Improved constraints on supersymmetric scenarios using SModelS analysis combination

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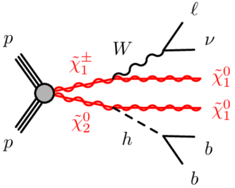
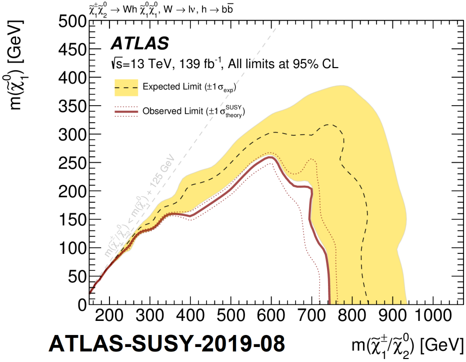
Data interpretation in LHC searches

arXiv:1105.2838

The ATLAS and CMS data are interpreted using a simplified model (minimal set of parameters).



TChiWH

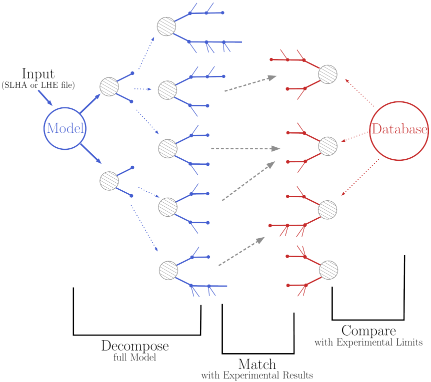


How would such results constraint a more complex model?

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

SModelS working principle

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

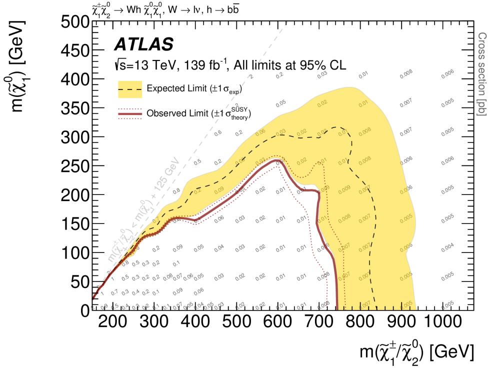


- 35 ATLAS and 39 CMS 13 TeV analyses in the database.
- Code and documentation available online: https://smodels.github.io/

Two methods to reinterpret results

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

- **Cross-section upper limits:**
  $\sigma^{\mathsf{BSM}} = \sum \sigma \prod \mathsf{BR} \leftarrow$ input file.
  $\sigma^{\mathsf{BSM}}_{\mathsf{UL}} \leftarrow$ experimental publications.



Two methods to reinterpret results

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

- **Efficiency maps:**
  $\sigma^{\text{BSM}} = \epsilon \times \mathcal{A} \sum \sigma \prod \text{BR}$ per signal region ← input file and exp. pub.
  $\sigma^{\text{BSM}}_{\text{UL}}$ ← exp. pub. or computed through an hypothesis test:

$$\sigma^{\text{BSM}}_{\text{UL}} = \mu_{\text{UL}} \frac{n_{\text{total signal}}}{luminosity}.$$

The signal strength upper limit (μ_{UL}) is reached when $\frac{p(\text{BSM})}{p(\text{SM only})} = 0.05$, where p is the p-value of the given hypothesis and is evaluated using the log likelihood ratio $q_\mu = -2\ln\left(\frac{L(\mu,\hat{\hat{\theta}})}{L(\hat{\mu},\hat{\theta})}\right)$ if $\hat{\mu} \leqslant \mu$, 0 otherwise.

The likelihood is Poissonian: $L(\mu,\theta|D) = \frac{(\mu+b+\theta)^{n_{obs}} e^{-(\mu+b+\theta)}}{n_{obs}!} e^{-\frac{\theta^2}{2\delta^2}}$.

Efficiency maps allow SModelS to compute likelihoods for the hypothesised signal (L_{BSM}, L_{SM}, L_{max}).

arXiv:2009.01809
arXiv:1811.10624

Two methods to reinterpret results

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

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

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

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

Combining uncorrelated analyses

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

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

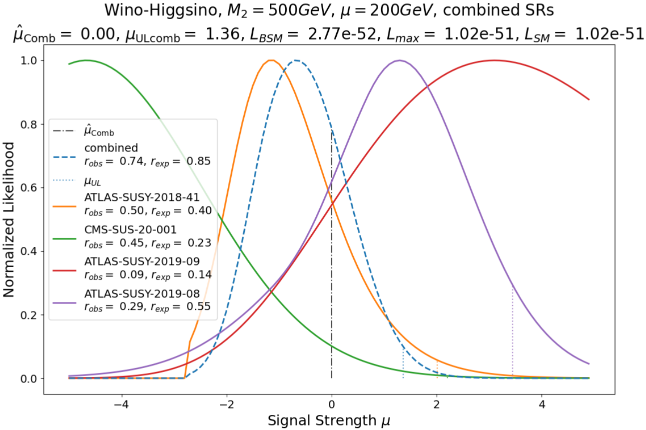
SModelS parameters.ini file

```
#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 elsewis
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
testCoverage = True ;Set True if topologies not covered by experiments (missing topologi
combineSRs = True ;Set True to combine signal regions when covariance matrix or pyhf JSO
best SR (faster).
combineAnas = ATLAS-SUSY-2018-41,ATLAS-SUSY-2019-08,ATLAS-SUSY-2019-09,CMS-SUS-20-001 ;
results only. Use with care! (Also, for the time being, it is advisable to use only if c

reportAllSRs = False ;Set True to report all signal regions, instead of best signal regi
experimentalFeatures = True ;Set True to enable experimental features that are not yet c
doing!!

```

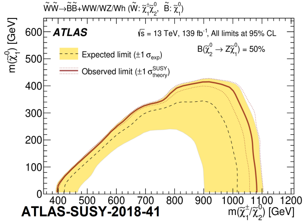
Combining uncorrelated analyses

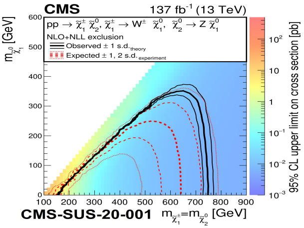
From SModelS v.2.2 on, it is possible to combine uncorrelated analyses.

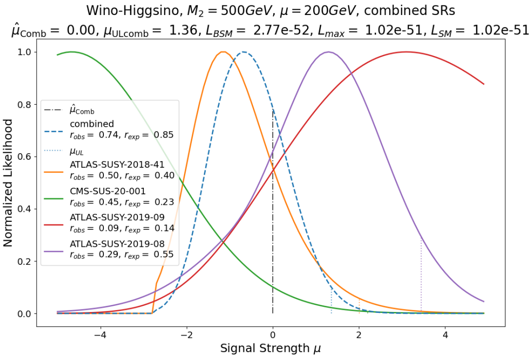
$$L_{\text{combined}}(\mu) = \prod_i L_i(\mu, \theta_i | D_i)$$



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

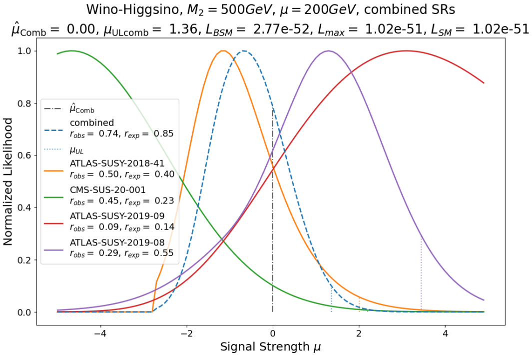


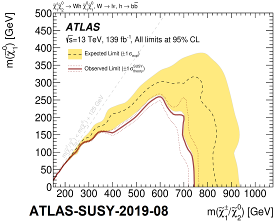


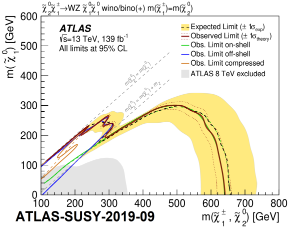


Under-fluctuation in the background leads to negative values for $\hat{\mu}$.

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



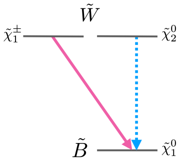




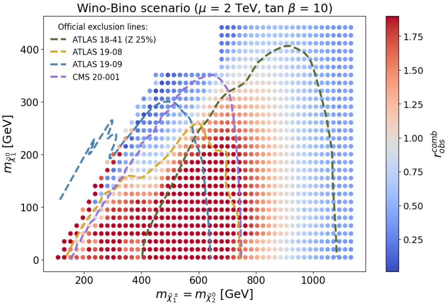
Excess in the data leads to positive values for $\hat{\mu}$.

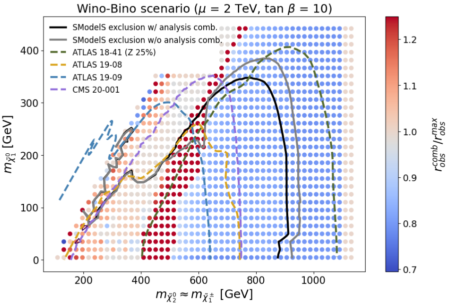
The wino-bino scenario

Scan over: $M_1 < M_2 \ll \mu = 2\,\mathrm{TeV}$



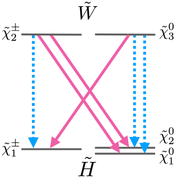
All other SUSY particles are assumed heavy (beyond LHC reach).
Mass spectra and branching ratios computed with SOFTSUSY 4.1.12.
Next-to-leading-order cross-sections computed with Prospino 2.1.

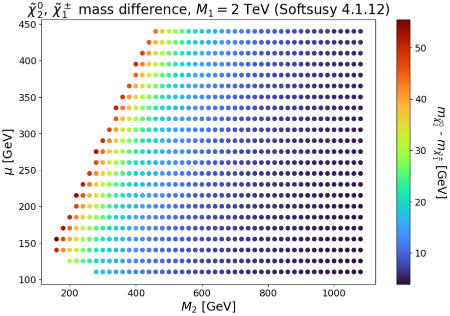


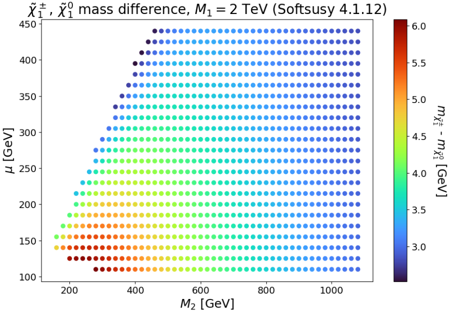


The wino-higgsino scenario

Scan over: $\mu < M_2 \ll M_1 = 2\,\mathrm{TeV}$



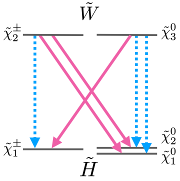


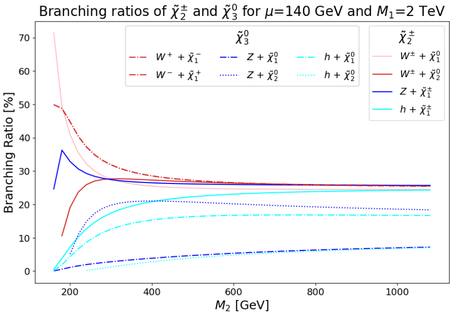


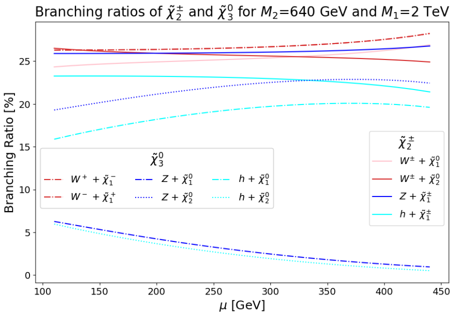
3.9 GeV $< m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^\pm} < 55.5$ GeV and 2.5 GeV $< m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} < 6.1$ GeV

The wino-higgsino scenario

Scan over: $\mu < M_2 \ll M_1 = 2\,\mathrm{TeV}$

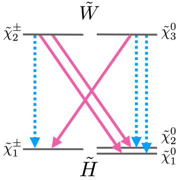




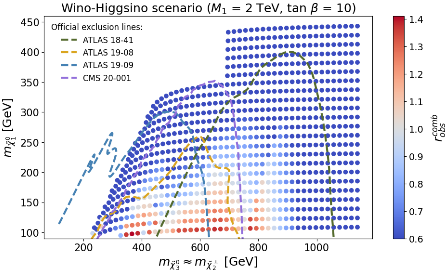


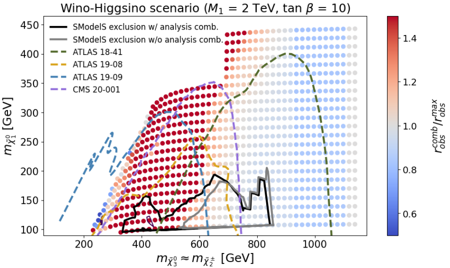
There are more branching ratios and no dominant decay.
When M_2 increases: less $W^{\pm}$, more higgs, same Z.
When μ increases: a bit more $W^{\pm}$, a bit less higgs, same Z.

The wino-higgsino scenario



Scan over: $\mu < M_2 \ll M_1 = 2\,\mathrm{TeV}$





The ATLAS and CMS contour line are obtained by making the assumption of a pure wino-bino scenario. Here, with more decays the sensitivity becomes much less.

Conclusion

- Reinterpreted LHC results may differ from the simplified model picture.
- For precise statistical statement, one needs to evaluate likelihoods.
- Combining analyses can lead to more robust constraints.
- Designing the upcoming BSM searches to be easily combinable would benefit reinterpretation effort.

Acknowledgments

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

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Backup Slides

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

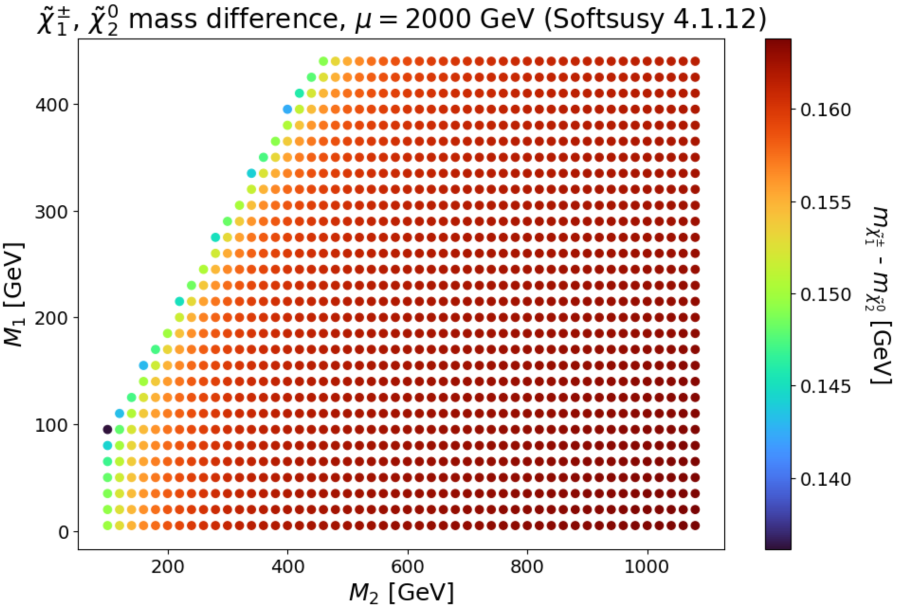
Run 1 - 8 TeV

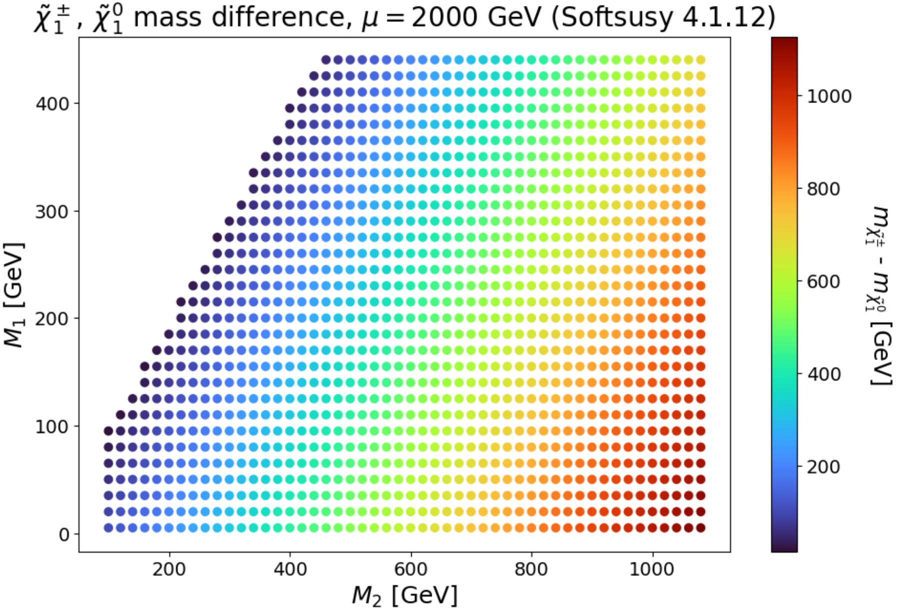
In total, we have results from 15 ATLAS and 18 CMS 8 TeV searches.

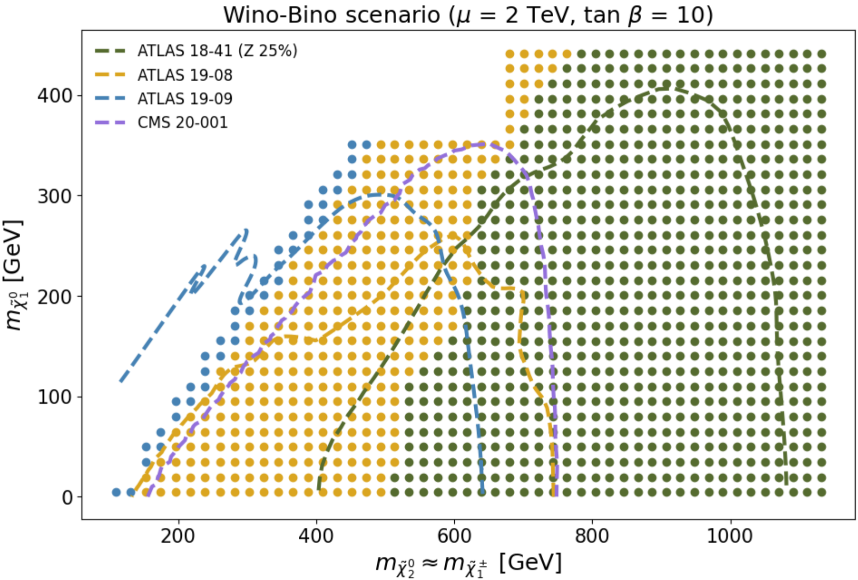
- ATLAS upper limits: 13 analyses, 34 results
- ATLAS efficiency maps: 10 analyses, 31 results, 269 individual maps
- CMS upper limits: 16 analyses, 56 (of which 3 LLP) results
- CMS efficiency maps: 9 analyses, 47 (of which 9 LLP) results, 980 individual maps

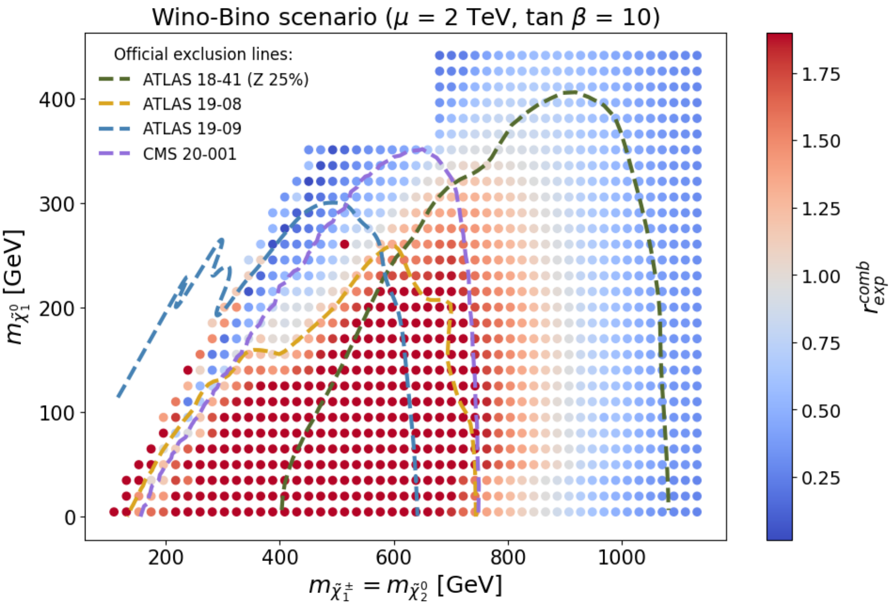
Modifiers and Constraints

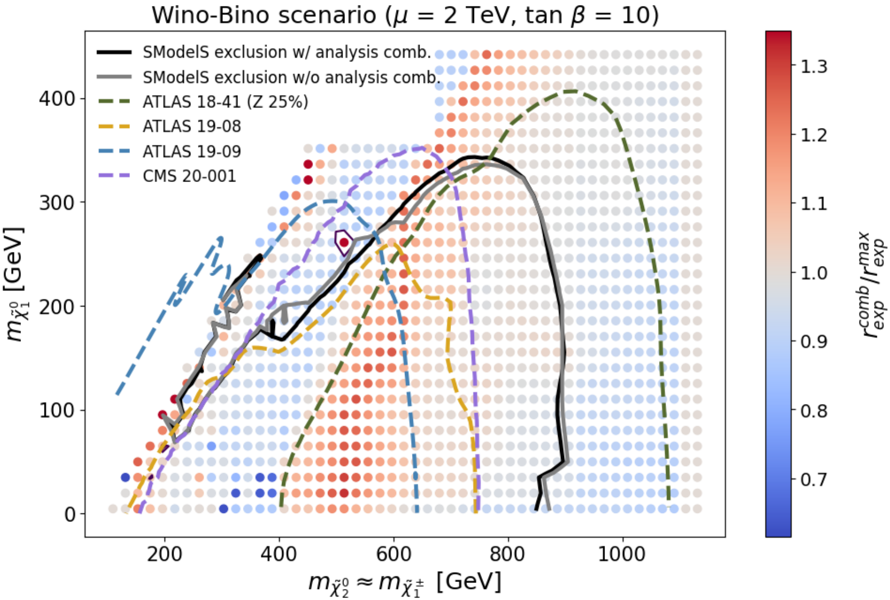
Description	Modification	Constraint Term c_χ	Input
Uncorrelated Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \text{Pois}\left(r_b = \sigma_b^{-2} \middle| \rho_b = \sigma_b^{-2}\gamma_b\right)$	σ_b
Correlated Shape	$\Delta_{scb}(\alpha) = f_p\left(\alpha \middle| \Delta_{scb,\alpha=-1}, \Delta_{scb,\alpha=1}\right)$	$\text{Gaus}\left(a = 0 \middle| \alpha, \sigma = 1\right)$	$\Delta_{scb,\alpha=\pm 1}$
Normalisation Unc.	$\kappa_{scb}(\alpha) = g_p\left(\alpha \middle| \kappa_{scb,\alpha=-1}, \kappa_{scb,\alpha=1}\right)$	$\text{Gaus}\left(a = 0 \middle| \alpha, \sigma = 1\right)$	$\kappa_{scb,\alpha=\pm 1}$
MC Stat. Uncertainty	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \text{Gaus}\left(a_{\gamma_b} = 1 \middle| \gamma_b, \delta_b\right)$	$\delta_b^2 = \sum_s \delta_{sb}^2$
Luminosity	$\kappa_{scb}(\lambda) = \lambda$	$\text{Gaus}\left(l = \lambda_0 \middle| \lambda, \sigma_\lambda\right)$	$\lambda_0, \sigma_\lambda$
Normalisation	$\kappa_{scb}(\mu_b) = \mu_b$		
Data-driven Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$		

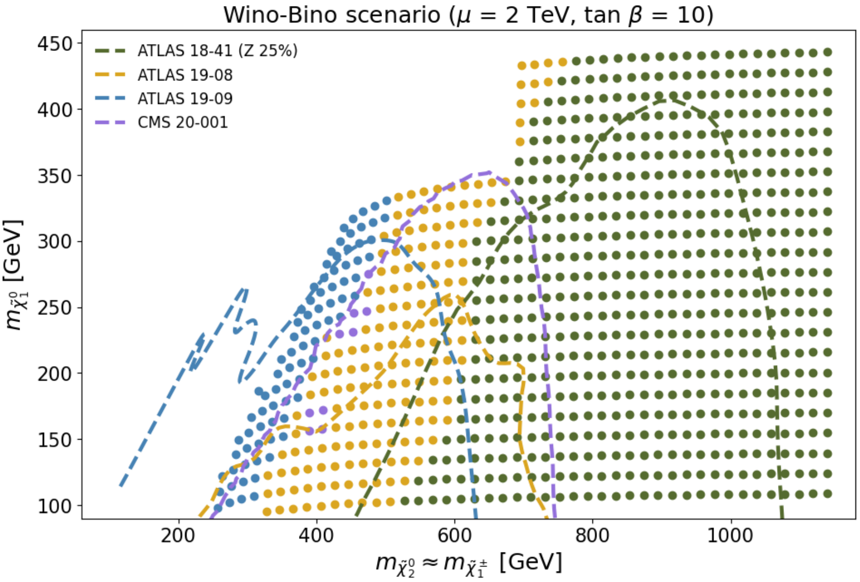

$\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$ mass difference, $\mu = 2000$ GeV (Softsusy 4.1.12)
M_1 [GeV]
M_2 [GeV]
$m_{\tilde{\chi}_1^{\pm}}$ - $m_{\tilde{\chi}_2^0}$ [GeV]
0
100
200
300
400
200
400
600
800
1000
0.140
0.145
0.150
0.155
0.160

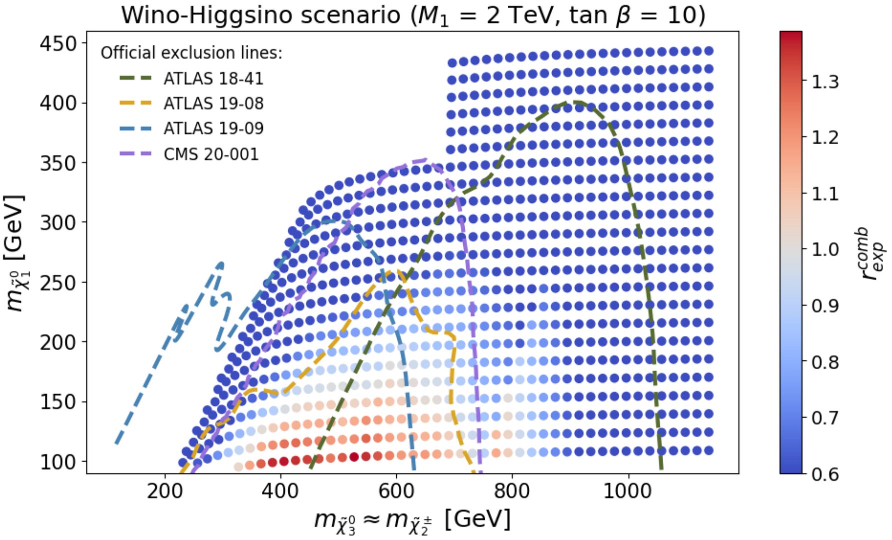

$\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$ mass difference, $\mu = 2000$ GeV (Softsusy 4.1.12)
M_1 [GeV]
M_2 [GeV]
$m_{\tilde{\chi}_1^\pm}$ - $m_{\tilde{\chi}_1^0}$ [GeV]
0
100
200
300
400
200
400
600
800
1000
200
400
600
800
1000

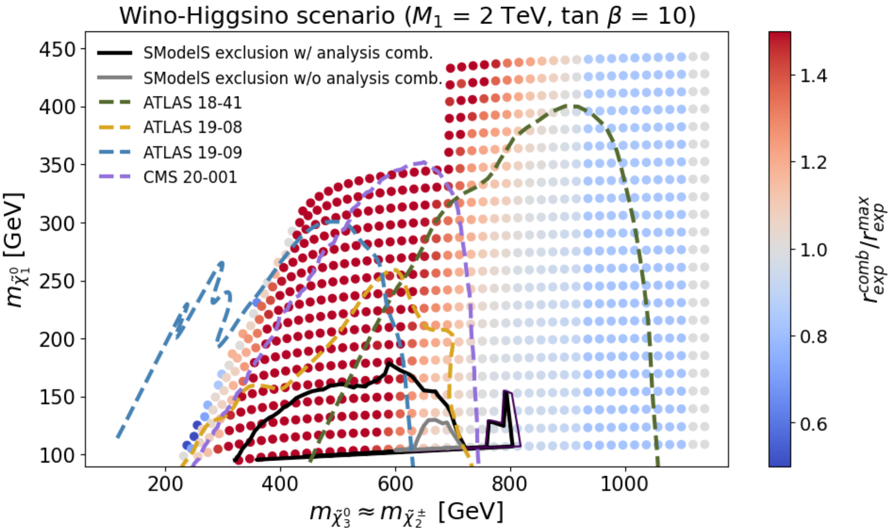

Wino-Bino scenario (μ = 2 TeV, tan β = 10)
ATLAS 18-41 (Z 25%)
ATLAS 19-08
ATLAS 19-09
CMS 20-001
400
300
200
100
0
$m_{\tilde{\chi}_1^0}$ [GeV]
200
400
600
800
1000
$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm}$ [GeV]


Wino-Bino scenario (μ = 2 TeV, tan β = 10)
Official exclusion lines:
ATLAS 18-41 (Z 25%)
ATLAS 19-08
ATLAS 19-09
CMS 20-001
$m_{\tilde{\chi}_1^0}$ [GeV]
0
100
200
300
400
200
400
600
800
1000
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$ [GeV]
1.75
1.50
1.25
1.00
0.75
0.50
0.25
r_{exp}^{comb}


Wino-Bino scenario (μ = 2 TeV, tan β = 10)
SModelS exclusion w/ analysis comb.
SModelS exclusion w/o analysis comb.
ATLAS 18-41 (Z 25%)
ATLAS 19-08
ATLAS 19-09
CMS 20-001
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm}$ [GeV]
$r_{exp}^{comb}/r_{exp}^{max}$
0
100
200
300
400
200
400
600
800
1000
0.7
0.8
0.9
1.0
1.1
1.2
1.3


Wino-Bino scenario (μ = 2 TeV, tan β = 10)
ATLAS 18-41 (Z 25%)
ATLAS 19-08
ATLAS 19-09
CMS 20-001
$m_{\tilde{\chi}_1^0}$ [GeV]
100
150
200
250
300
350
400
450
200
400
600
800
1000
$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm}$ [GeV]


Wino-Higgsino scenario (M_1 = 2 TeV, tan β = 10)
Official exclusion lines:
ATLAS 18-41
ATLAS 19-08
ATLAS 19-09
CMS 20-001
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_3^0} \approx m_{\tilde{\chi}_2^\pm}$ [GeV]
r_{exp}^{comb}
450
400
350
300
250
200
150
100
200
400
600
800
1000
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6


Wino-Higgsino scenario (M_1 = 2 TeV, tan β = 10)
SModelS exclusion w/ analysis comb.
SModelS exclusion w/o analysis comb.
ATLAS 18-41
ATLAS 19-08
ATLAS 19-09
CMS 20-001
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_3^0} \approx m_{\tilde{\chi}_2^\pm}$ [GeV]
$r_{exp}^{comb}/r_{exp}^{max}$
100
150
200
250
300
350
400
450
200
400
600
800
1000
0.6
0.8
1.0
1.2
1.4