SUSY at the LHC

Current status in a personal selection

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HELMHOLTZ

Outline

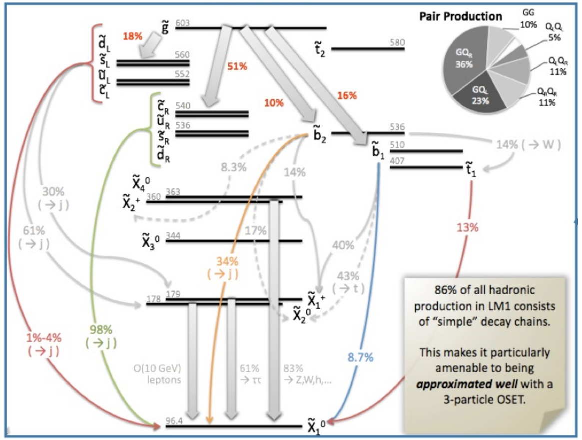
- Introduction
- Simplified model analyses targeting specific scenarios – turning every stone ☺
- Full models
- Summary

Introduction

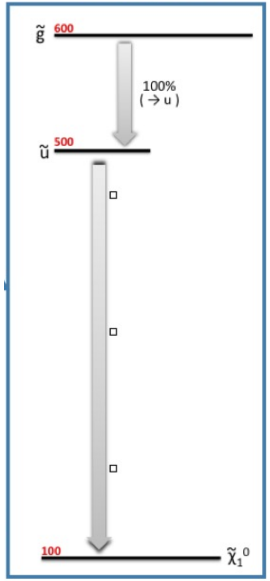
Development of the SUSY models and analyses over the years of LHC

- Before the LHC:
  - Few full (vanilla) models, e.g. constrained MSSM)

CMSSM



- Shortly after turning on the LHC:
  - First simplified models



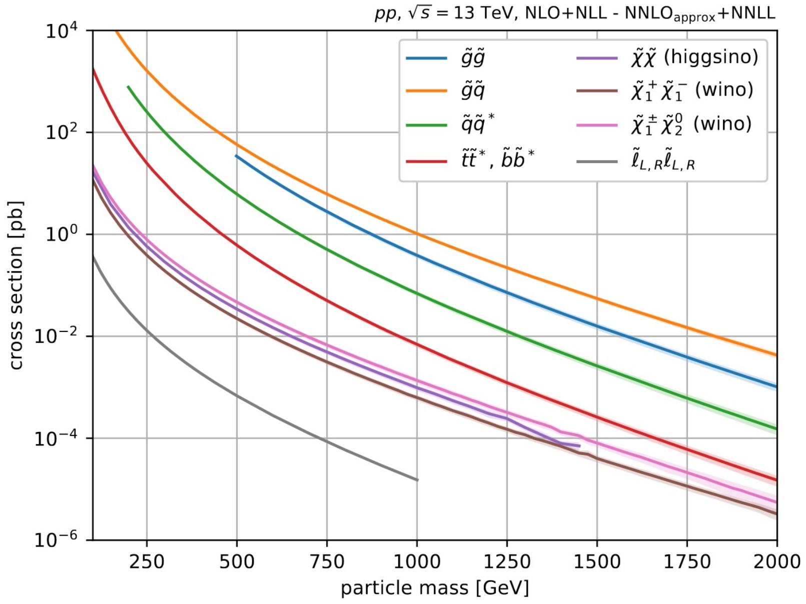
- After years of not finding SUSY:
  - Search in uncommon signatures, e.g.
    - Long-lived searches
    - Extended RPV searches program

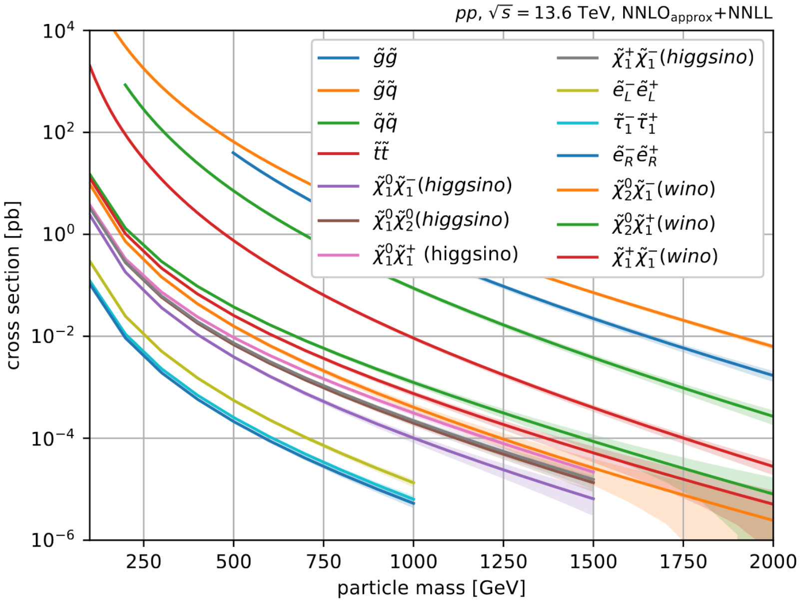
- Interpretation in full models
  - By theorists, e.g.
    - SmodelS
    - GAMBIT
  - By the experiments
    - ATLAS (ATLAS-CONF-2023-055)
    - CMS (work in progress)

SUSY cross sections

Strong production favored at the LHC, but also sensitivity to electroweak prduction

13 TeV **vs** **13.6 TeV**

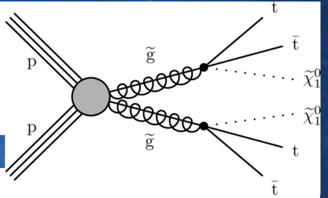


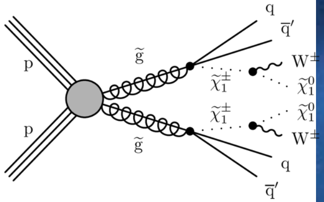


Will go on the next slides from high to low cross section with few example analyses

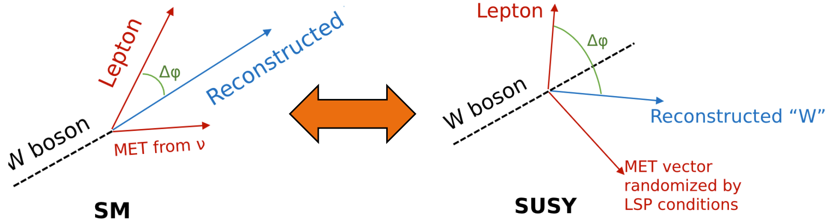
Gluino search

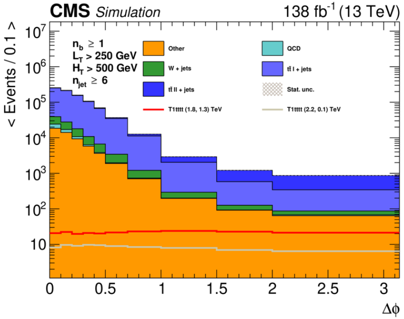
High cross section – simplified models for different decays





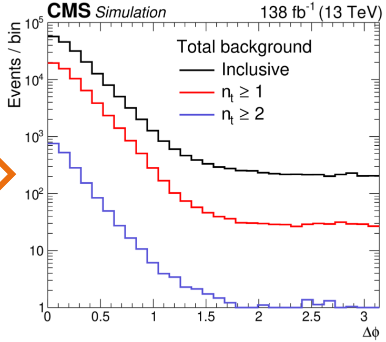
- DESY analysis in single lepton channel:
  - High branching ratio
  - Low QCD background
  - Main variable to distinguish background from signal: $\Delta\phi$ between W and p_T^{miss}





Add top (or W) tagging

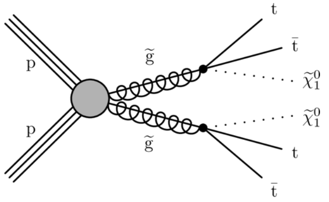
to further reduce background

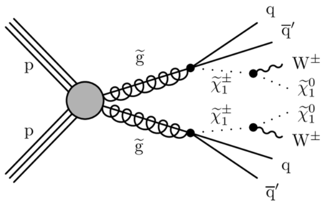


arXiv:2211.08476 JHEP 09 (2023) 149

Gluino search

Highest cross section – simplified models for different decays



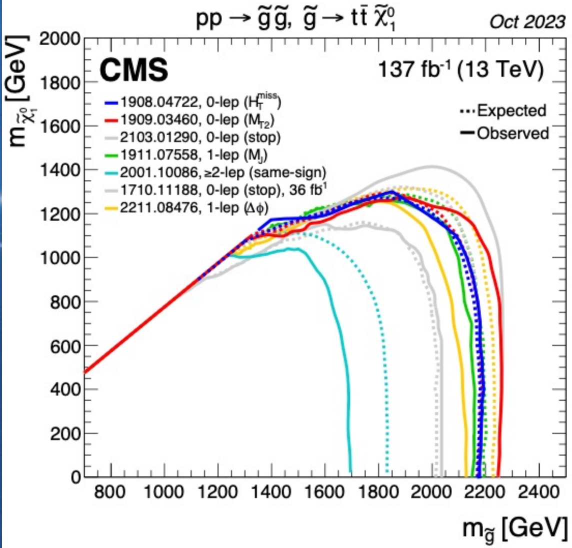


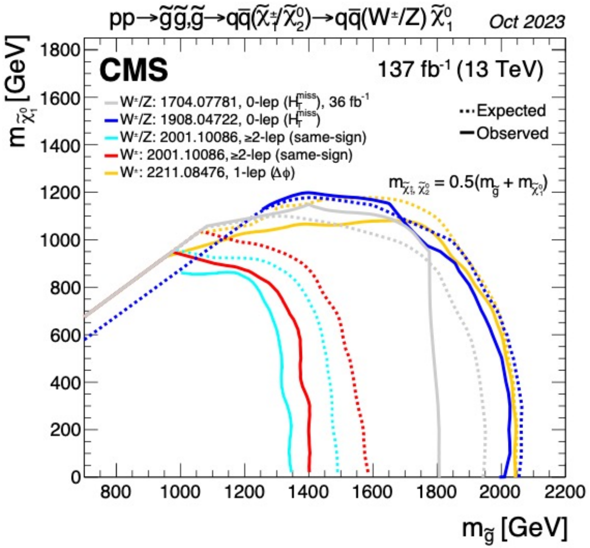
Exclusion limit depends on

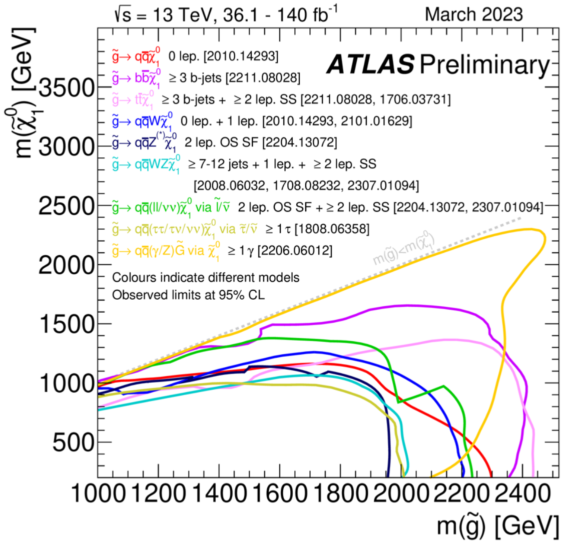
- final state
- signal model

Simplified models exclude gluinos < 2.0 – 2.4 TeV

arXiv:2211.08476 JHEP 09 (2023) 149





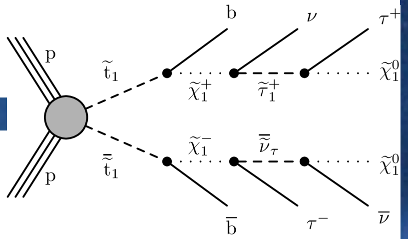


Search for top squarks with decay to tau leptons

Targeting higgsino-like and high tanβ scenarios

arXiv:2304.07174 JHEP 07 (2023) 110

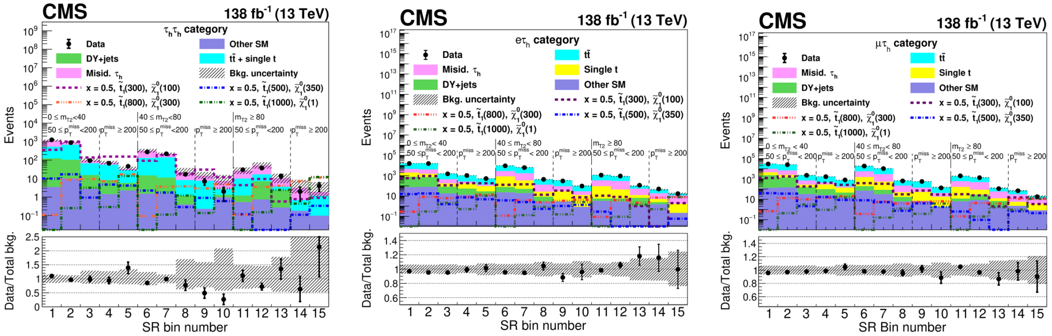
- High tanβ → charginos preferably decay to 3rd gen. leptons
- Charginos and staus/sneutrinos in the cascade decay
  - Stau and sneutrino considered mass degenerate
- Two τ leptons in the final state
  - $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ categories

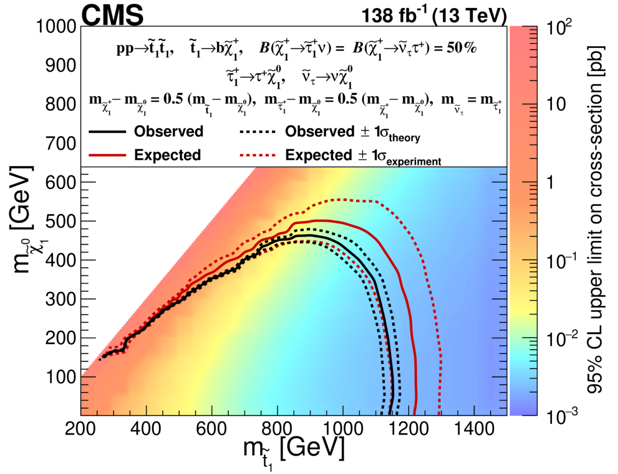


- Search variables:
  - p_T^{miss}, $m_{T2} = \min_{\vec{p}_T^{X(1)}+\vec{p}_T^{X(2)}=\vec{p}_T^{miss}} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right]$

$H_T = \sum p_T(\tau_h) + \sum p_T(\text{jet})$

$S_T = p_T(e/\mu) + p_T(\tau_h) + \sum p_T(\text{jet})$





Top squark masses excluded up to 1150 GeV for $m(X_1^0)$=1 GeV

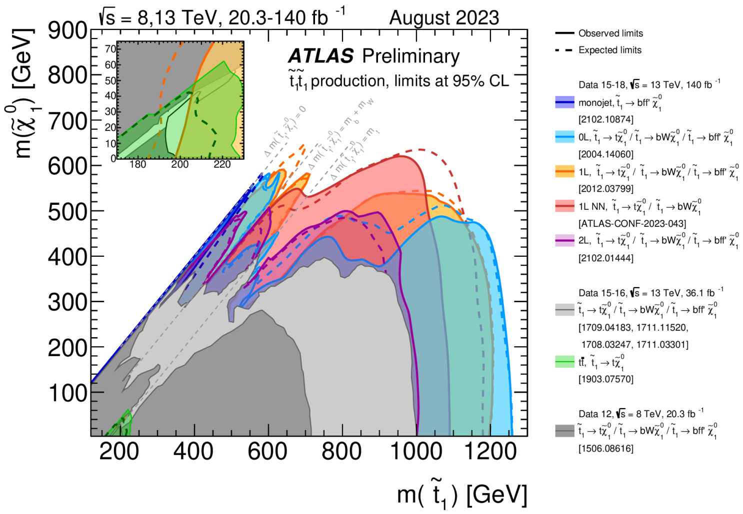
Limits on top squark production

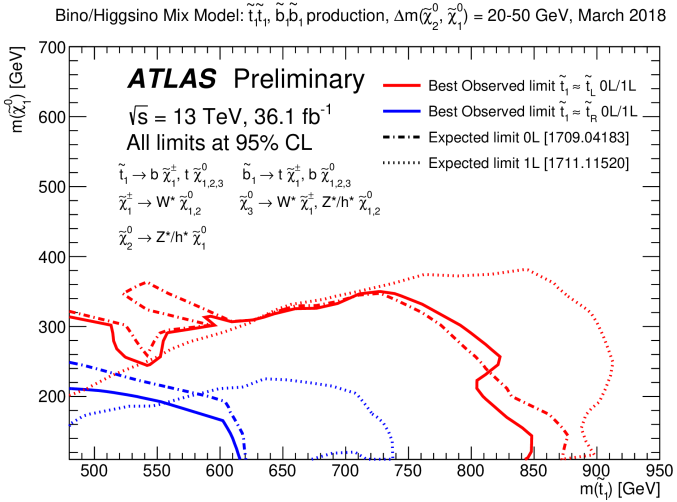
Comparing different simplified models

Exclusion limit depends on
- final state
- signal model

Simplified models exclude top squarks < 1.3 TeV

Sensitivity going down as soon as one adds some model assumption, here left vs right-handed partner

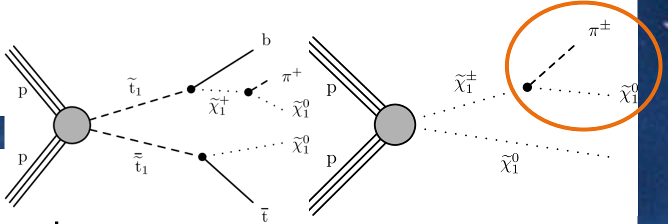


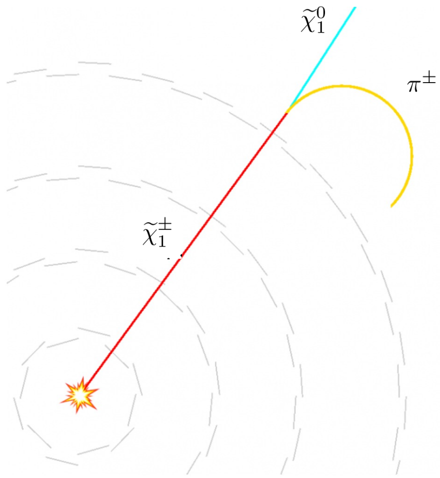


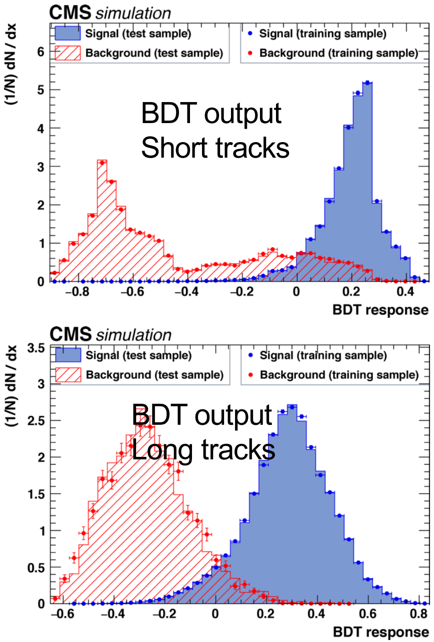
Search for disappearing tracks

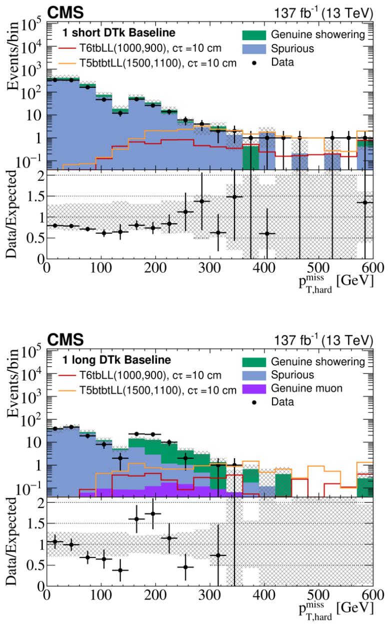
Tackling compressed spectra with long-lived particles

- To appear in scenarios with decays including small mass differences
- Chargino decaying to (invisible) pion and neutralino → disappearing track
- Identify short and long tracks using a BDT









arXiv:2309.16823

Search for disappearing tracks

Tackling compressed spectra with long-lived particles

- To appear in scenarios with decays including small mass differences
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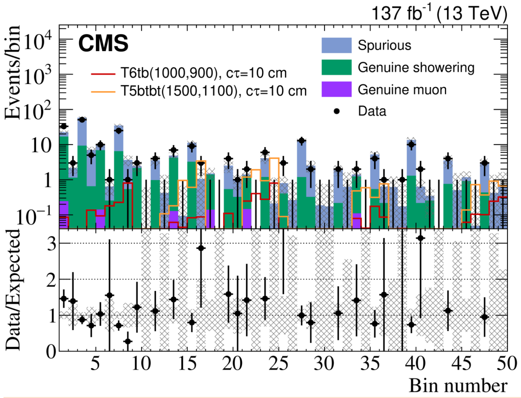
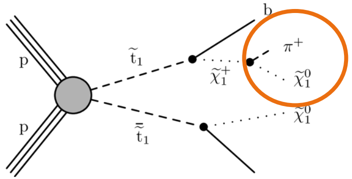
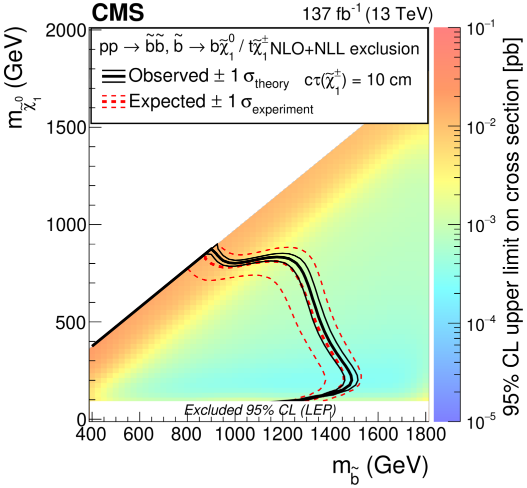
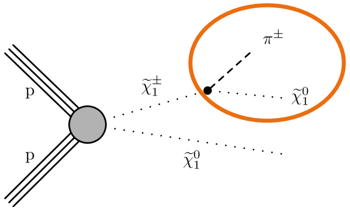
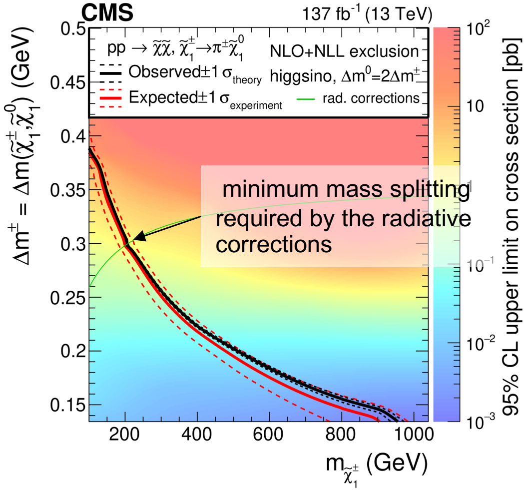










Exclude:

- bottom squarks < 1540 GeV
- **top squarks < 1590 GeV**
- gluinos < 2300 GeV
- winos < 650 GeV
- **higgsinos < 210 GeV**

Electroweakino searches

Reminder: several scenarios (even for simplified models)

- Every gauge field has a spin ½ partner → mixing

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

Bino, Wino, Higgsino — Neutralinos

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$

Charginos

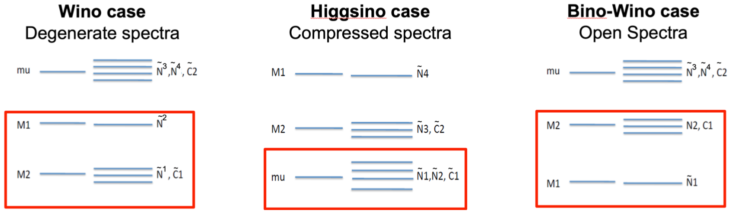
$$\begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

- Masses of the gauge eigenstates depend on 4 parameters: M1, M2, μ, tanβ

- **Mass spectra depend on the mass hierarchy of the EWKino mass parameters**

- If μ is **large**, the lightest chargino is a Wino, with mass M_2
  → its interactions to (s)fermions are governed by gauge couplings

- If M_2 is **large**, the lightest chargino is a Higgsino, with mass μ
  → its interactions are governed by Yukawa couplings



Electroweakino searches

Targeting a number of scenarios with low cross sections

- Special challenge: compressed spectra (small mass splitting between the next-to-LSP and the LSP)
  - Such scenarios usually have low visible energy
    → Require e.g. a high-p_T ISR jet to access the compressed cases
  - Small number of events (on top of the small XS)
    → Extremely challenging searches - benefit from combinations, e.g. in recent CMS paper:

Model	gaugino		GMSB			higgsino-bino			sleptons
Search	WZ	WH	ZZ	HZ	HH	WW	HH	WH	$\ell^+\ell^-$
$2/3\ell$ soft [17]	all								2ℓ soft
2ℓ on-Z [15]	EW		EW	EW					
2ℓ non-res. [15]									Slepton
$\geq 3\ell$ [18]	SS, A(NN)	SS, A–F	all	all	all			SS, A–F	
$1\ell 2b$ [16]		all						all	
4b [19]					all		3-b, 4-b, 2-bb		
Hadr. WX [20]	all	b-tag				b-veto		b-tag	

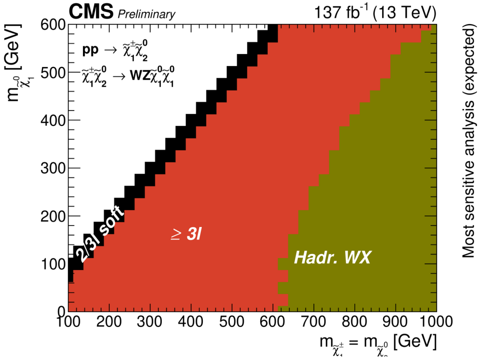
arXiv:2402.01888

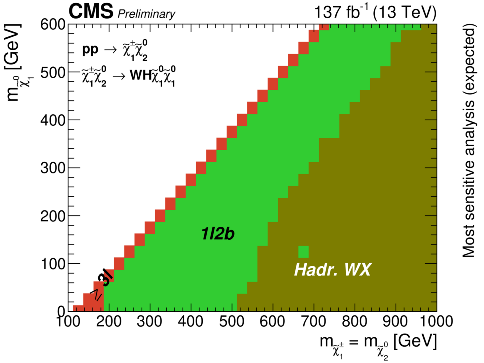
Electroweakino searches

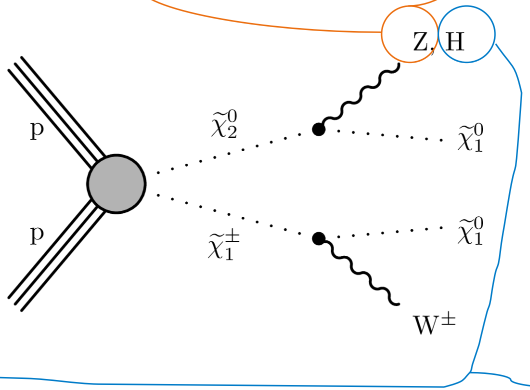
Combination tackling wino-bino model

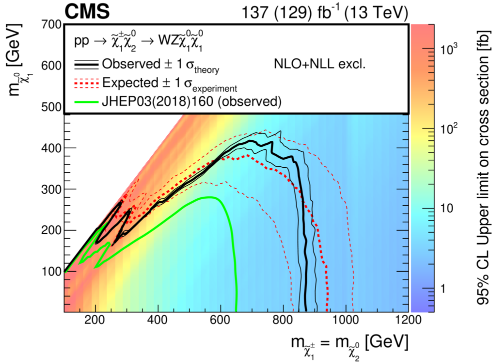
- Different final states have highest sensitivity depending on the model

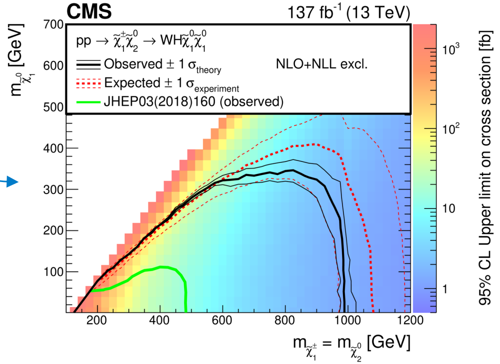
arXiv:2402.01888











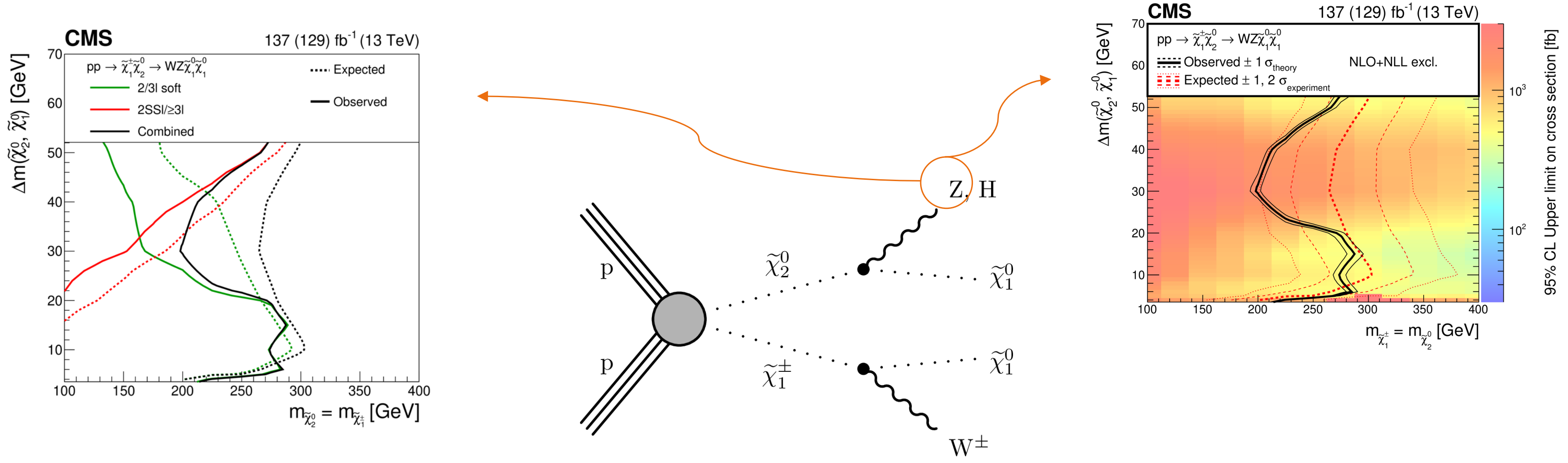
Exclude wino-like NLSPs

< 900-1000 GeV, depending on higgsino-gaugino mixing

Electroweakino searches

Combination tackling wino-bino model

- Same model, but limits for compressed masses



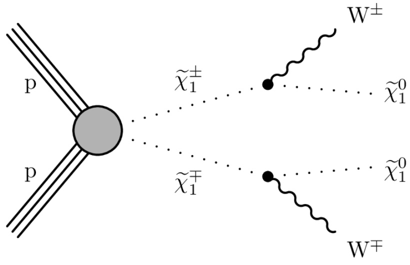
Exclude wino-like NLSPs
< 200-300 GeV, depending on mass splitting in compressed models

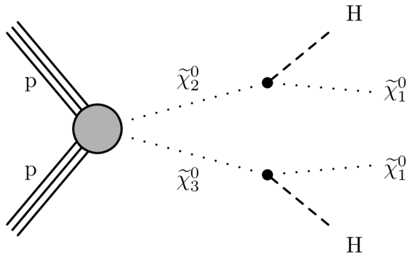
arXiv:2402.01888

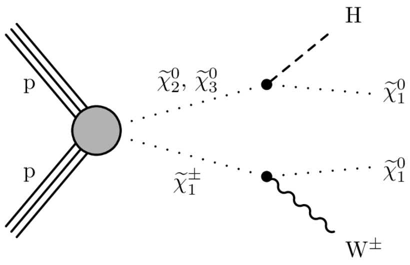
Electroweakino searches

Targeting a number of scenarios with low cross sections

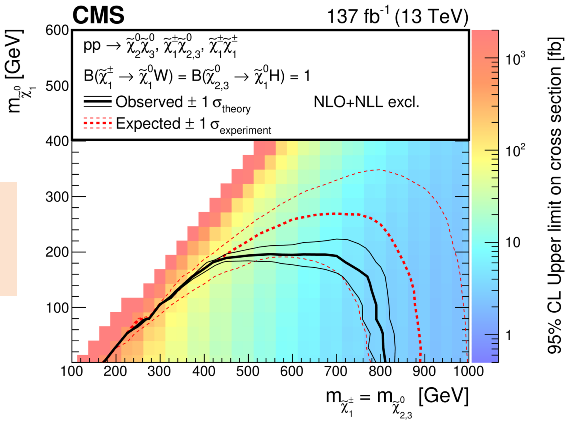
- Higgsino-bino scenario: mass-degenerate higgsino-like χ_2^0, χ_3^0, and $\chi_2^{\pm}$ decaying to bino-like χ_1^0 +W/H







Exclude higgsino-like NLSPs < 800 GeV



But what about small mass splitting?

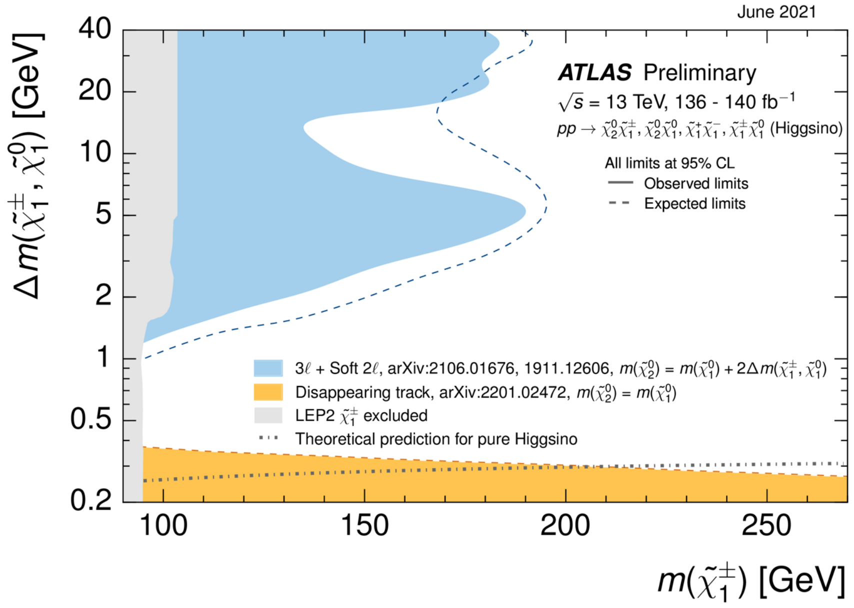
arXiv:2402.01888

Electroweakino searches

Specific analysis targeting small mass splitting for Higgsino case

- Higgsino scenario: mass-degenerate higgsino-like χ_1^0, χ_2^0, and $\chi_2^{\pm}$
  - Target small mass differences with disappearing tracks and soft leptons

arXiv:2402.01888

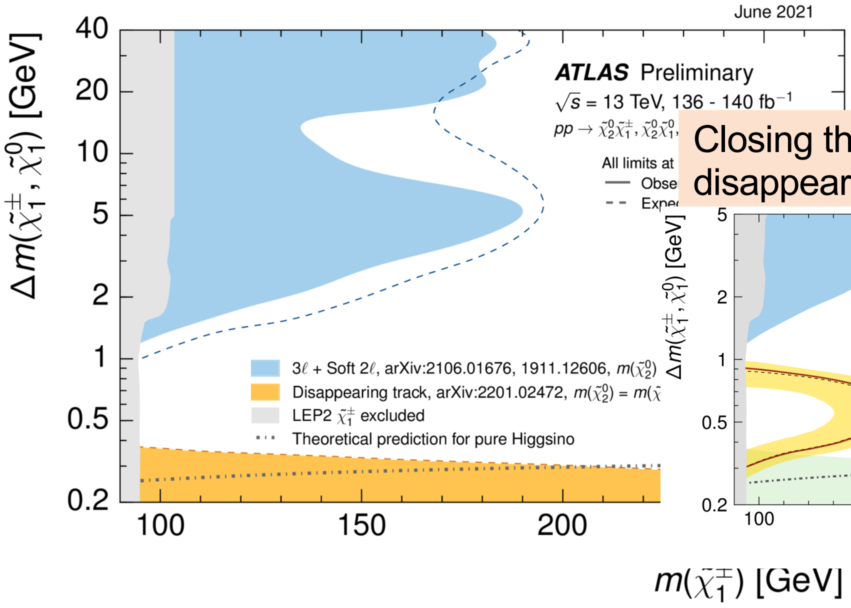


Exclude higgsino-like NLSPs < 190 GeV with Δm = 5 GeV

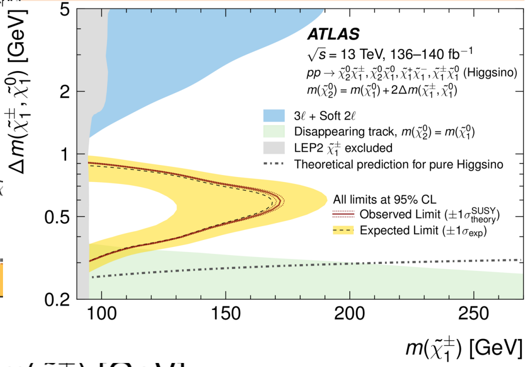
Electroweakino searches

Specific analysis targeting small mass splitting for Higgsino case

- Higgsino scenario: mass-degenerate higgsino-like χ_1^0, χ_2^0, and $\chi_2^{\pm}$
  - New: Search in events with an energetic jet, missing transverse momentum, and a **low-momentum track with a significant transverse impact parameter**



Closing the gap between disappearing track and soft 2l



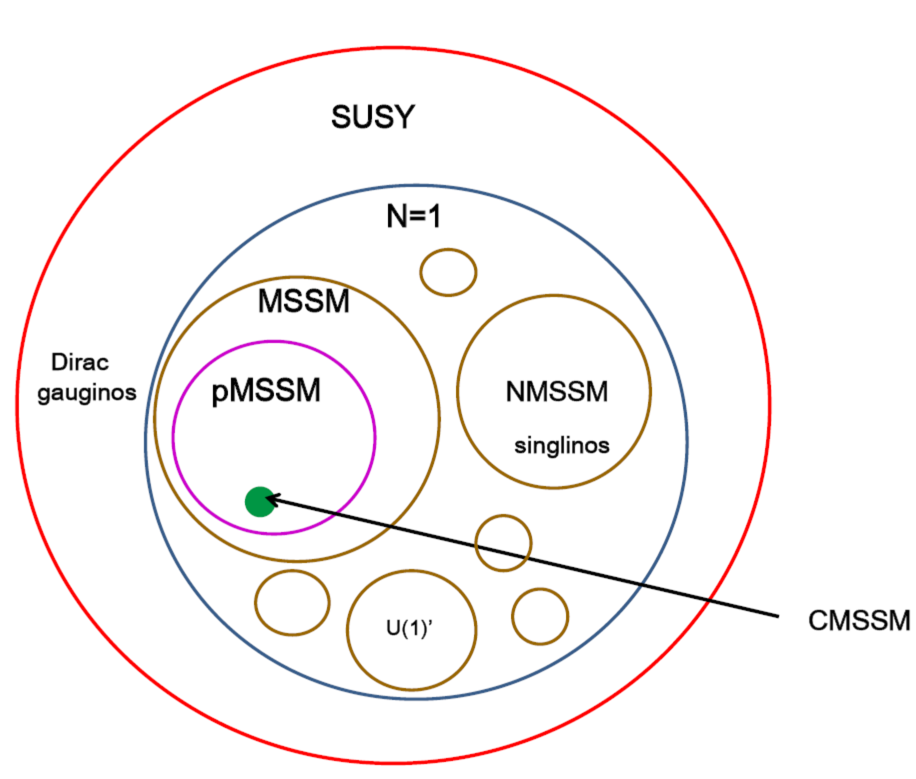
But are all mass regions that seem excluded really ruled out?

→ Let's check some pMSSM models next!

Investigating the reach of our SMS analyses in the pMSSM

BTW what is pMSSM?

- **MSSM** → Minimal Supersymmetric Standard Model:
  105 free parameters (masses, couplings, phases)
- **pMSSM** → phenomenological MSSM:
  19 free parameters (first two sfermion generations degenerate, and with negligible Yukawa couplings)
  - 10 sfermion masses
  - 3 gaugino masses
  - 3 tri-linear couplings (A_b,A_t,A_τ)
  - μ, M_A, $\tan\beta$
  - R-parity conserved



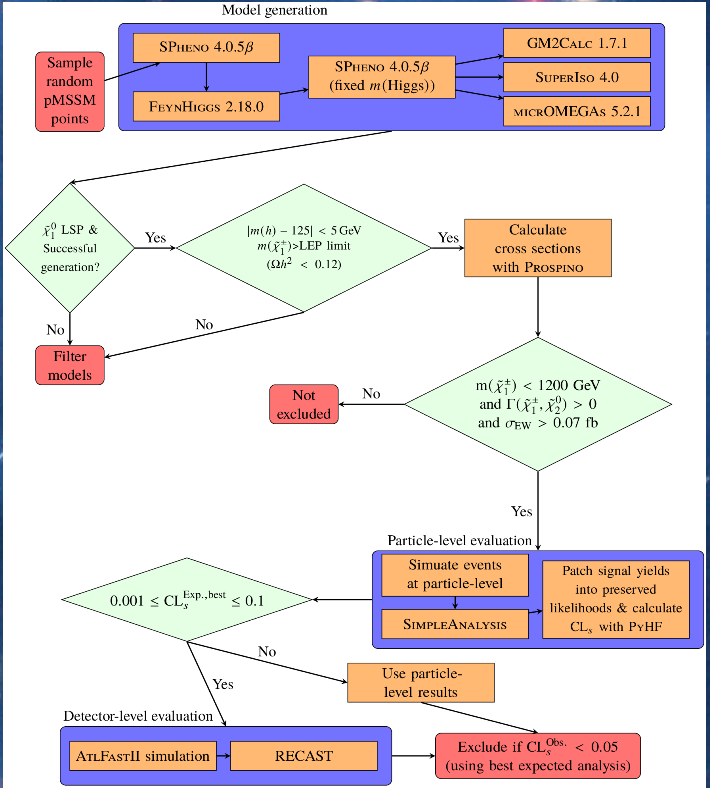
Investigating the reach of our SMS analyses in the pMSSM

Electroweakino scan

ATLAS-CONF-2023-055

AtTLAS strategy:

- Randomly sample EWK pMSSM
- Scenarios which the eight included searches may have potential sensitivity to are simulated (20.000 models)
    - The CLs is calculated at "particle-level" (for each analysis) to provide a "first pass" of sensitivity
- Samples which have "ambiguous" exclusion
    - The CLs is then evaluated at detector level using ATLAS FastSim 2 and then RECAST
- The CLs are used to dictate if a scenario is excluded:
    - CLs < 0.001 (for at least one analysis) - "Likely excluded”
    - CLs > 0.1 (for every analysis) - "Likely non-excluded”
    - 0.001 < CLs < 0.1 - "Ambiguous” → (2000 models)
- Full analysis reinterpretation only for ambiguous models

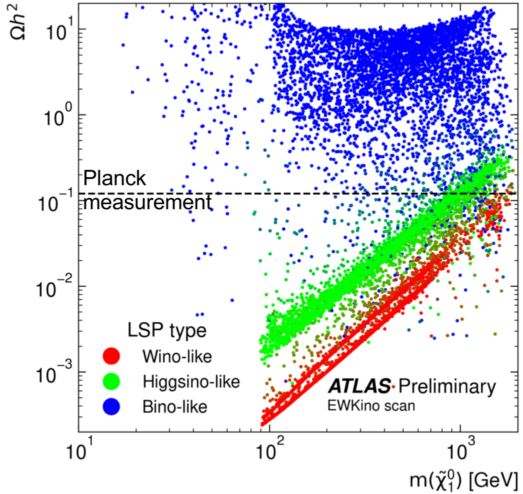


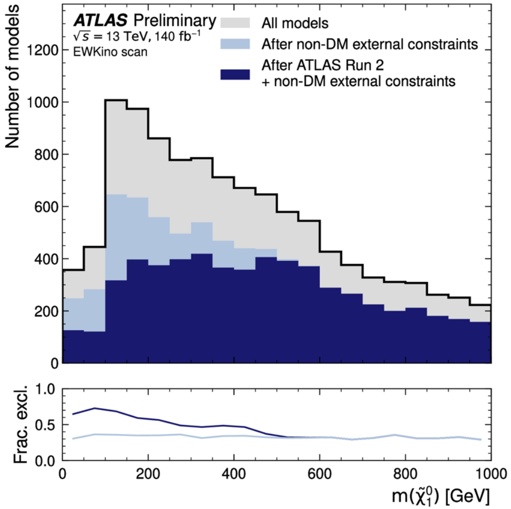
Investigating the reach of our SMS analyses in the pMSSM

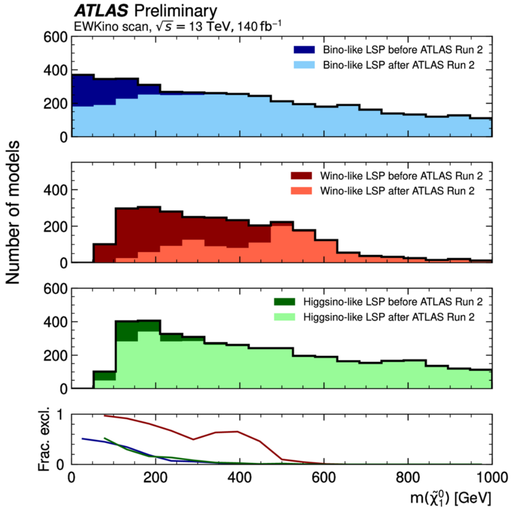
Electroweakino scan

ATLAS-CONF-2023-055

- Constraints can be placed on the likely composition of the LSP when considering the EWKino scan
  - The impact of ATLAS constraints is much more significant at lower LSP mass
  - Most low-mass (< 100 GeV) models possess a Bino-like LSP (with 50% excluded by ATLAS)
  - For masses < 400 GeV, over 50% of the Wino-like LSP phase space is excluded





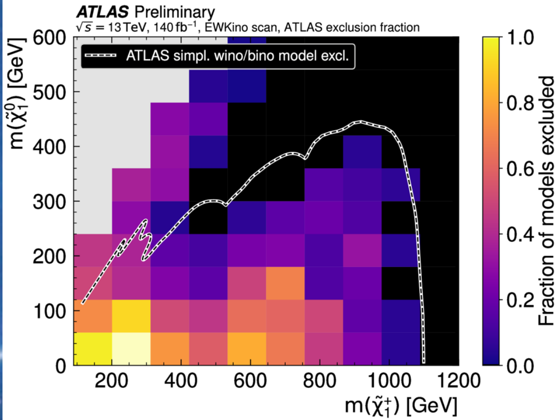


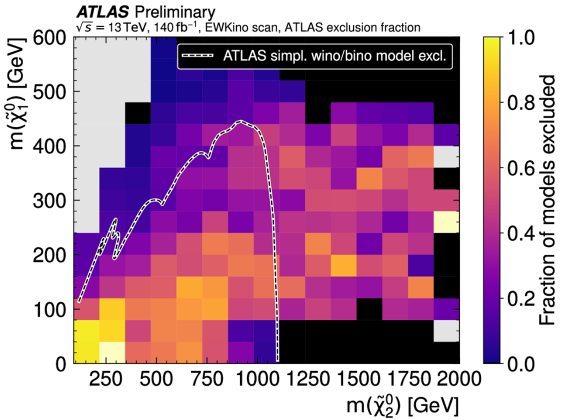
Investigating the reach of our SMS analyses in the pMSSM

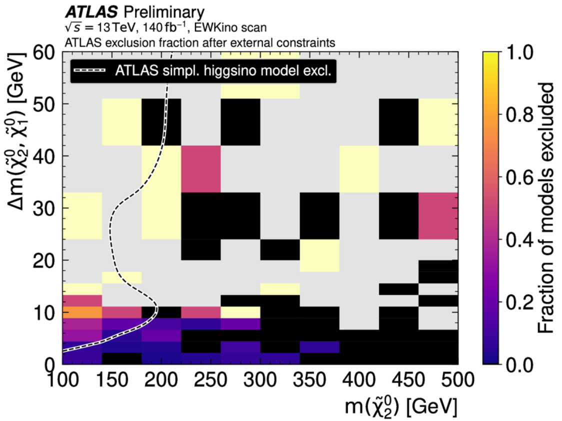
Electroweakino scan

ATLAS-CONF-2023-055

- Comparison of the reach of simplified models to the remaining scenarios in the pMSSM







Grey - No models remain after filtering
Black -No models are excluded

- **Excluded chargino/next-to-lightest neutralino mass significantly lower than the simplified model scenario**
- **Significant number of uncovered models in the compressed regions**

Summary and Conclusion

- SUSY searches at the LHC have ruled out a large vanilla phase space
- More difficult scenarios are being tackled now as well
- We might still be able to find SUSY at the LHC, but will never be able to rule it out, while other well-motivated BSM theories didn't survive…
- Let's continue our journey!