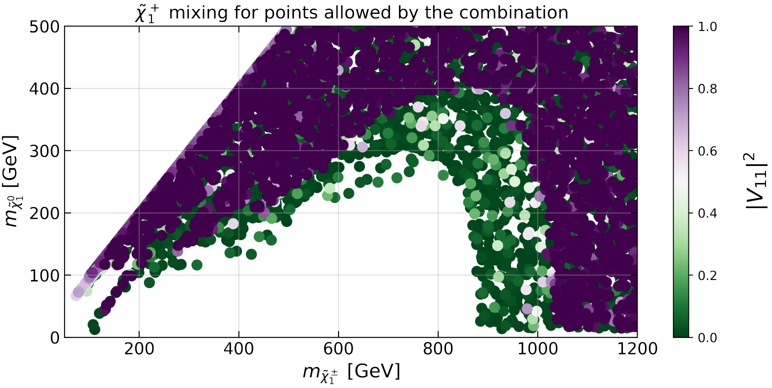
Select the points excluded only by the combination or un-excluded by it: 637 points.



The upper "arc" is the exclusion contour for $\tilde{W}$ NLSP and $\tilde{B}$ LSP
The lower "arc" is the exclusion contour for $\tilde{H}$ NLSP and $\tilde{B}$ LSP.

Points allowed by the combination

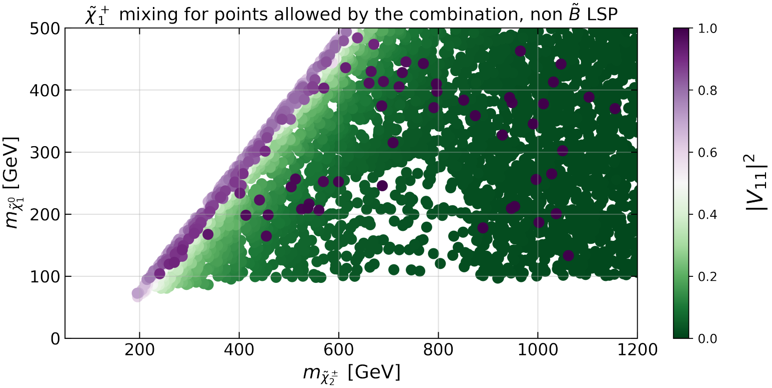
The points not excluded by the combination can shed light on the nature of the two "arcs"



Purple: $\tilde{W}$ NLSP
Green: $\tilde{H}$ NLSP

The $m_{\tilde{\chi}_2^\pm}$ vs $m_{\tilde{\chi}_1^0}$ plane

So far, the focus was on the $\tilde{B}$ LSP. Let's now focus on $\tilde{W}$ and $\tilde{H}$ LSP

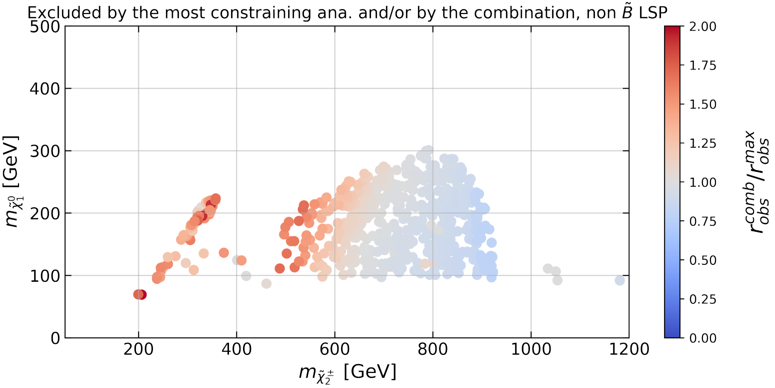


Purple points: $\tilde{W}$ LSP. Green points: $\tilde{H}$ LSP

Except on the diagonal, mainly $\tilde{W}$ NLSP and $\tilde{H}$ LSP

The $m_{\tilde{\chi}_2^\pm}$ vs $m_{\tilde{\chi}_1^0}$ plane

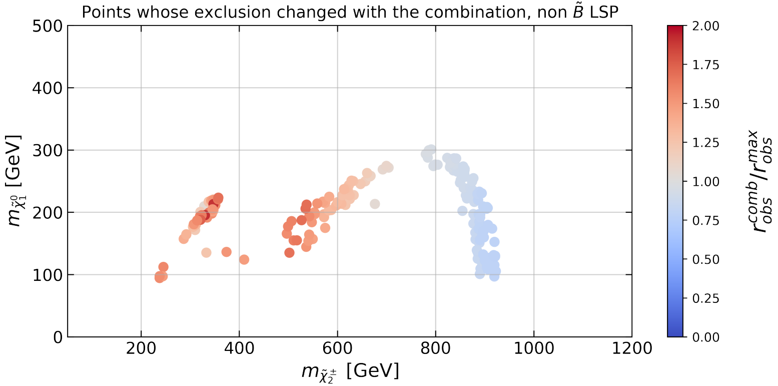
More decays due to the $\tilde{H}$ LSP, the signal is reduced and so is the exclusion power
Number of points excluded by most constraining anlysis and/or the combination: 607



For $m_{\tilde{\chi}_2^\pm} < 500$ GeV: dominated by the ATLAS 3 ℓ + MET search (TChiWZ)
For 500 Gev $< M_{\tilde{\chi}_2^\pm} < 1000$ GeV: constrained by the ATLAS hadronic search
For 1000 GeV $< m_{\tilde{\chi}_2^\pm}$: dominated by the ATLAS 3 ℓ + MET search (TChiWZoff)

The $m_{\tilde{\chi}_2^\pm}$ vs $m_{\tilde{\chi}_1^0}$ plane

Number of points excluded only by the combination or un-exclued by it: 183

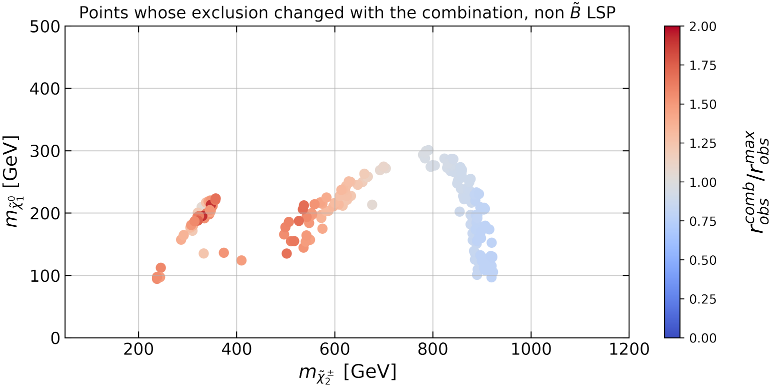


For $m_{\tilde{\chi}_2^\pm} < 500$ GeV: excluded when combining ATLAS 3 ℓ + MET search with ATLAS 2 ℓ + MET searches (TChiWZ)

For 500 GeV $< m_{\tilde{\chi}_2^\pm} < 750$ GeV: the ATLAS hadronic search constraint is enhanced by the under-fluctuation of the ATLAS 2 ℓ + jets + MET search

The $m_{\tilde{\chi}_2^\pm}$ vs $m_{\tilde{\chi}_1^0}$ plane

Number of points excluded only by the combination or un-exclued by it: 183



For 750 GeV $< m_{\tilde{\chi}_2^\pm} <$ 1000 GeV: the ATLAS hadronic search constraint is dampened by the excess of the CMS hadronic search

Conclusion

- LHC constraints set on EW-ino masses have been revisited in light of a global combination of EW-ino searches present in the SModelS database v2.3
- The ATLAS 3 ℓ + MET search dominated the combination for off-shell decays
- The ATLAS and CMS hadronic searches dominated the combination for on-shell decays (ATLAS-SUSY-2018-41 and CMS-SUS-21-002)
- The excess seen by the CMS hadronic search seems to be compensated by the under-fluctuation seens by the ATLAS hadronic search

Acknowledgments

Many thanks to the RiF 2023 organizers and to the coordinators of the reinterpretation studies / pheno.

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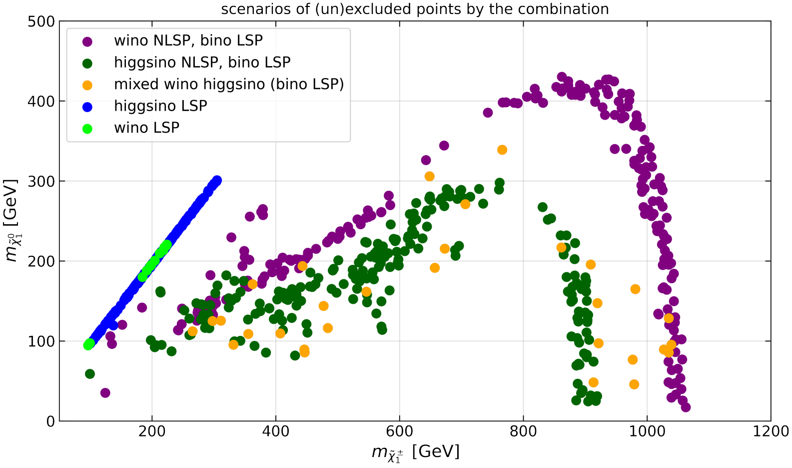
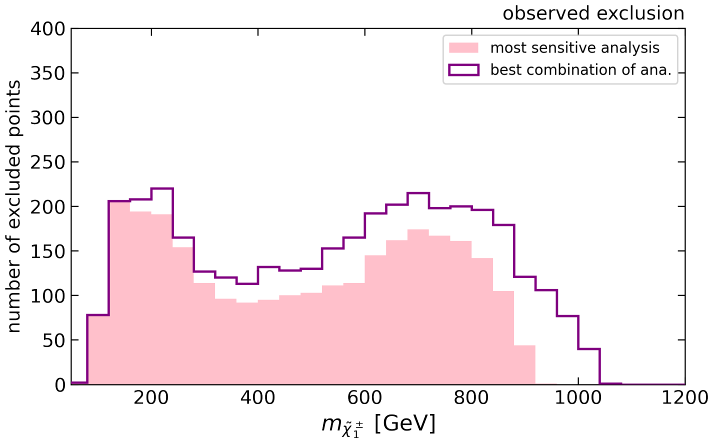
Backup Slides


scenarios of (un)excluded points by the combination
wino NLSP, bino LSP
higgsino NLSP, bino LSP
mixed wino higgsino (bino LSP)
higgsino LSP
wino LSP
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
0
100
200
300
400
500
600
800
1000
1200

Most sensitive analysis

$$\text{excluded} \Leftrightarrow r = \frac{\sigma^{\text{BSM}}}{\sigma^{\text{BSM}}_{\text{UL}}} = \frac{1}{\mu_{\text{UL}}} \geqslant 1$$



On the contrary the exclusion power is almost always enhanced when comparing to the most sensitive analysis (lowest μ_{UL} obtained with $n_j^{obs} = b_j$)

Most sensitive analysis

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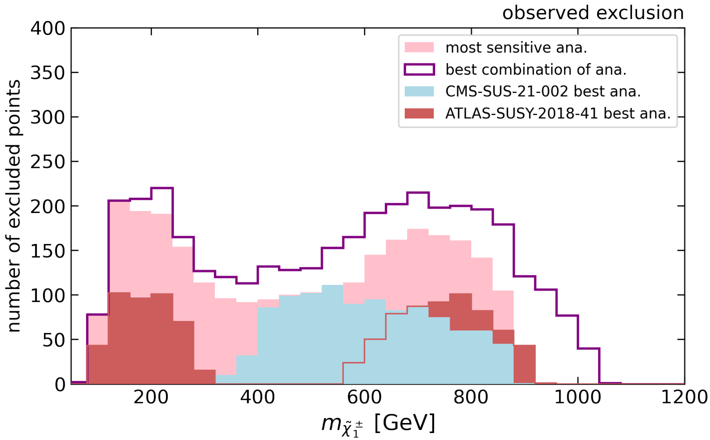
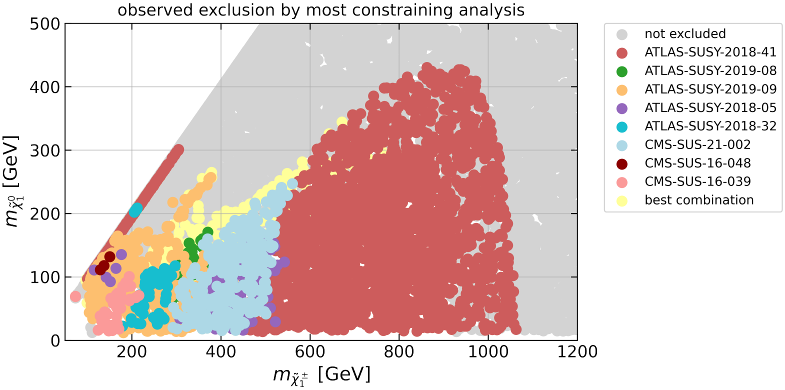
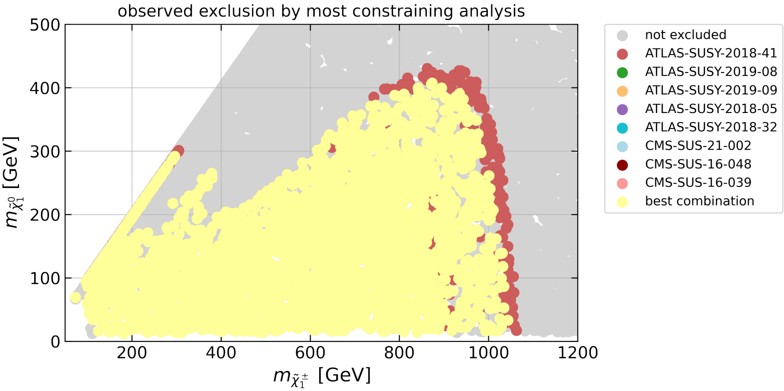
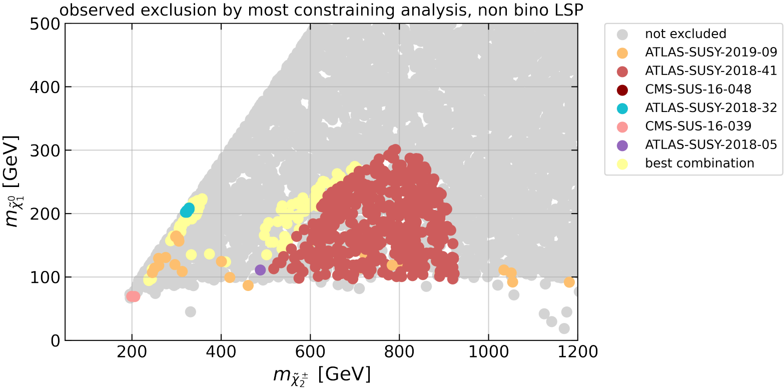
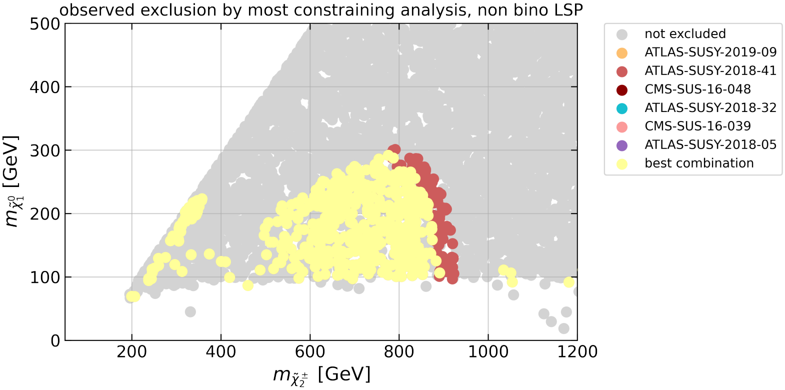


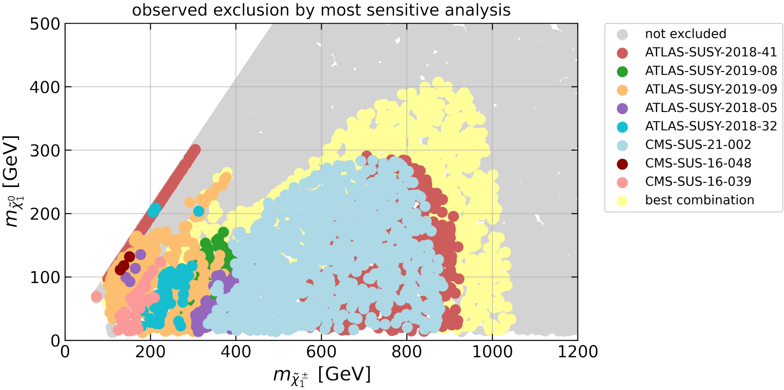
An analysis that observed an under-fluctuation is sensitive at high $m_{\tilde{\chi}_1^\pm}$

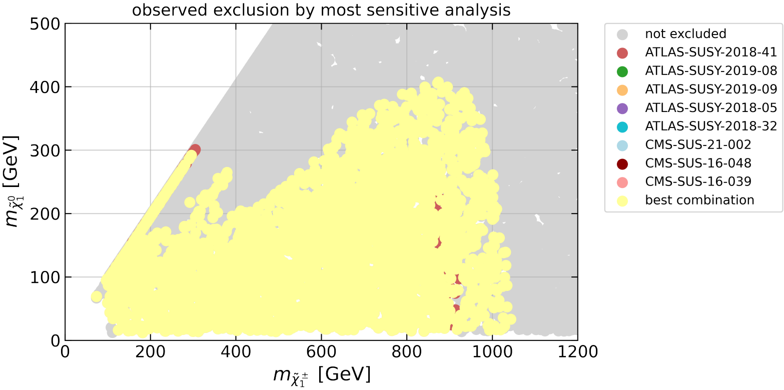

observed exclusion by most constraining analysis
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
0
100
200
300
400
500
200
400
600
800
1000
1200
not excluded
ATLAS-SUSY-2018-41
ATLAS-SUSY-2019-08
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-05
ATLAS-SUSY-2018-32
CMS-SUS-21-002
CMS-SUS-16-048
CMS-SUS-16-039
best combination

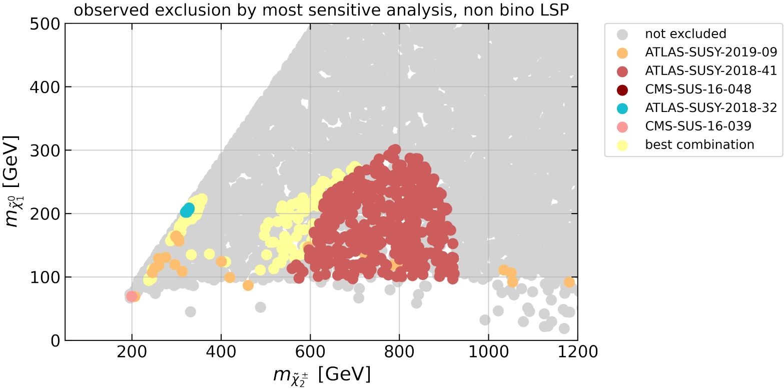

observed exclusion by most constraining analysis
500
400
300
200
100
0
200
400
600
800
1000
1200
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
not excluded
ATLAS-SUSY-2018-41
ATLAS-SUSY-2019-08
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-05
ATLAS-SUSY-2018-32
CMS-SUS-21-002
CMS-SUS-16-048
CMS-SUS-16-039
best combination

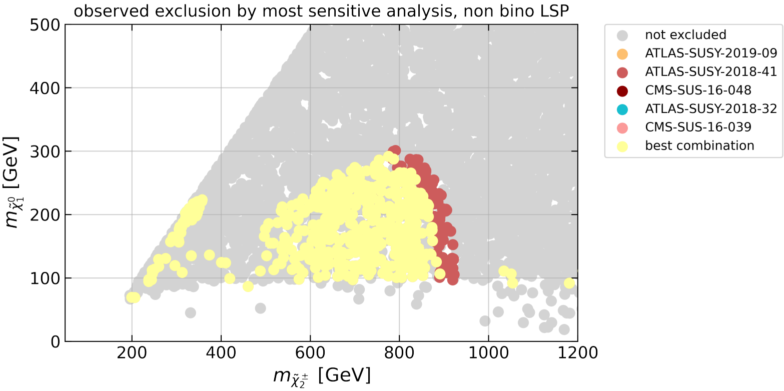

observed exclusion by most constraining analysis, non bino LSP
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^\pm}$ [GeV]
0
100
200
300
400
500
200
400
600
800
1000
1200
not excluded
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-41
CMS-SUS-16-048
ATLAS-SUSY-2018-32
CMS-SUS-16-039
ATLAS-SUSY-2018-05
best combination


observed exclusion by most constraining analysis, non bino LSP
not excluded
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-41
CMS-SUS-16-048
ATLAS-SUSY-2018-32
CMS-SUS-16-039
ATLAS-SUSY-2018-05
best combination
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^\pm}$ [GeV]
0
100
200
300
400
500
200
400
600
800
1000
1200

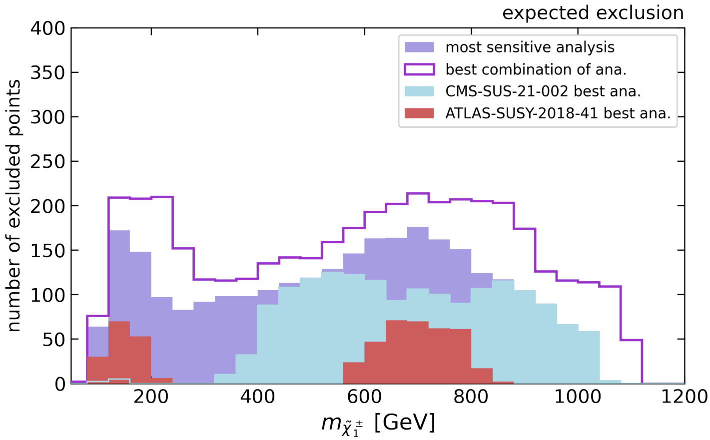

observed exclusion by most sensitive analysis
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
0
100
200
300
400
500
0
200
400
600
800
1000
1200
not excluded
ATLAS-SUSY-2018-41
ATLAS-SUSY-2019-08
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-05
ATLAS-SUSY-2018-32
CMS-SUS-21-002
CMS-SUS-16-048
CMS-SUS-16-039
best combination

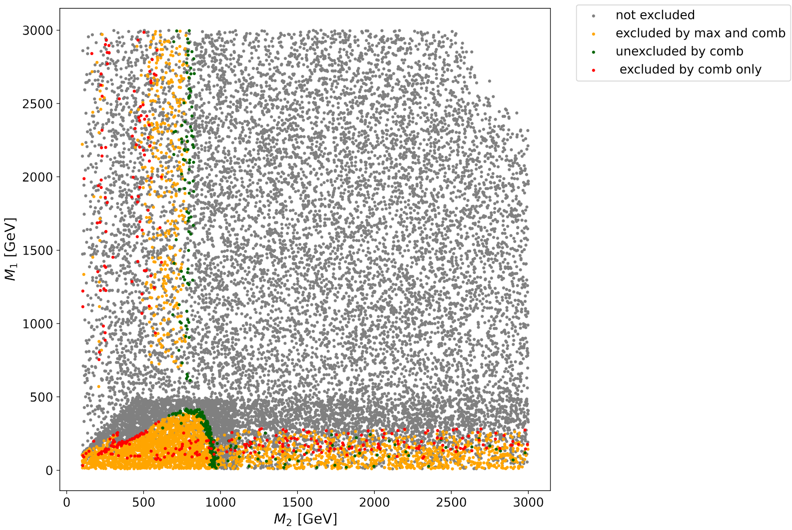

observed exclusion by most sensitive analysis
500
400
300
200
100
0
0
200
400
600
800
1000
1200
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
not excluded
ATLAS-SUSY-2018-41
ATLAS-SUSY-2019-08
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-05
ATLAS-SUSY-2018-32
CMS-SUS-21-002
CMS-SUS-16-048
CMS-SUS-16-039
best combination

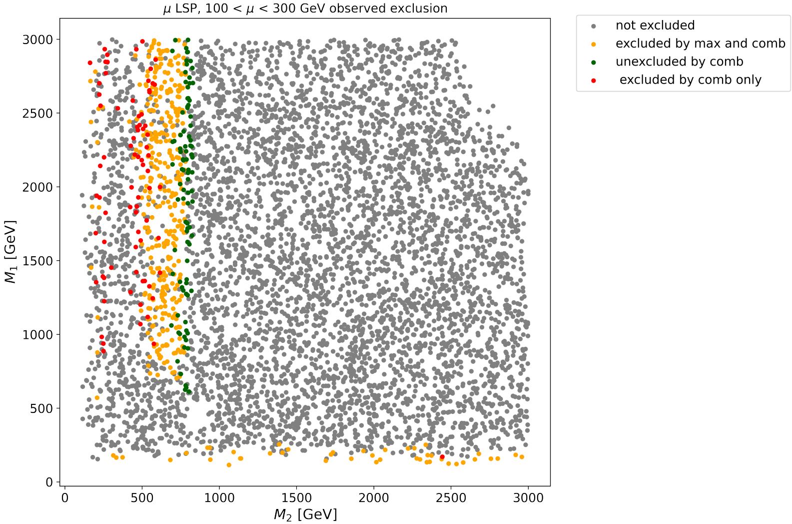

observed exclusion by most sensitive analysis, non bino LSP
500
400
300
200
100
0
200
400
600
800
1000
1200
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^\pm}$ [GeV]
not excluded
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-41
CMS-SUS-16-048
ATLAS-SUSY-2018-32
CMS-SUS-16-039
best combination


observed exclusion by most sensitive analysis, non bino LSP
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^\pm}$ [GeV]
0
100
200
300
400
500
200
400
600
800
1000
1200
not excluded
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-41
CMS-SUS-16-048
ATLAS-SUSY-2018-32
CMS-SUS-16-039
best combination

$$\text{excluded} \Leftrightarrow r^{\text{exp}} = \frac{\sigma^{\text{BSM}}}{\sigma_{\text{UL}}^{\text{BSM, exp}}} = \frac{1}{\mu_{\text{UL}}^{\text{exp}}} \geqslant 1$$




not excluded
excluded by max and comb
unexcluded by comb
excluded by comb only
M_1 [GeV]
M_2 [GeV]
0
500
1000
1500
2000
2500
3000


μ LSP, 100 < μ < 300 GeV observed exclusion
not excluded
excluded by max and comb
unexcluded by comb
excluded by comb only
M_1 [GeV]
M_2 [GeV]
0
500
1000
1500
2000
2500
3000