Constraining the electroweakino sector of the MSSM through the combination of orthogonal LHC searches

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SUSY 2023

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

Why combine LHC searches?

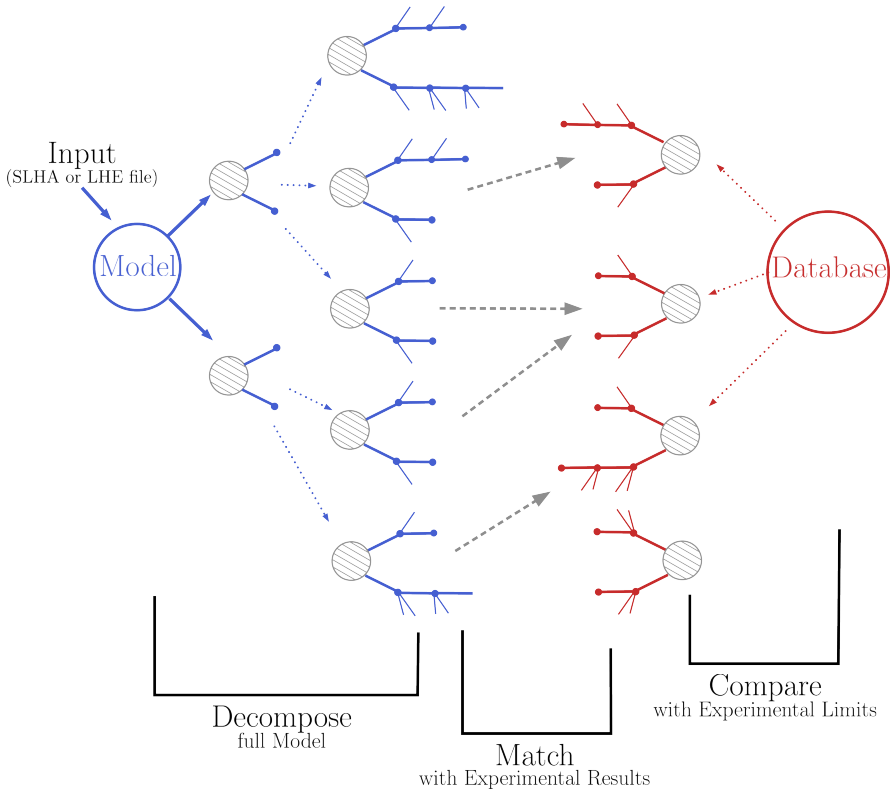
- Increases the results' robustness
- Enables the combination of search channels
- Accounts for both excesses and under-fluctuations in a consistent way

Keep in mind:

- ATLAS and CMS use simplified models (i.e. BR=100%, pure wino-bino states most of the time)
- Searches are made channel by channel

SModelS working principle

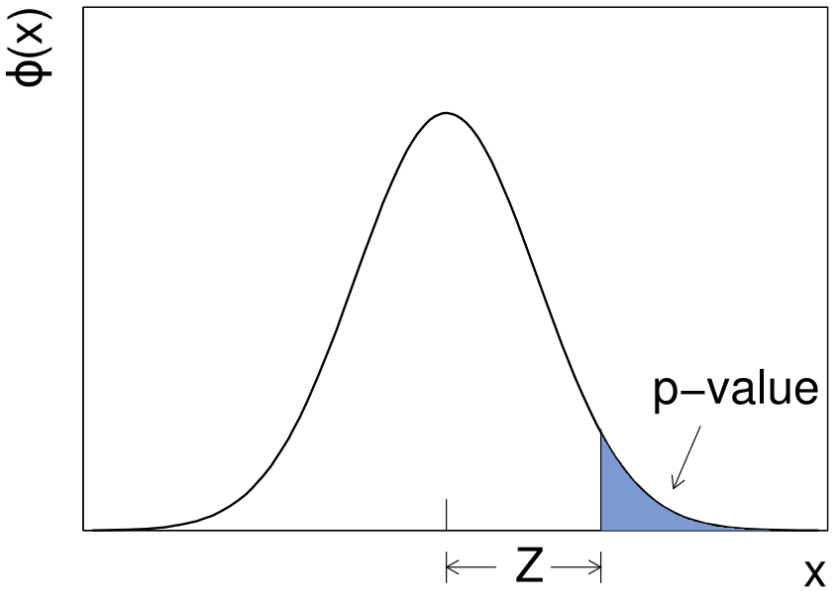
Public tool to confront BSM signals with a $\mathbb{Z}_2$-like symmetry against simplified model results from the LHC.



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

Building a global likelihood through SModelS

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



arXiv:1007.172

$\mu_{\mathrm{UL}} = \mu_{95}$ when p-value ≈ 0.05

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

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):

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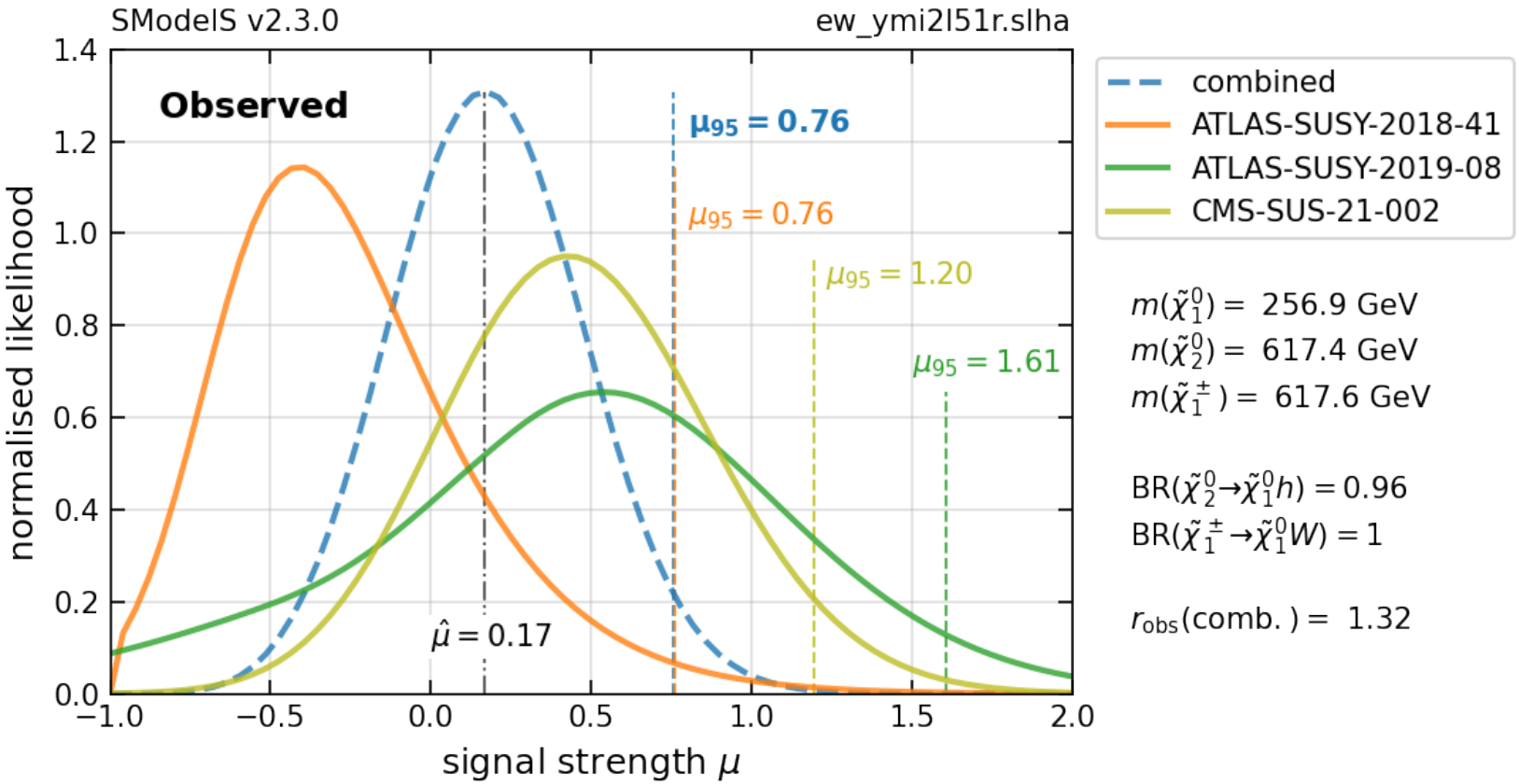
If the combination of signal regions (SRs) is not possible, use the most sensitive one (" best SR "), i.e. lowest μ_{UL} obtained with $n_j^{obs} = b_j$

Building a global likelihood through SModelS

$\hat{\mu} < 0$
under-fluctuation
⟵

$\hat{\mu} > 0$
excess
⟶



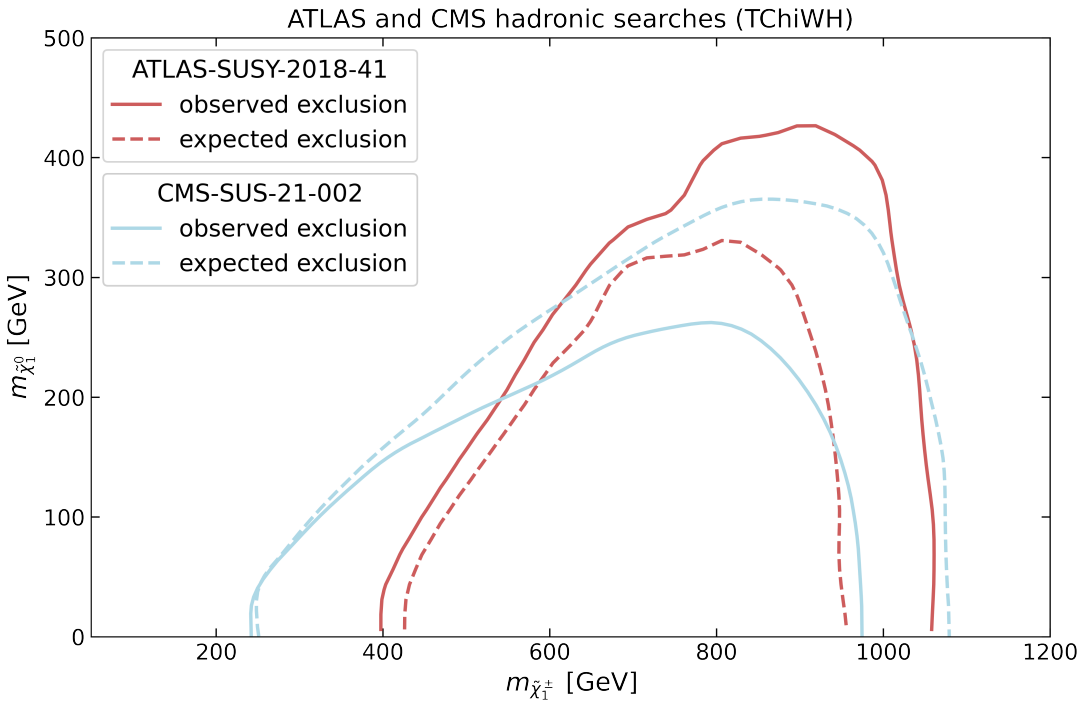
EWino searches in SModelS database v2.3

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 $1\ell + 2$ 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

EWino 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;

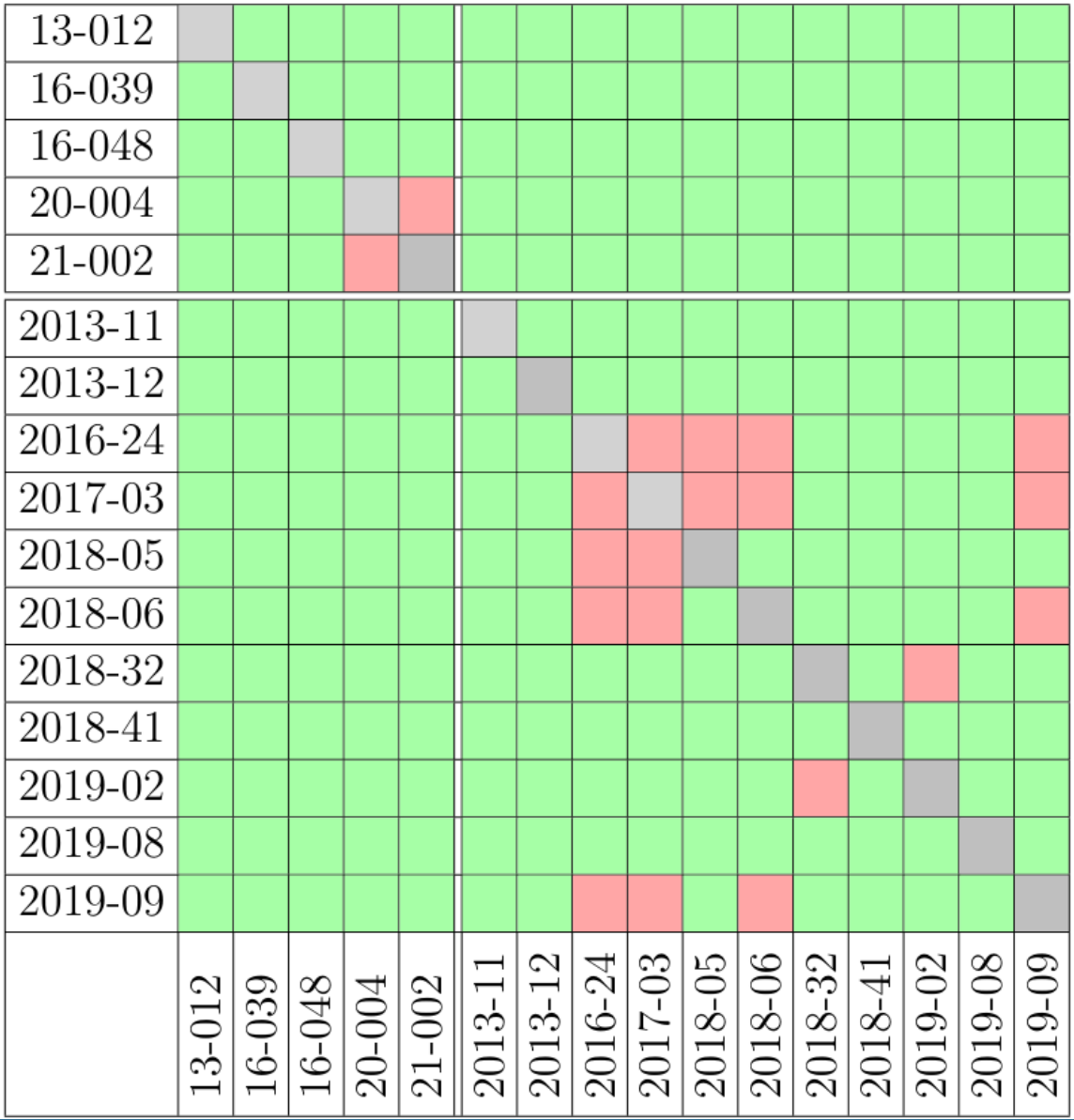
Disclaimer

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 a result for the tested model: "CMS-SUS-20-004","CMS-SUS-21-002","ATLAS-SUSY-2018-05",...

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- Once all the combinations have been found, remove the subsets
  - ↳ i.e. if you have "CMS-SUS-20-004" and "CMS-SUS-20-004,ATLAS-SUSY-2018-05", remove "CMS-SUS-20-004"

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- For each remaining combination, compute $\frac{L^{\text{exp}}_{\text{BSM}}}{L^{\text{exp}}_{\text{SM}}}$

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- For each remaining combination, compute $\frac{L^{\text{exp}}_{\text{BSM}}}{L^{\text{exp}}_{\text{SM}}}$
- The combination with the lowest ratio is taken as the best combination (the most sensitive)

Selected points

Random scan over:
(all other scales decoupled)

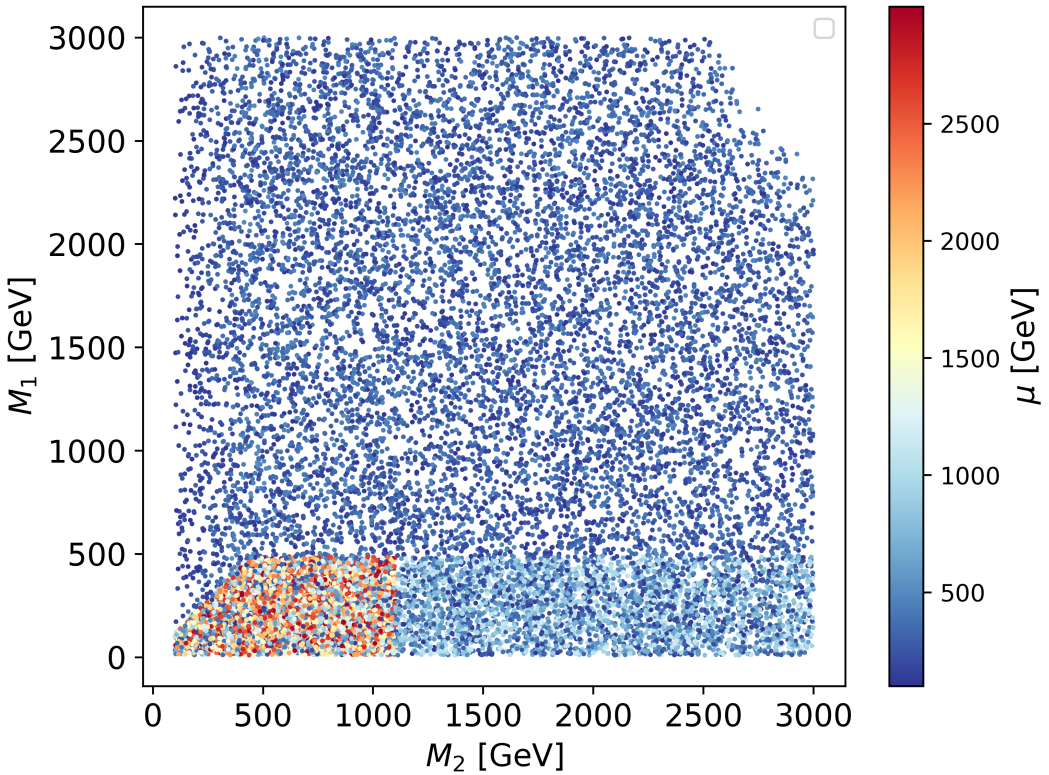
$$10 \text{ GeV} < M_1 < 3 \text{ TeV}$$
$$100 \text{ GeV} < M_2 < 3 \text{ TeV}$$
$$100 \text{ GeV} < \mu < 3 \text{ TeV}$$
$$5 < \tan\beta < 50$$

SUSY spectrum: SoftSUSY 4.1.11

NLO x-sec: Resummino 3.1.2

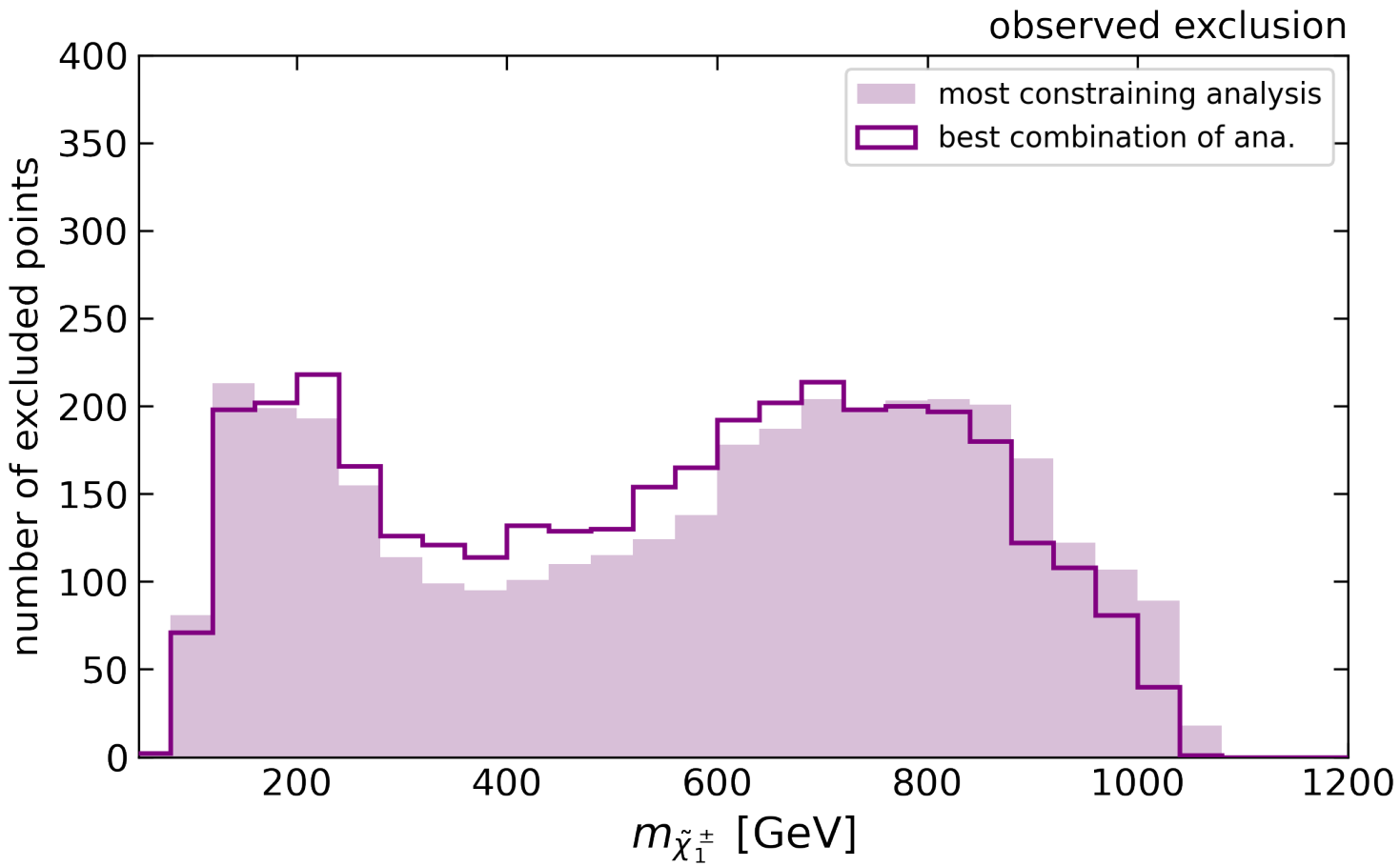
$$m_{\tilde{\chi}_1^0} < 500 \text{ GeV}$$
$$m_{\tilde{\chi}_1^\pm} < 1200 \text{ GeV}$$
$$\Gamma_{\tilde{\chi}_1^\pm} > 10^{-11} \text{ GeV}$$

In the end: 18305 points



Most constraining analysis

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



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

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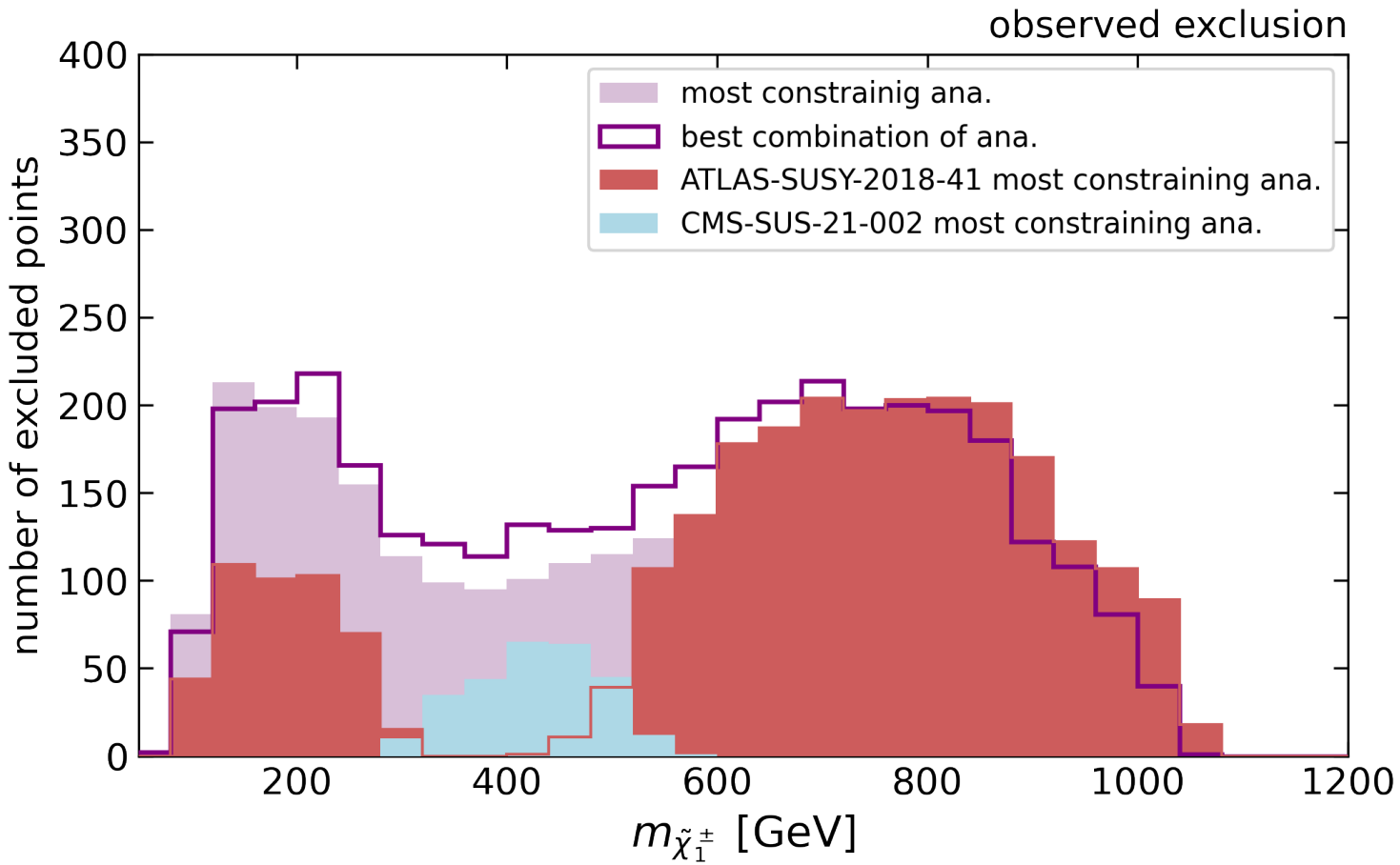
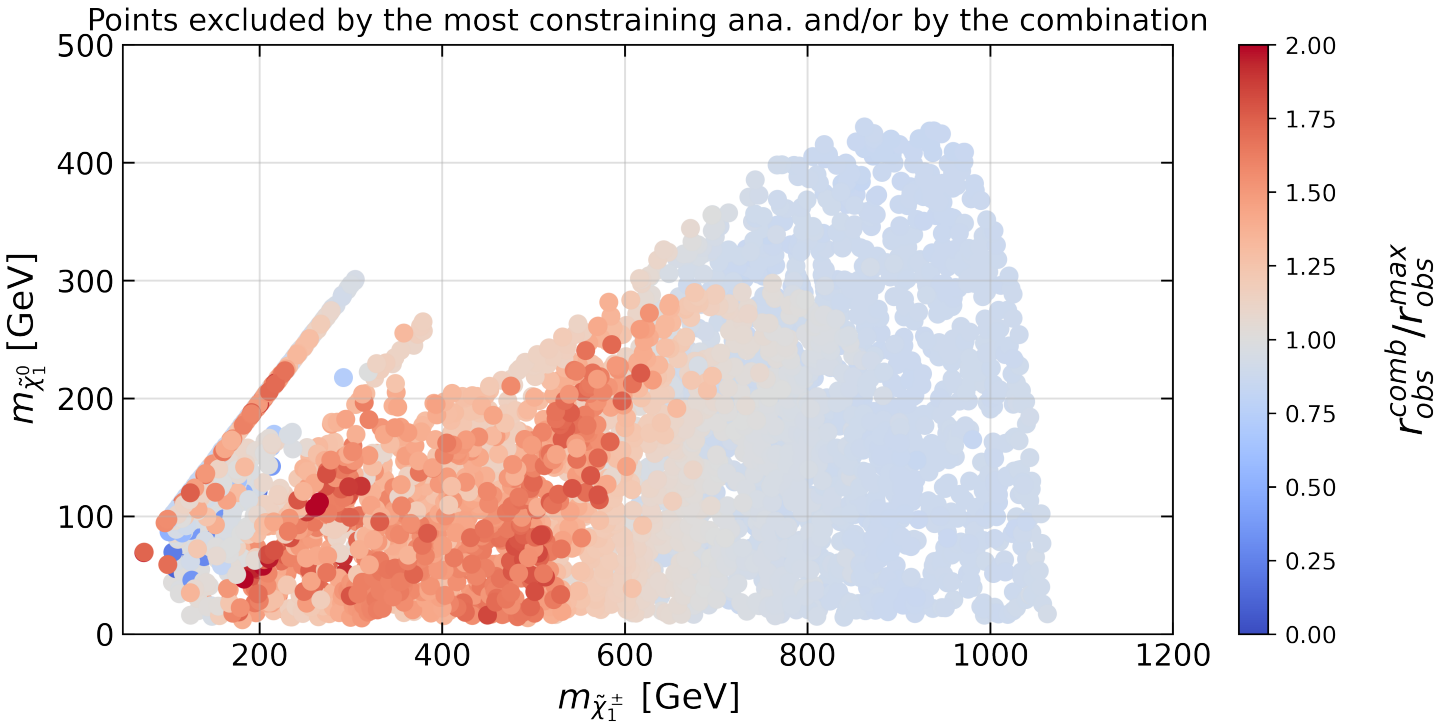


The most constraining analysis is the ATLAS hadronic search
Red bars below 300 GeV: mainly higgsino LSP (some wino LSP too)

Variation of the exclusion power

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

Select the points excluded by the most constraining analysis and/or by the combination: 3974 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

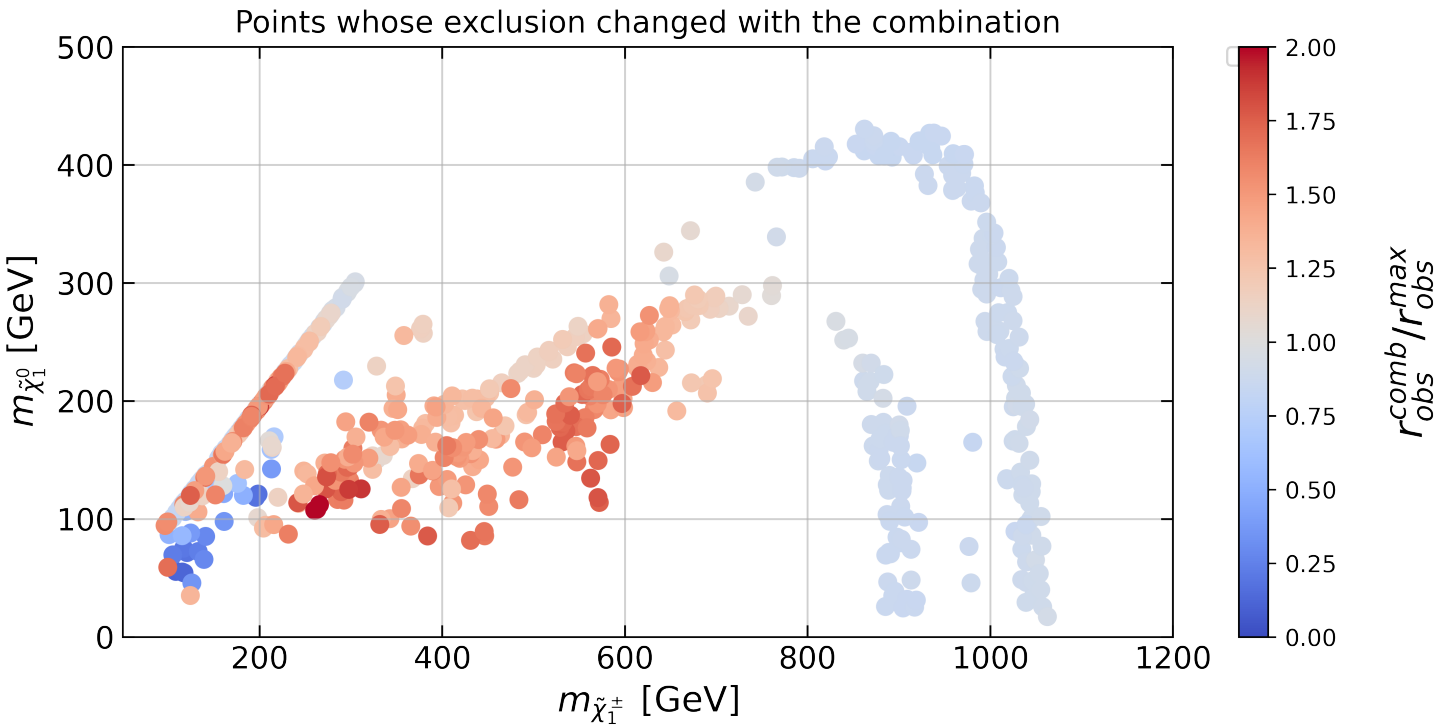
For 200 GeV $< m_{\tilde{\chi}_1^\pm} < 600$ GeV: CMS hadronic search is combined with analyses which have recorded under-fluctuations (except for ATLAS 1 ℓ + 1 b-jet + MET search)

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

Variation of the exclusion power

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

Select the points excluded only by the combination or un-excluded by it: 666 points.

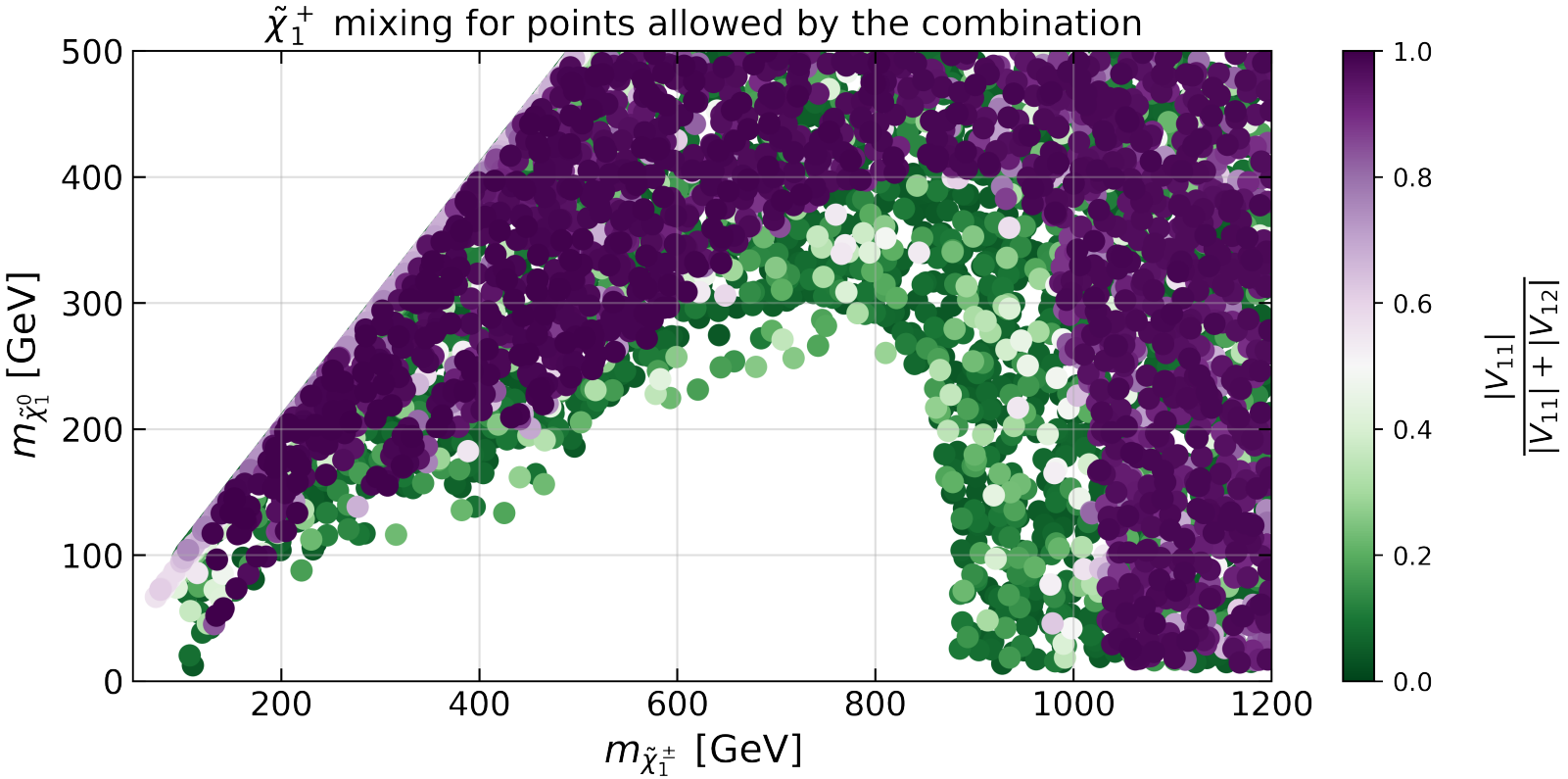


Blue points on the bottom left: $\tilde{B}$ LSP, TChiWZoff, excluded at first by ATLAS 3 ℓ + MET search and un-excluded by the combination when adding ATLAS and CMS 2 ℓ + MET searches

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

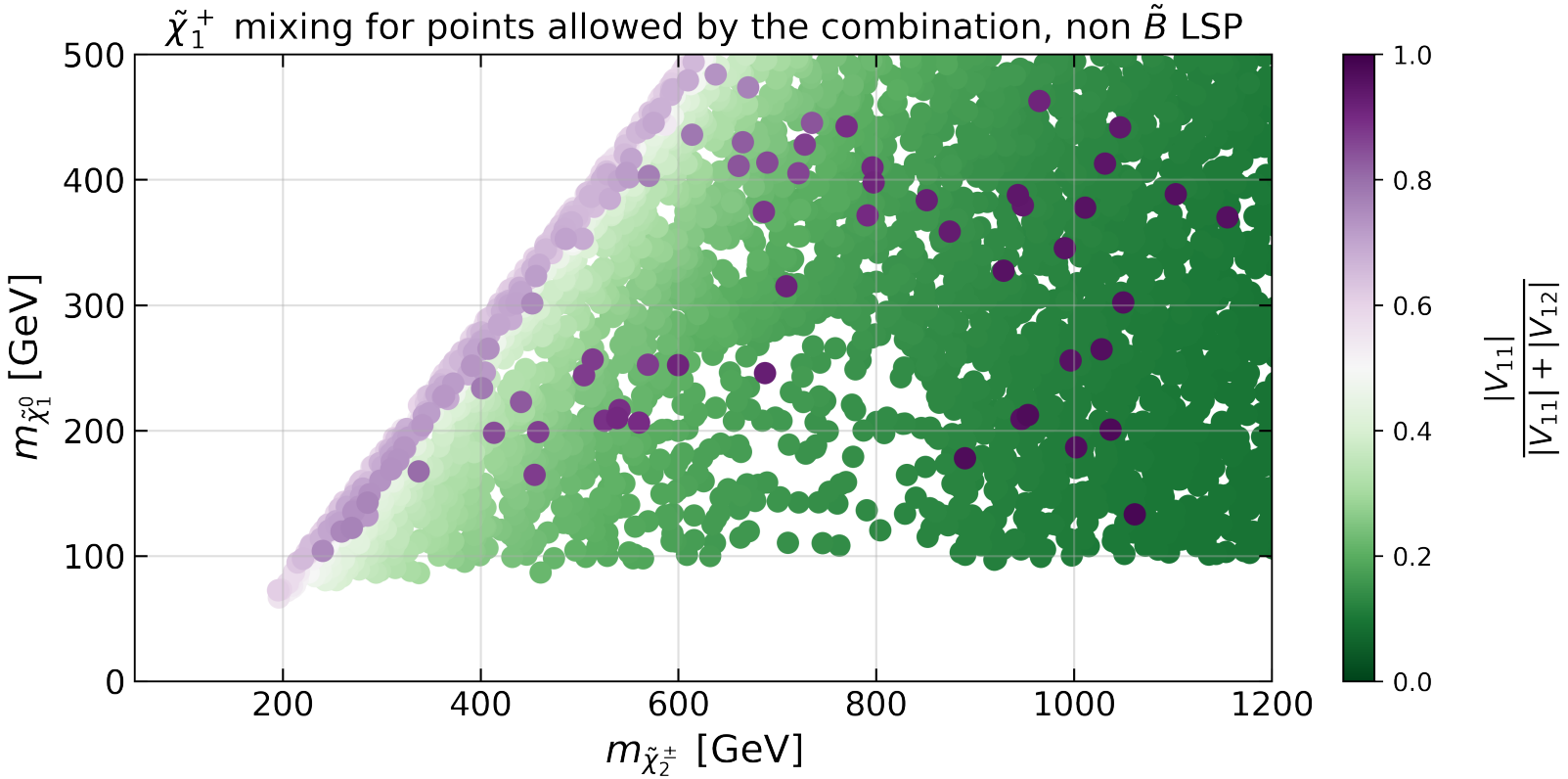
The points not excluded by the combination can shed light on the nature of the two "arcs"



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

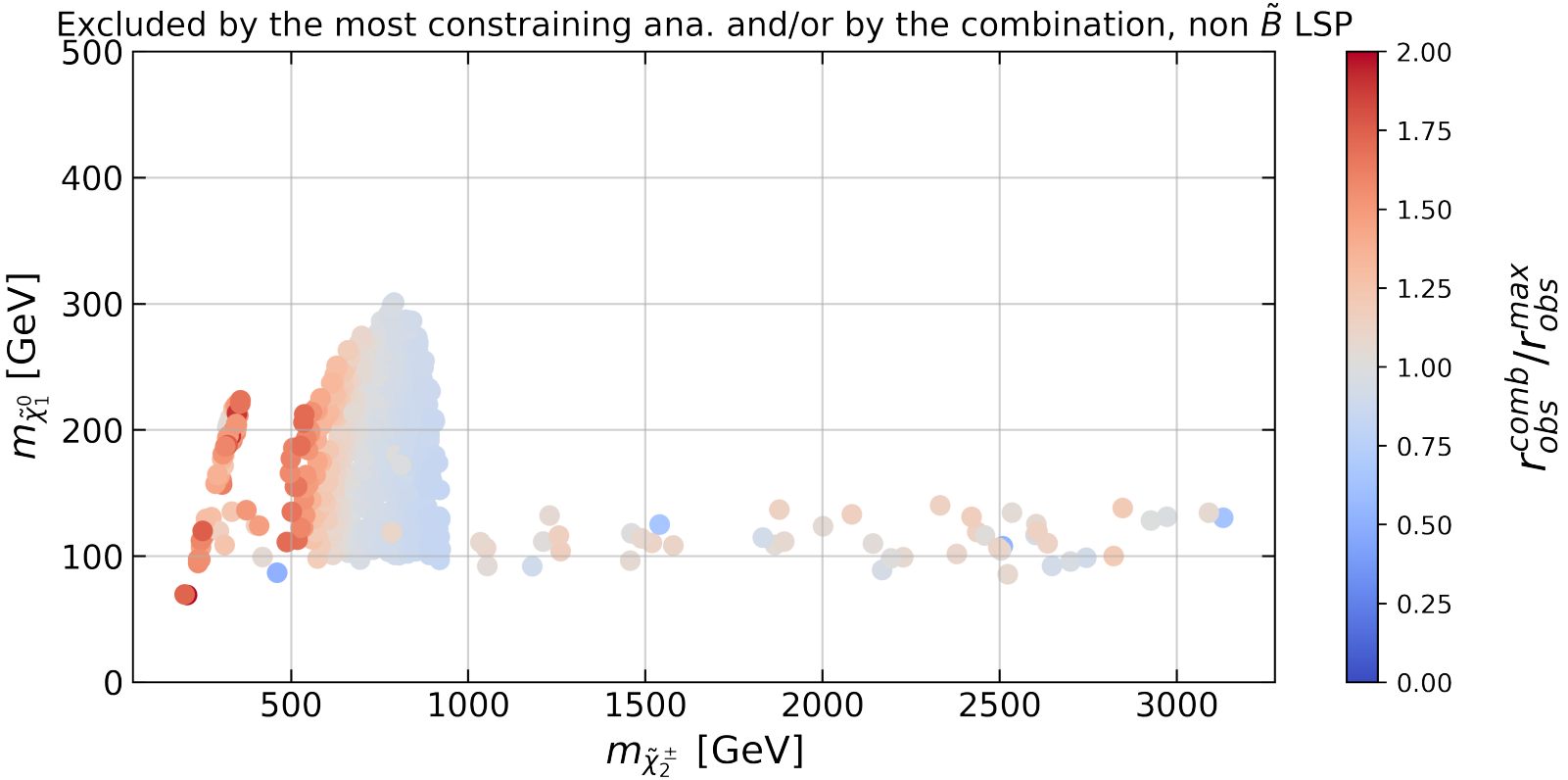


Purple points: $\tilde{W}$ LSP. Green points: $\tilde{H}$ LSP

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: 610



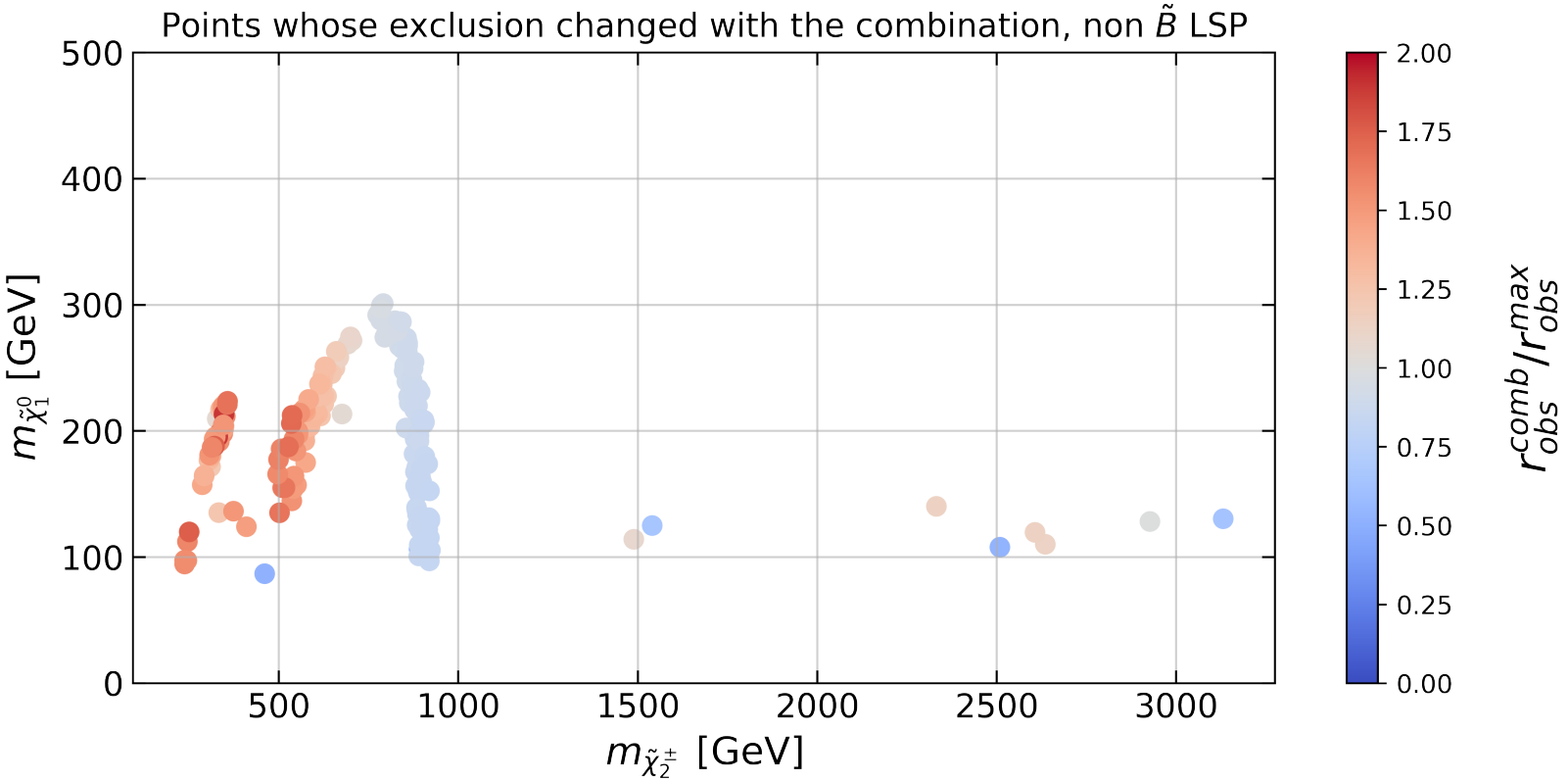
For $m_{\tilde{\chi}_2^\pm} < 500$ GeV: dominated by the ATLAS 3 ℓ + MET search (TChiWZ)

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: 193

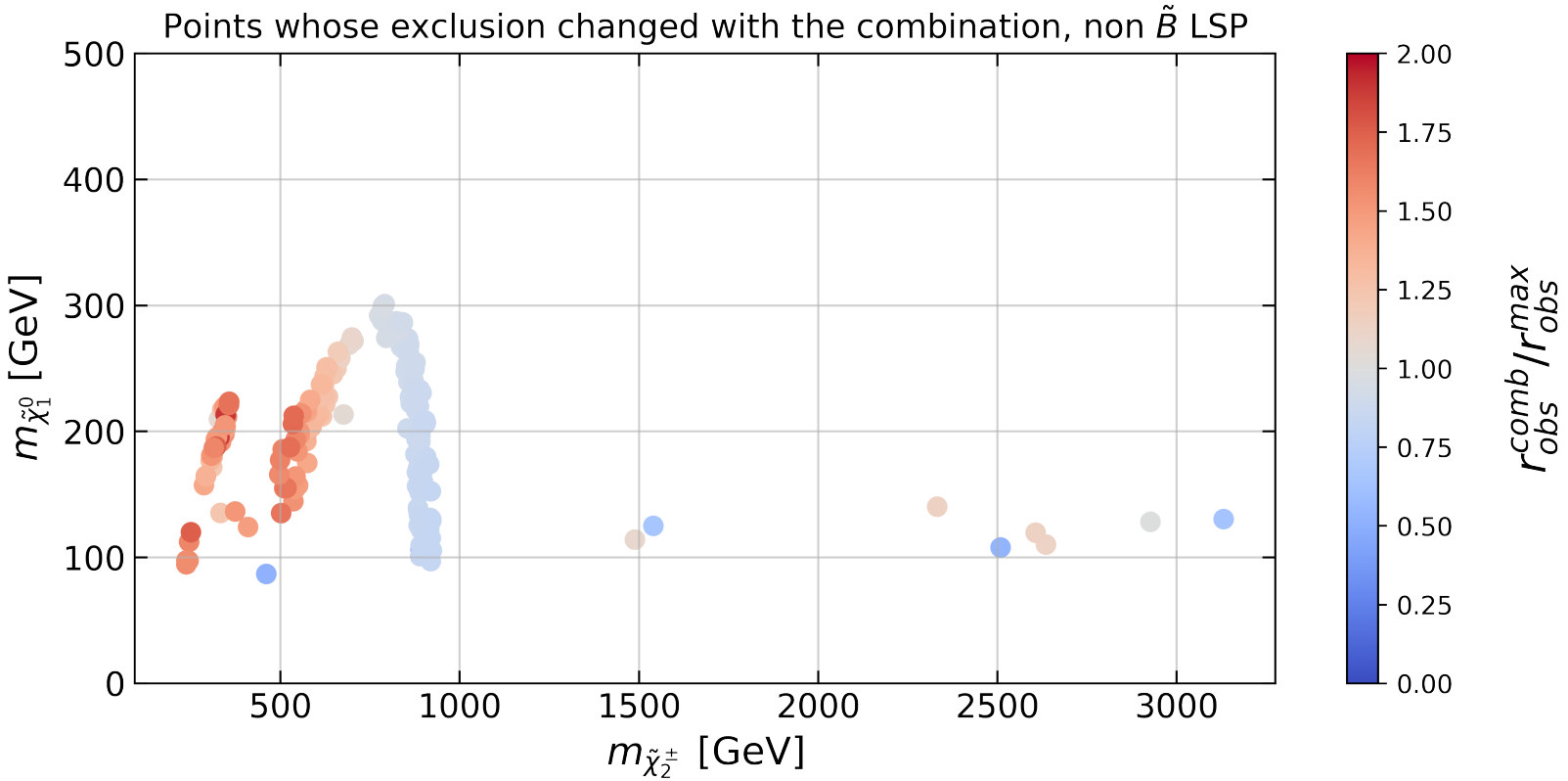


For $m_{\tilde{\chi}_2^\pm} < 500$ GeV: excluded when combining ATLAS 3 ℓ + MET search with ATLAS 2 ℓ + MET searches (TChiWZ)

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: 193



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

For 1000 GeV $< m_{\tilde{\chi}_2^\pm}$: ATLAS 3 ℓ + MET search is combined with ATLAS 2 ℓ + jets + MET search and with CMS 2 ℓ or more + MET searches (TChiWZoff)

Conclusion

- LHC constraints set on EWino masses have been revisited in light of a global combination of EWino 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
- Non EW scales were decoupled
- Next step: include long lived particles searches

Acknowledgments

Many thanks to the SUSY 2023 organizers and to the coordinators of the phenomenology and experiment section.

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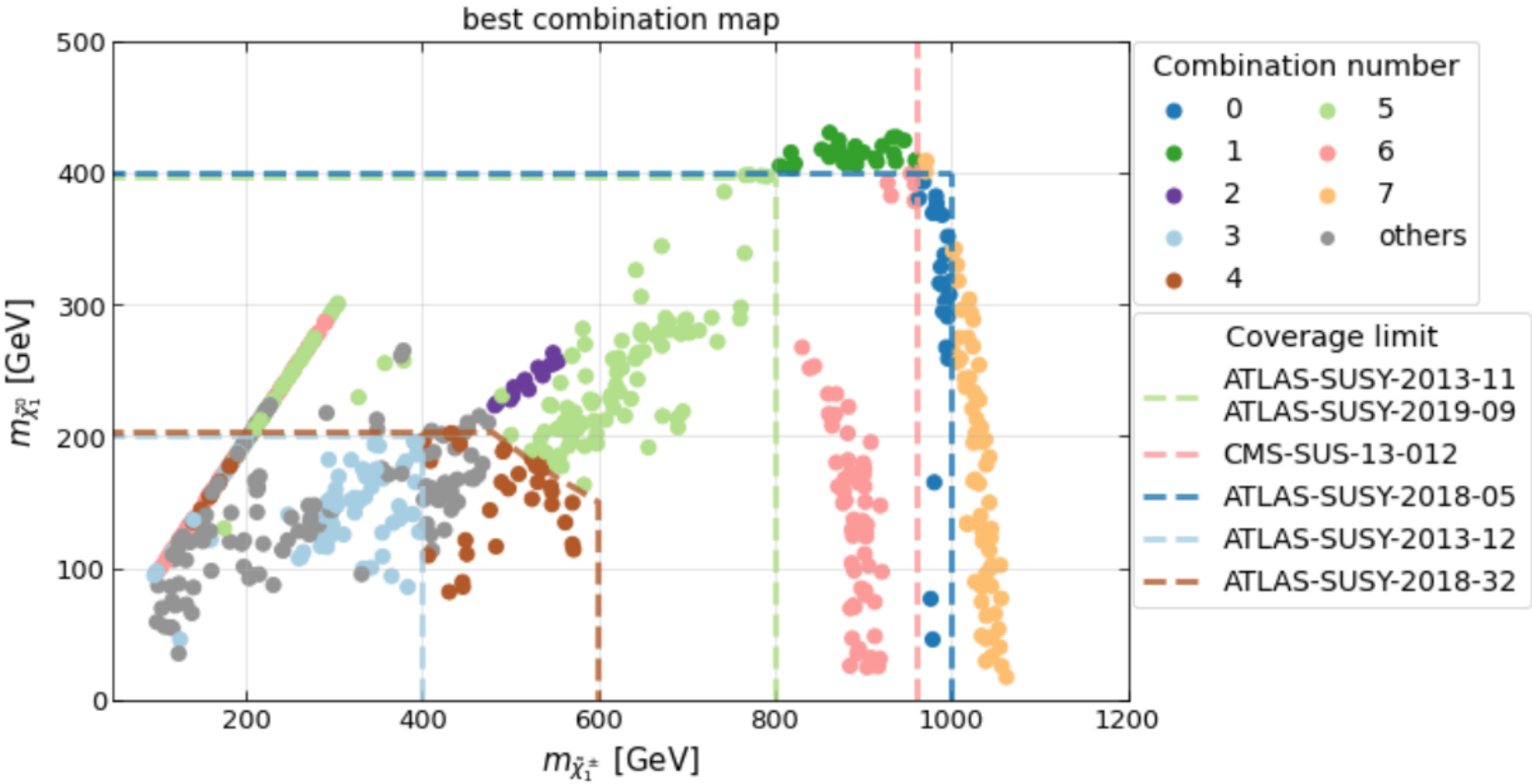
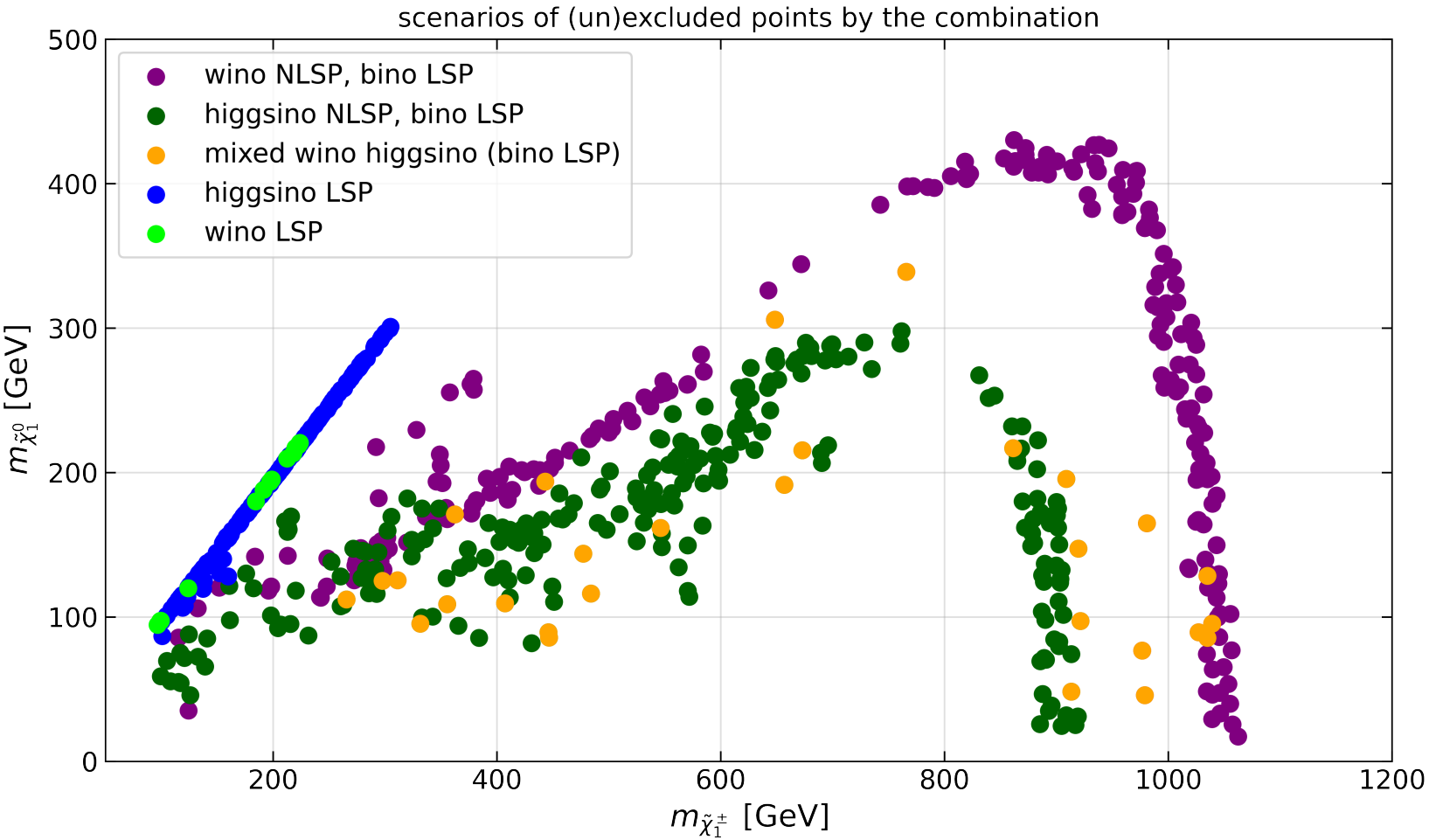
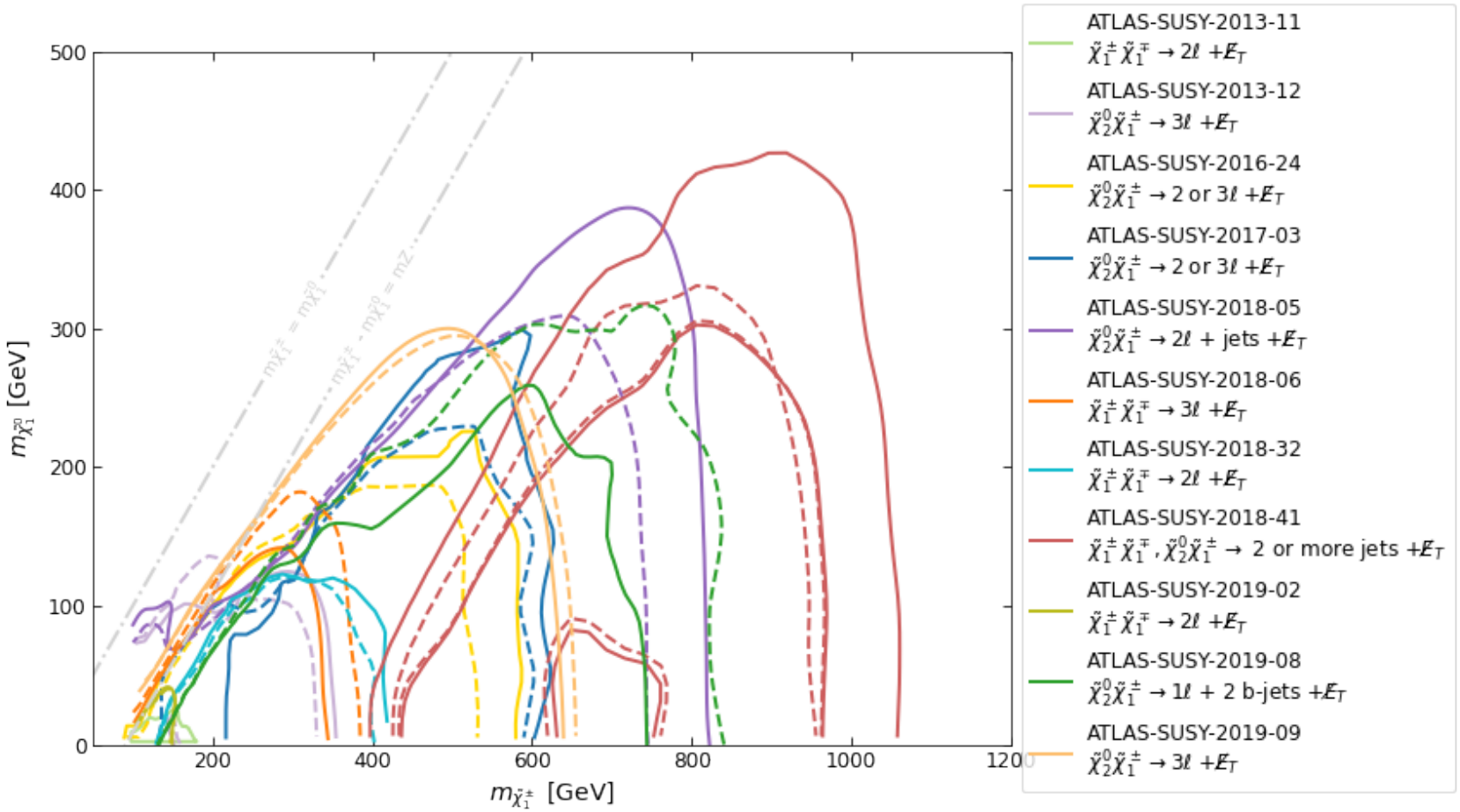
Backup Slides

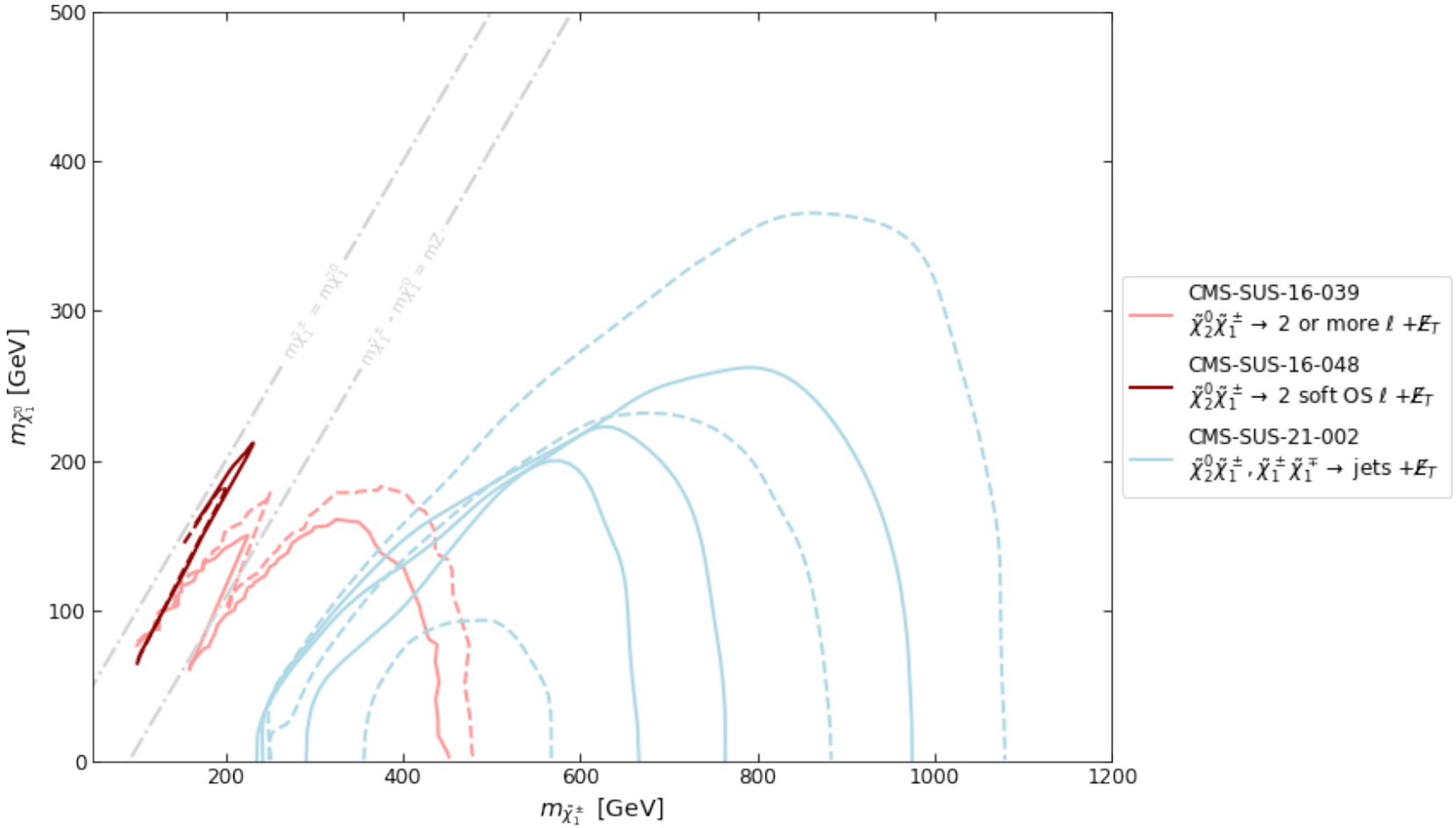

best combination map
Combination number
0
1
2
3
4
5
6
7
others
Coverage limit
ATLAS-SUSY-2013-11
ATLAS-SUSY-2019-09
CMS-SUS-13-012
ATLAS-SUSY-2018-05
ATLAS-SUSY-2013-12
ATLAS-SUSY-2018-32
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
0
100
200
300
400
500
200
400
600
800
1000
1200


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
200
400
600
800
1000
1200

All ATLAS contours

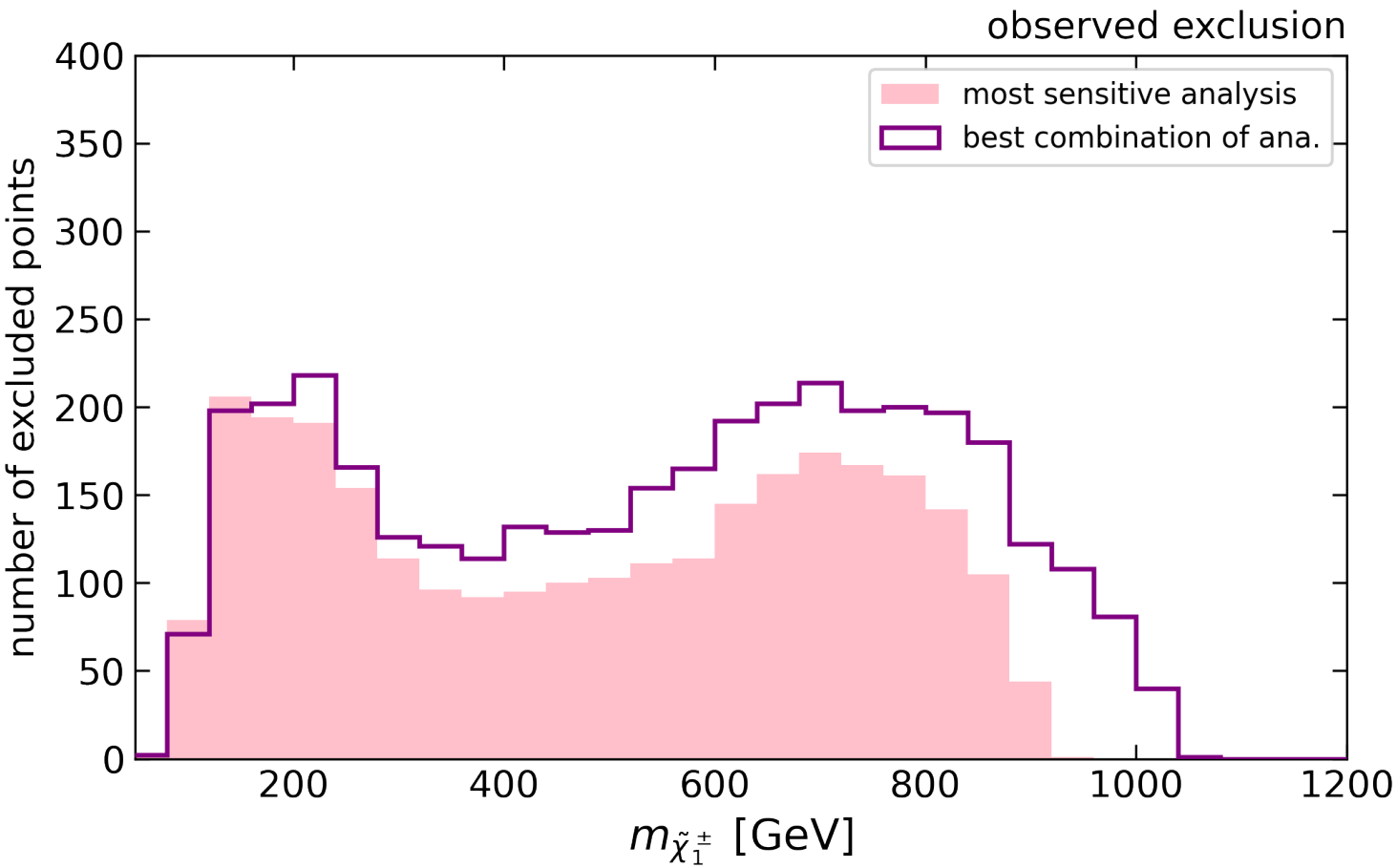


All CMS contours



Most sensitive analysis

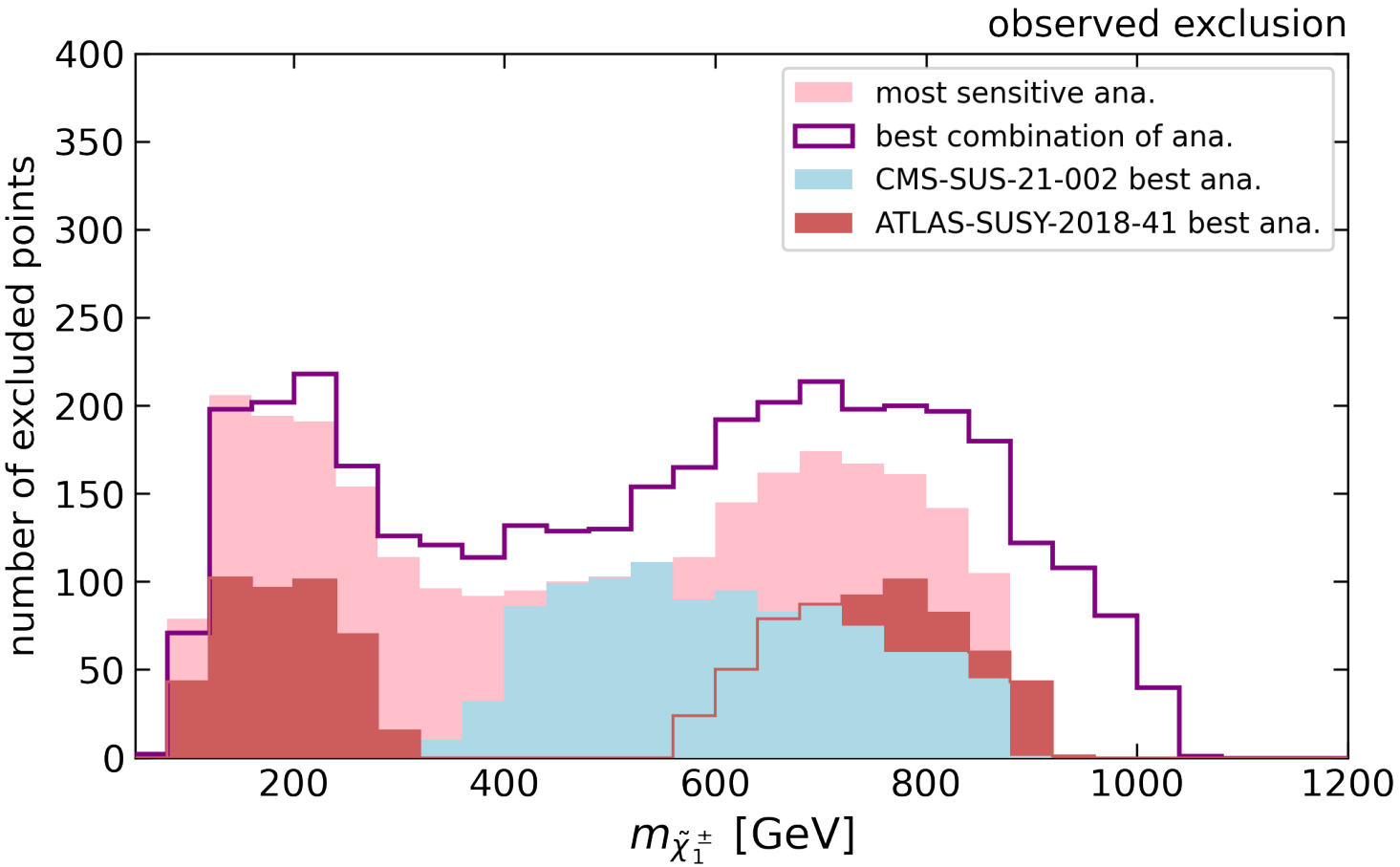
$$\text{excluded} \Leftrightarrow r = \frac{\sigma^{\text{BSM}}}{\sigma^{\text{BSM}}_{\text{UL}}} = \frac{1}{\mu_{\text{UL}}} \geqslant 1$$



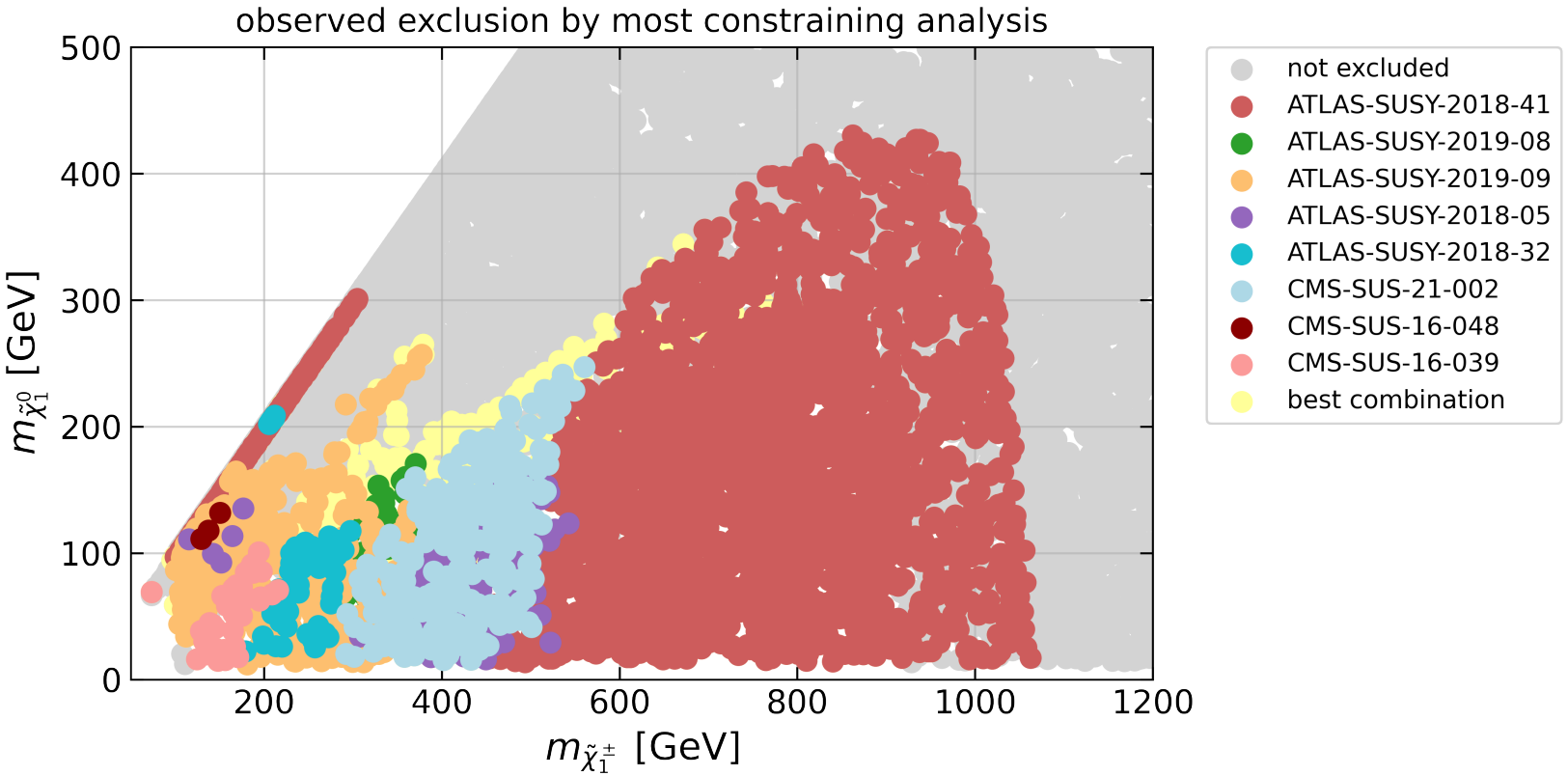
On the contrary the exclusion power is almost always enhanced when comparing to the most sensitive analysis (lowest μ_{UL} obtained with $n_j^{obs} = b_j$)

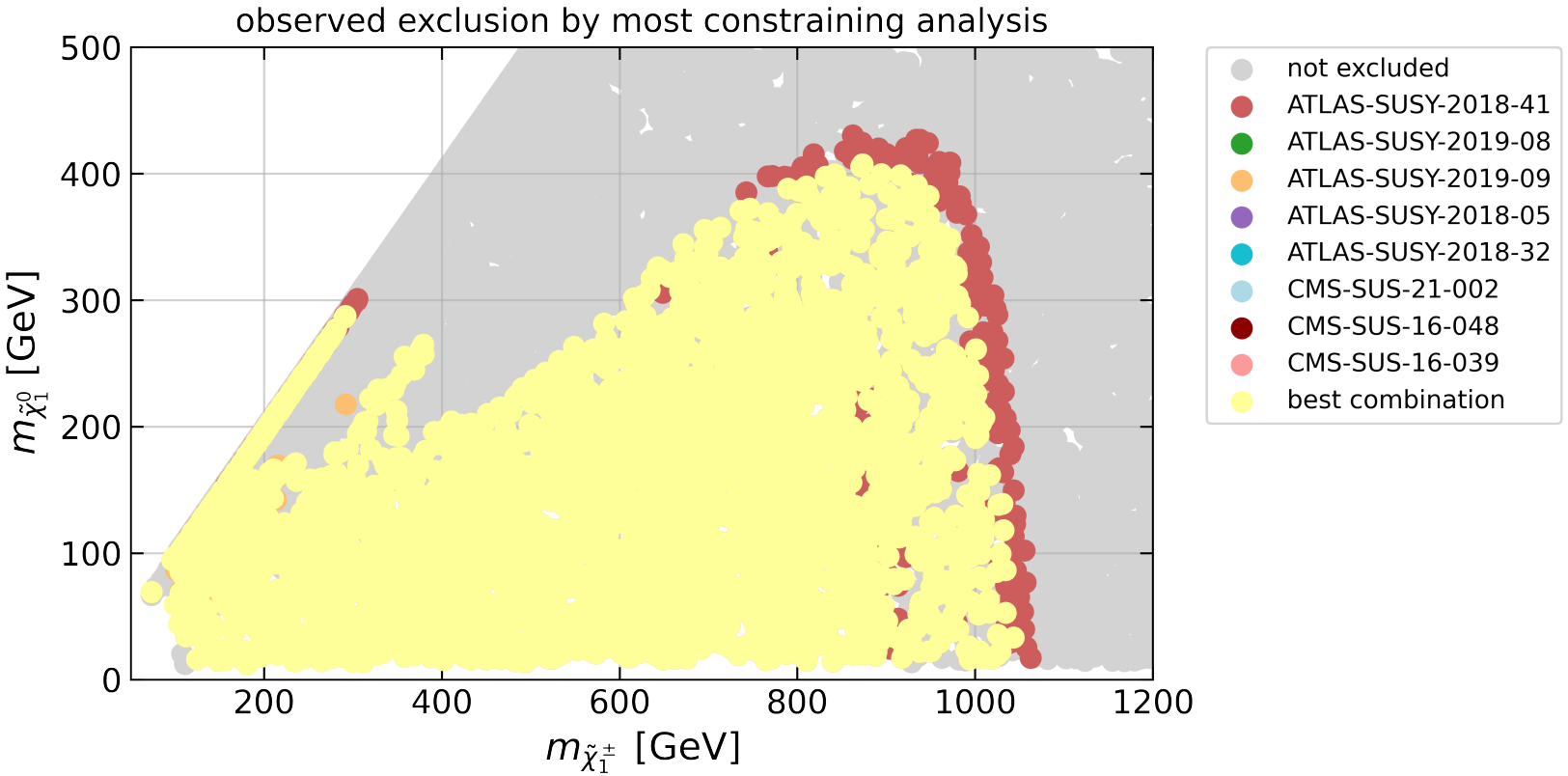
Most sensitive analysis

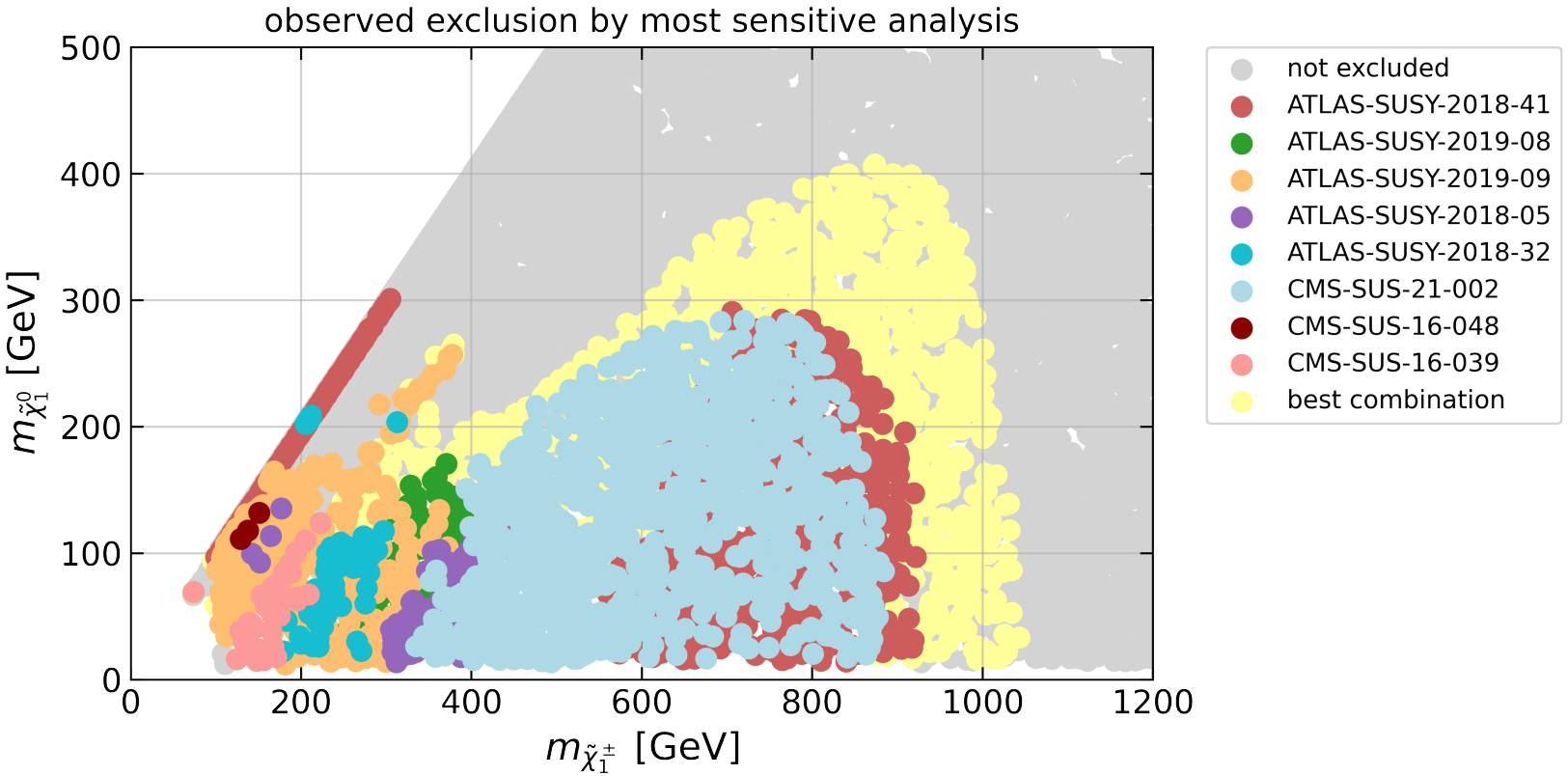
$$\text{excluded} \Leftrightarrow r = \frac{\sigma^{\text{BSM}}}{\sigma^{\text{BSM}}_{\text{UL}}} = \frac{1}{\mu_{\text{UL}}} \geqslant 1$$

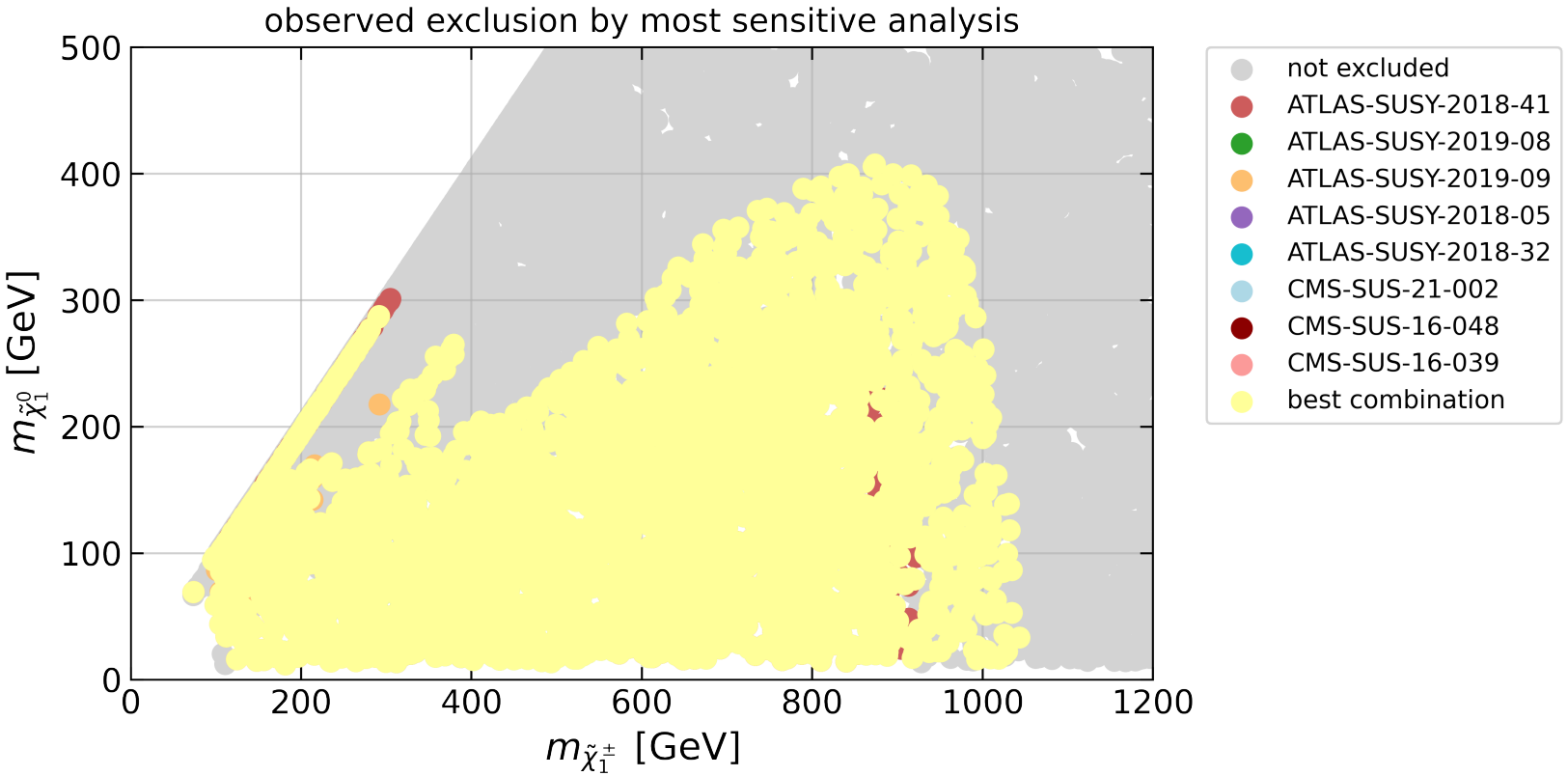


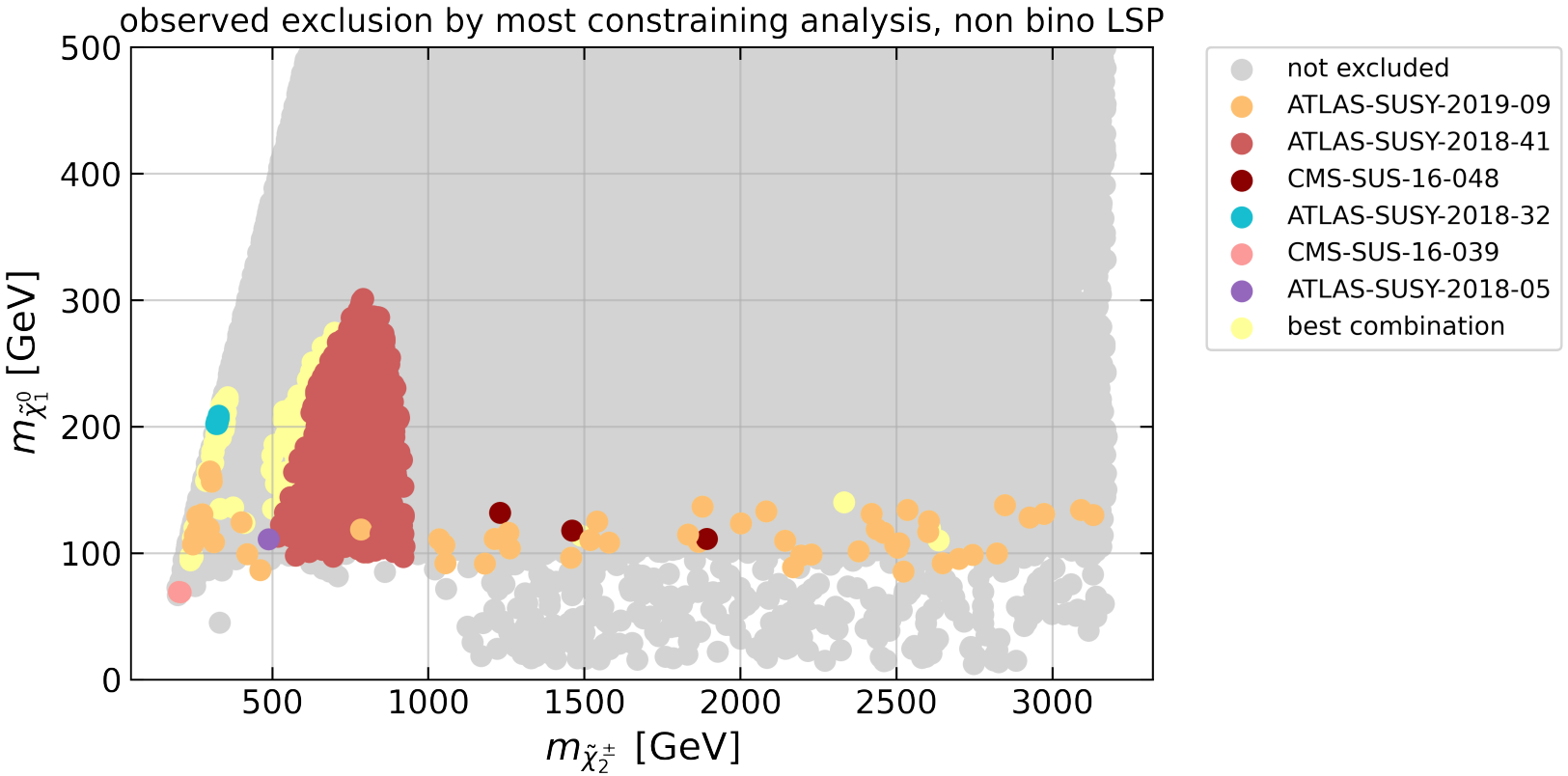
An analysis that observed an under-fluctuation is sensitive at high $m_{\tilde{\chi}_1^\pm}$

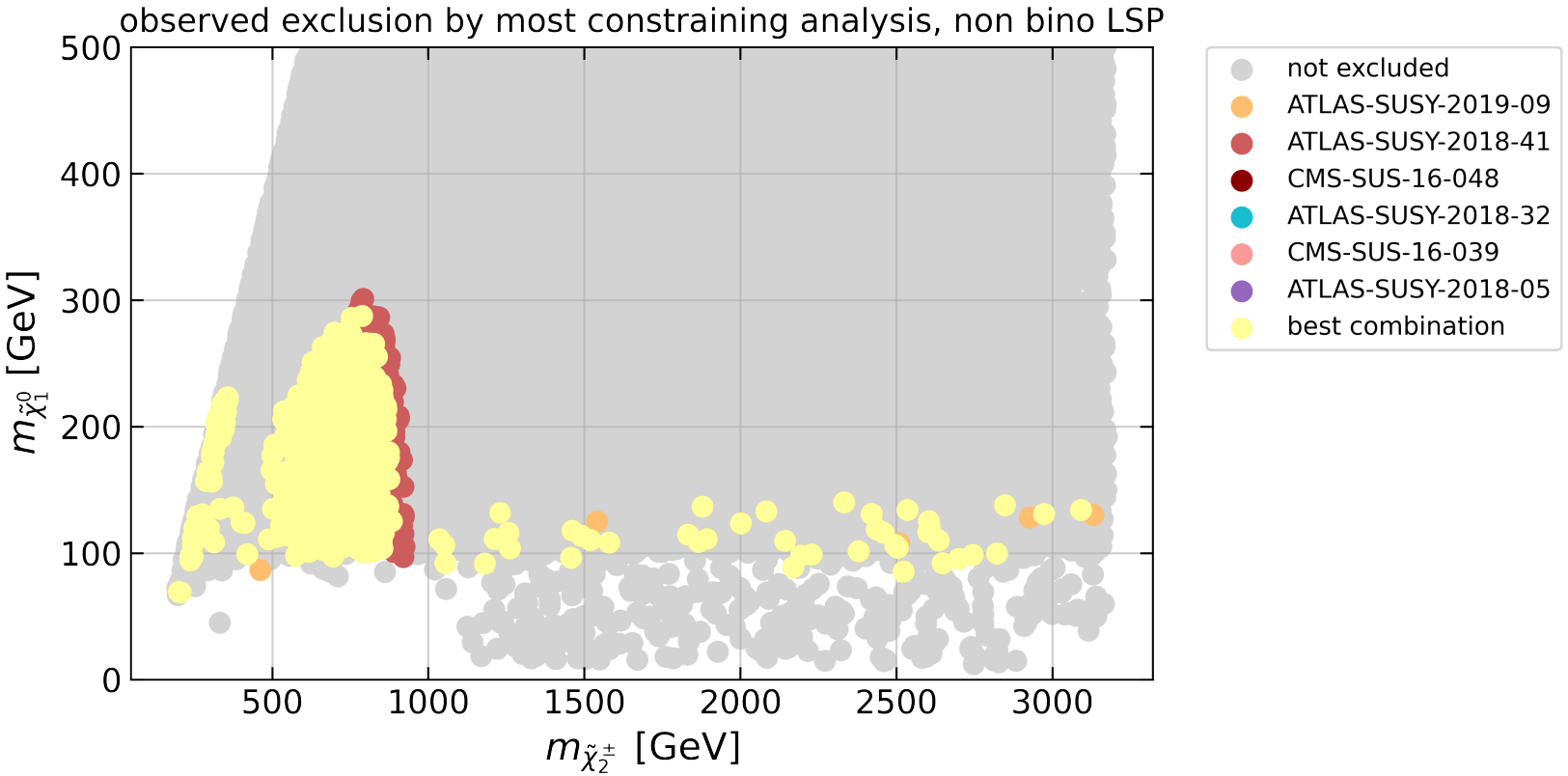

observed exclusion by most constraining analysis
500
400
300
200
100
0
200
400
600
800
1000
1200
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
not excluded
ATLAS-SUSY-2018-41
ATLAS-SUSY-2019-08
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-05
ATLAS-SUSY-2018-32
CMS-SUS-21-002
CMS-SUS-16-048
CMS-SUS-16-039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


observed exclusion by most constraining analysis
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

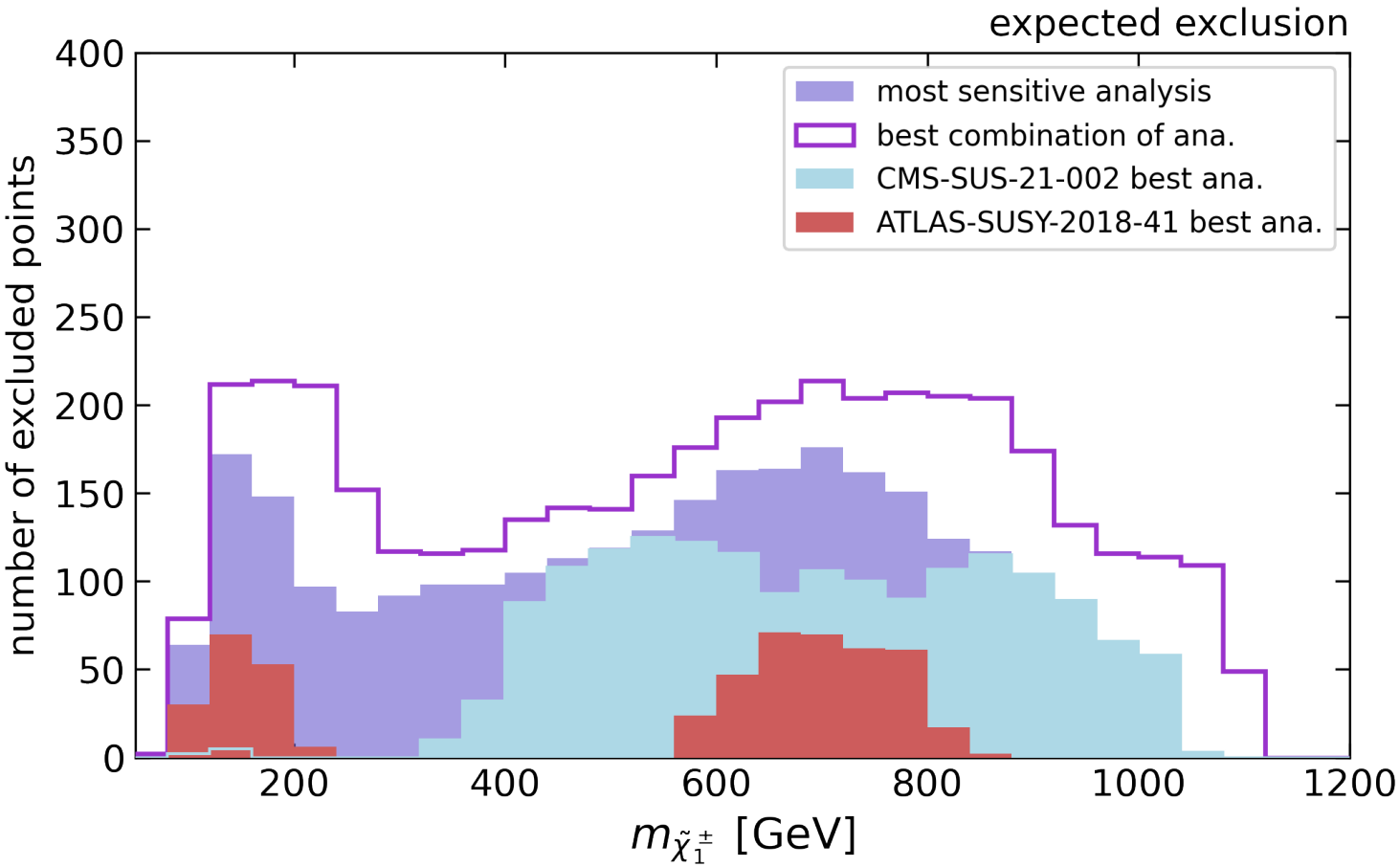

observed exclusion by most sensitive analysis
not excluded
ATLAS-SUSY-2018-41
ATLAS-SUSY-2019-08
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-05
ATLAS-SUSY-2018-32
CMS-SUS-21-002
CMS-SUS-16-048
CMS-SUS-16-039
best combination
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
0
100
200
300
400
500
0
200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

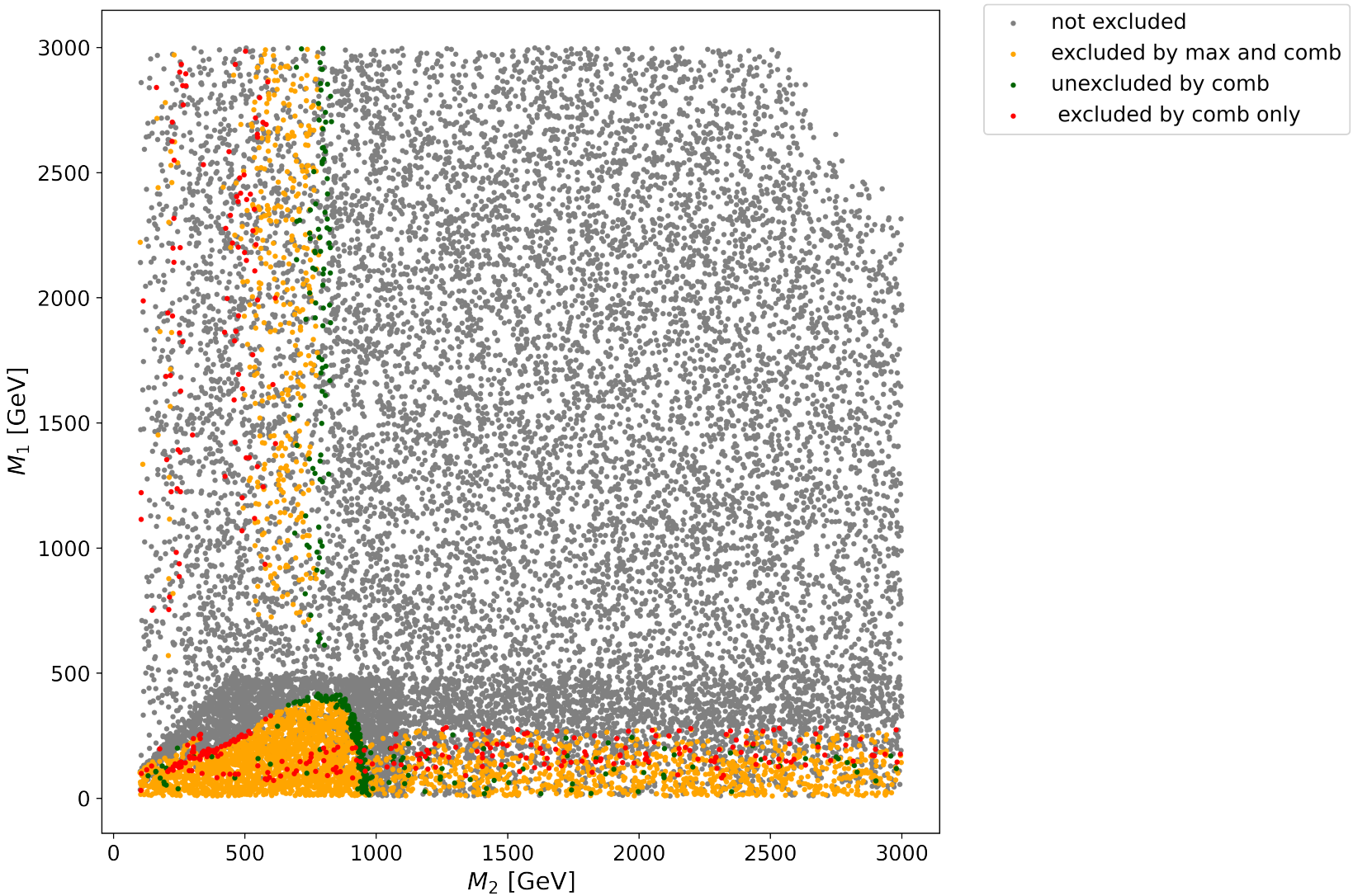

observed exclusion by most sensitive analysis
500
400
300
200
100
0
0
200
400
600
800
1000
1200
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_1^\pm}$ [GeV]
not excluded
ATLAS-SUSY-2018-41
ATLAS-SUSY-2019-08
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-05
ATLAS-SUSY-2018-32
CMS-SUS-21-002
CMS-SUS-16-048
CMS-SUS-16-039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

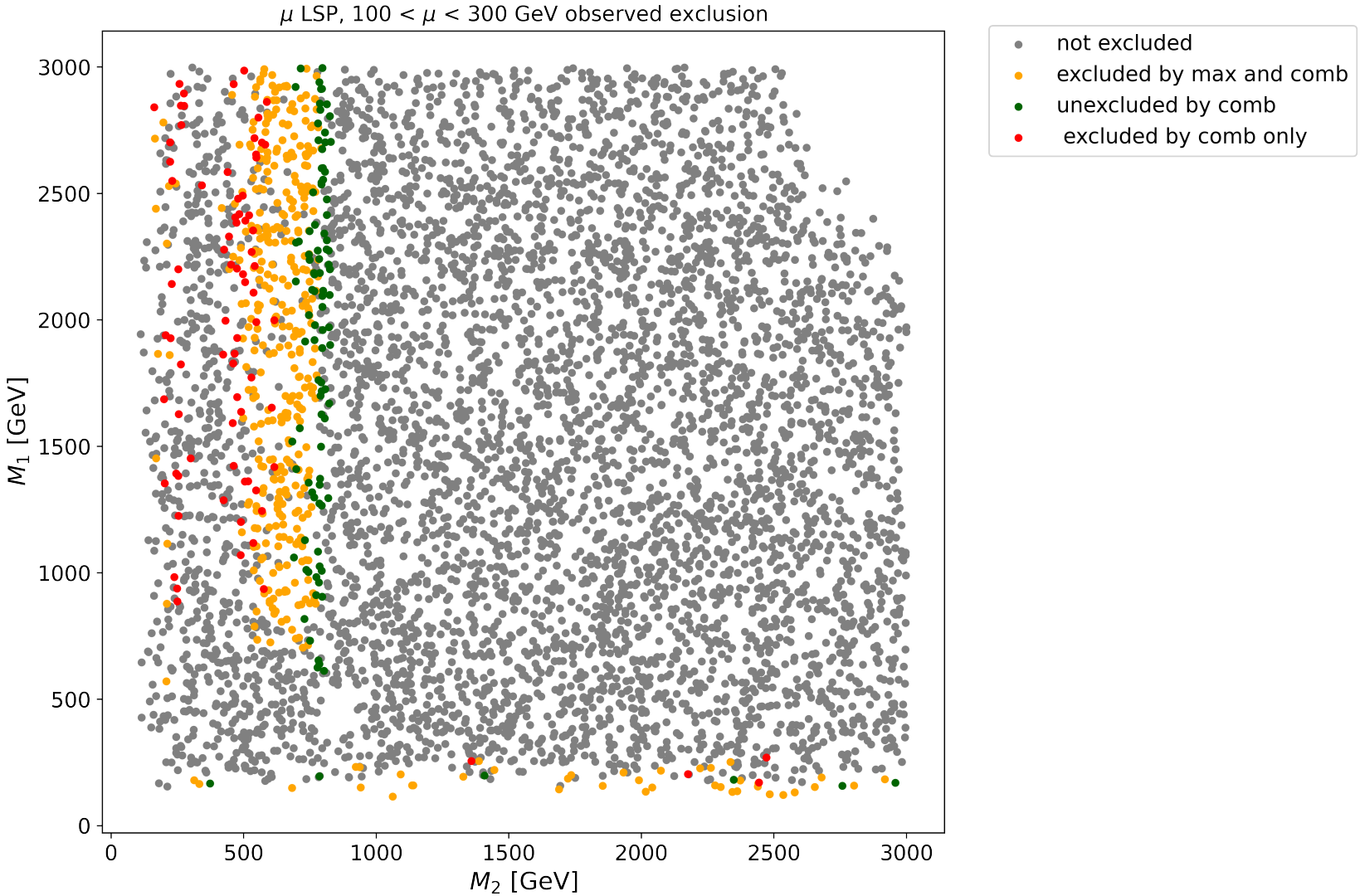

observed exclusion by most constraining analysis, non bino LSP
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^\pm}$ [GeV]
0
100
200
300
400
500
500
1000
1500
2000
2500
3000
not excluded
ATLAS-SUSY-2019-09
ATLAS-SUSY-2018-41
CMS-SUS-16-048
ATLAS-SUSY-2018-32
CMS-SUS-16-039
ATLAS-SUSY-2018-05
best combination


observed exclusion by most constraining analysis, non bino LSP
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^\pm}$ [GeV]
0
100
200
300
400
500
500
1000
1500
2000
2500
3000
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

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




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