Searches for electroweak production of supersymmetric particles with the ATLAS detector

Blois 2024

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On behalf of the ATLAS Collaboration

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The EW SUSY particle zoo

See Francesco's talk for discussion of strong SUSY

Pre-EWSB:
U(1) gauge field: B

SU(2) gauge fields:
W^0, W^+, W^-

Z W γ

SUSY partners of the SM pre-EWSB B and W fields are the "Wino" and "Bino"

Wino

$\tilde{W}^0$ $\tilde{W}^{+-}$

$\tilde{B}$ **Bino**

Leptons

e μ τ

ν_e ν_μ ν_τ

Higgs

h A

H H^{+-}

Sleptons

$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$

$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$

Higgsinos

$\tilde{H}$

The EW SUSY particle zoo

See Francesco's talk for discussion of strong SUSY

Pre-EWSB:
U(1) gauge field: B

SU(2) gauge fields:
W^0, W^+, W^-

Z W
γ

Electroweakinos:
2x charginos
4x neutralinos
➜ bino/wino/higgsino mix

Neutralinos

$\tilde{\chi}^0_i$

Leptons

e μ τ
ν_e ν_μ ν_τ

Higgs

h A
H H^{+-}

Sleptons

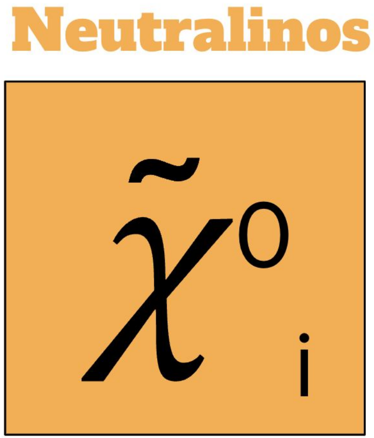
$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$
$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$

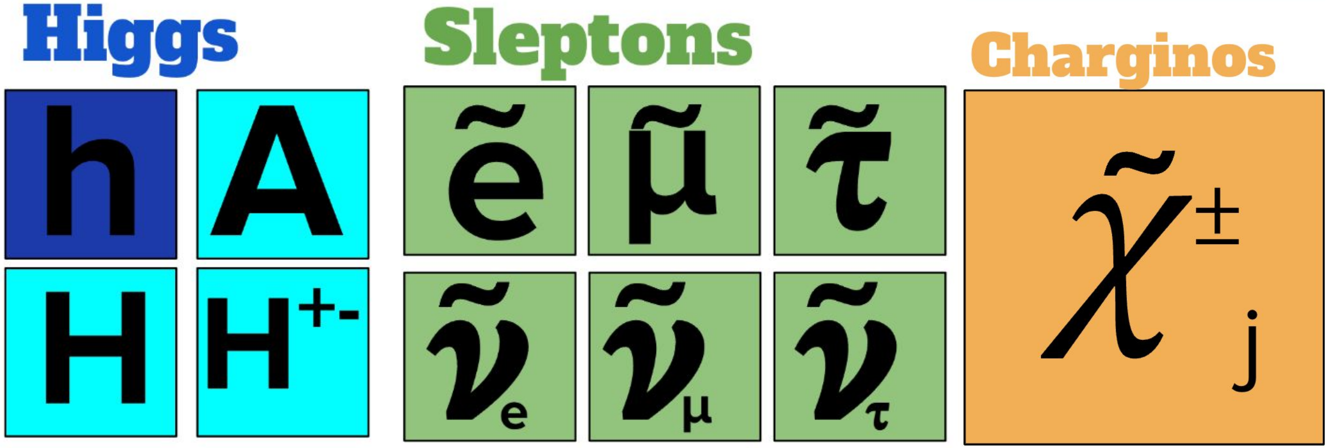
Charginos

$\tilde{\chi}^\pm_j$

The EW SUSY particle zoo

- Smallest production cross-sections ➔ Limits are weakest
- Lightest neutralino is expected to be the lightest SUSY particle (LSP) and can be a dark matter candidate.
- Dark matter constraints favour scenarios with an LSP mass at or below O(1 TeV).
- Light higgsino favoured by naturalness
- Compressed spectra favoured by DM, g-2 and naturalness considerations
  - ➢ Challenging signatures with soft objects

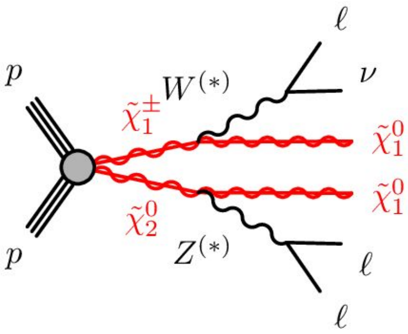




SUSY signal models

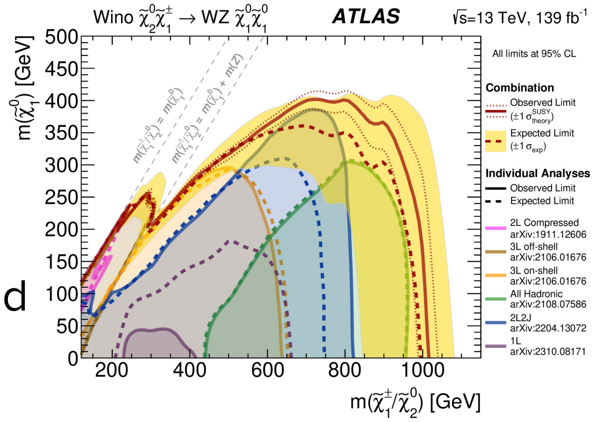
Minimal Supersymmetric Standard Model (MSSM)

- ➢ “SUSY breaking terms” parameterize our ignorance about the SUSY breaking mechanism
- ➢ > 100 unknown parameters



Simplified models

- ➢ One SUSY production process
- ➢ One decay chain with BR = 100%
- ➢ Pure bino/wino/higgsino states
- ➢ Used for ATLAS search optimization and interpretation (2D exclusion contours)



Phenomenological MSSM (pMSSM)

- ➢ Includes all sparticle production and decay modes
- ➢ Assumes no new ~~CP~~ or FCNCs, 1st/2nd gen. sfermion universality, R-parity conservation
- ➢ 19 parameters

1) pMSSM interpretation of early Run 2 searches

pMSSM scan workflow

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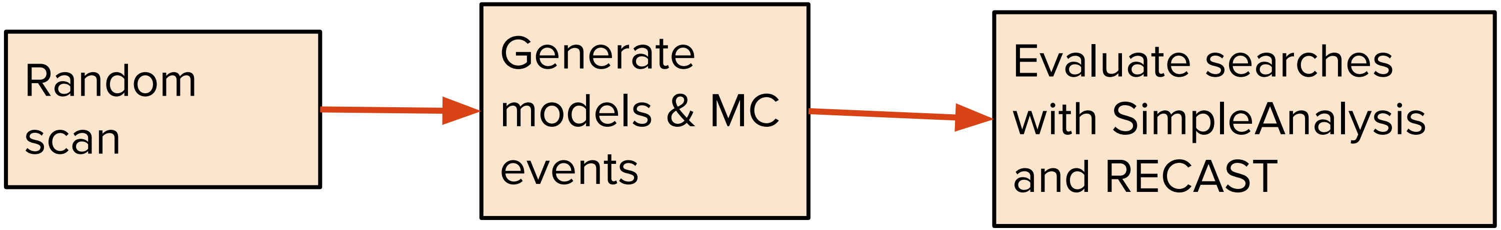
- Scan the 19-dimensional pMSSM to produce sets of models
- Reinterpret early Run 2 searches to determine which models are (not) excluded
- Produce global picture of ATLAS' sensitivity to electroweak SUSY
- Identify scenarios we've missed due to non-simplified phenomenology



ATLAS pMSSM sensitivity

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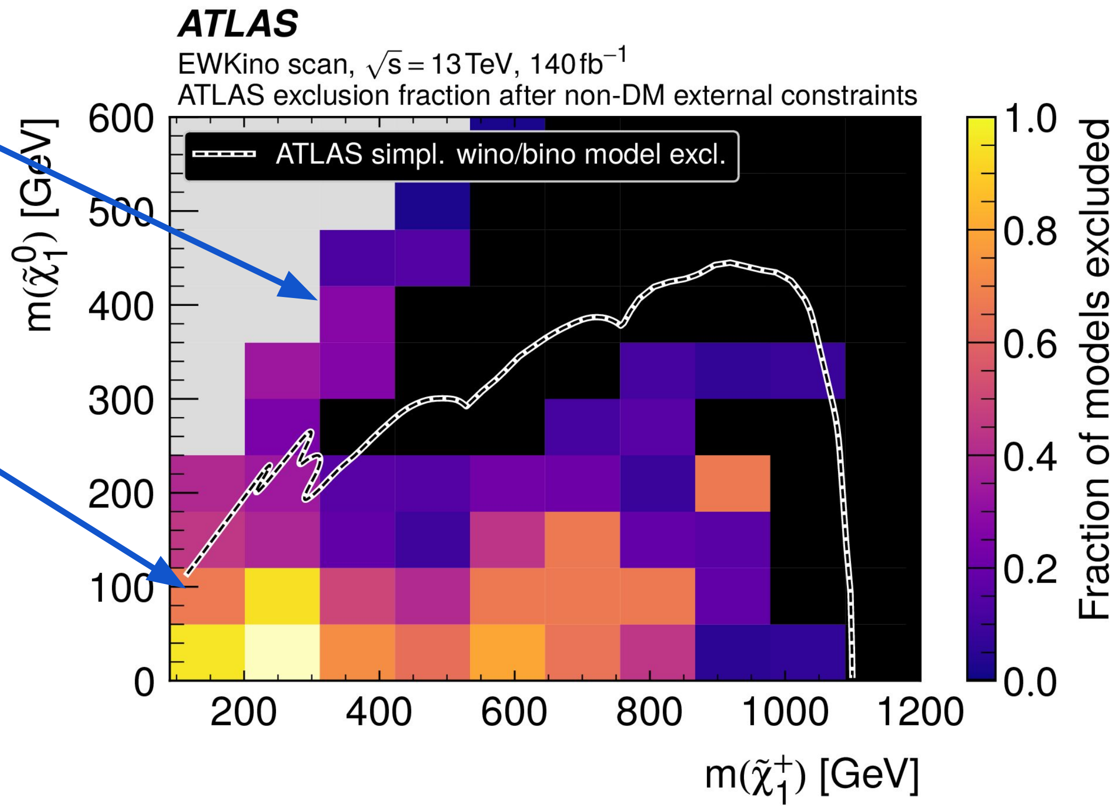
Some sensitivity to compressed scenarios through heavier electroweakino decays

Even low mass bins don't have 100% exclusion…

Important to improve depth of sensitivity as well as target new regions!



ATLAS pMSSM sensitivity

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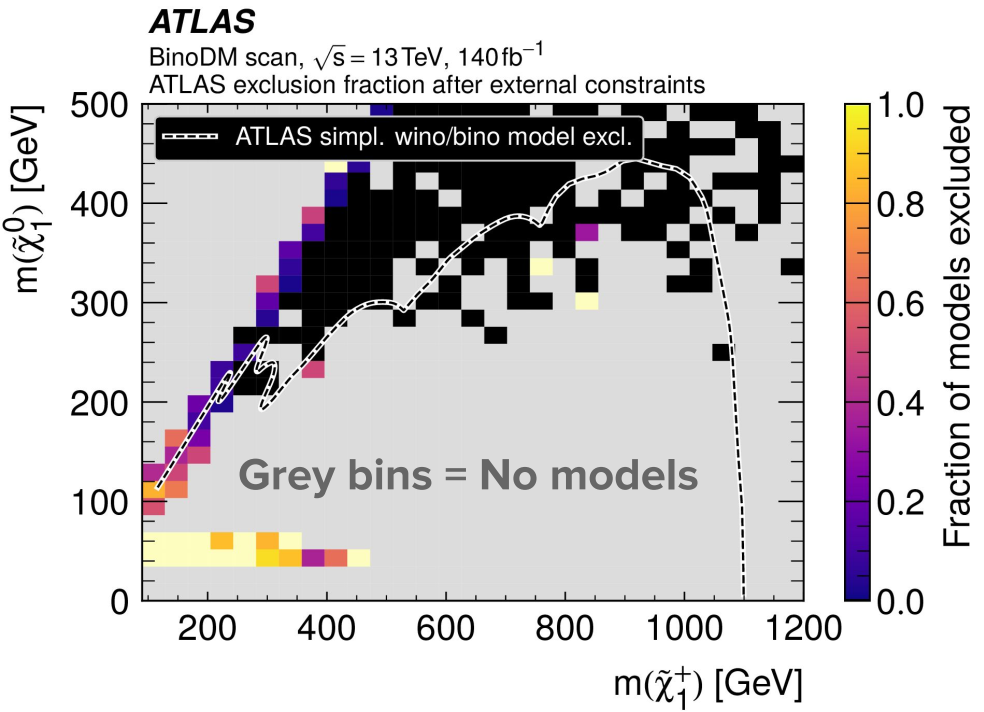
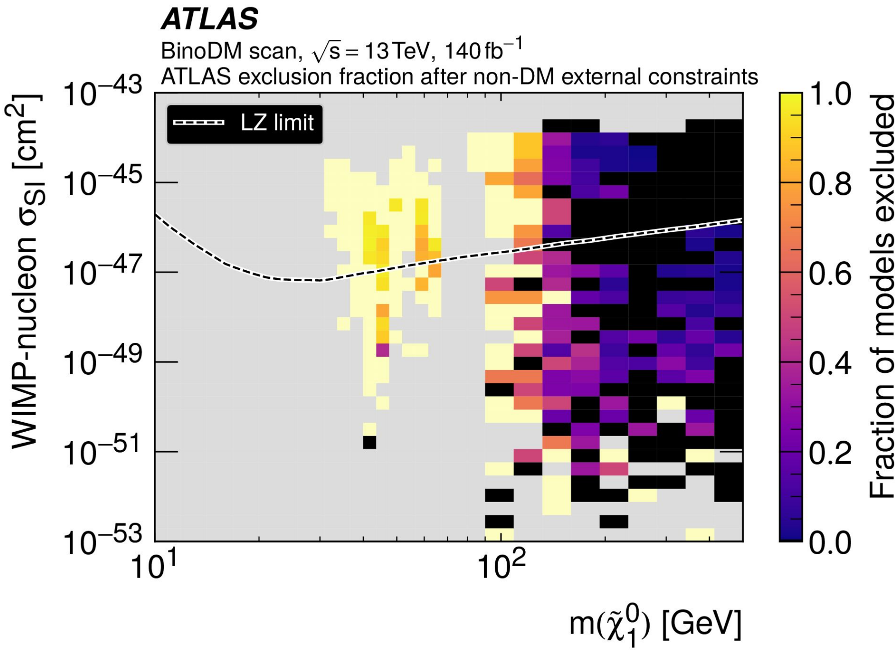


Complementarity between ATLAS and direct detection experiments



With dark matter constraints:

- Z/h funnel well constrained
- Mostly compressed scenarios remain

ATLAS pMSSM sensitivity

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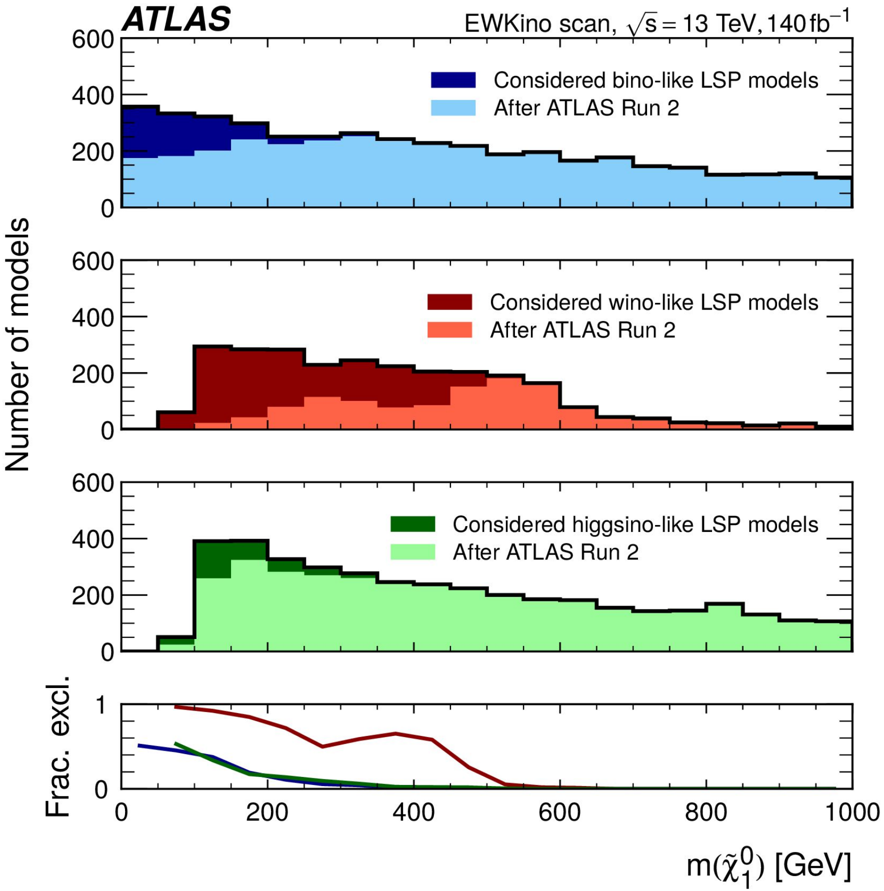


Disappearing track (Eur. Phys. J. C 82 (2022) 606) **does a good job constraining wino-LSP scenarios**

Bino and Higgsino-LSP scenarios remain viable even at 100 GeV and below

2) Recent ATLAS search results

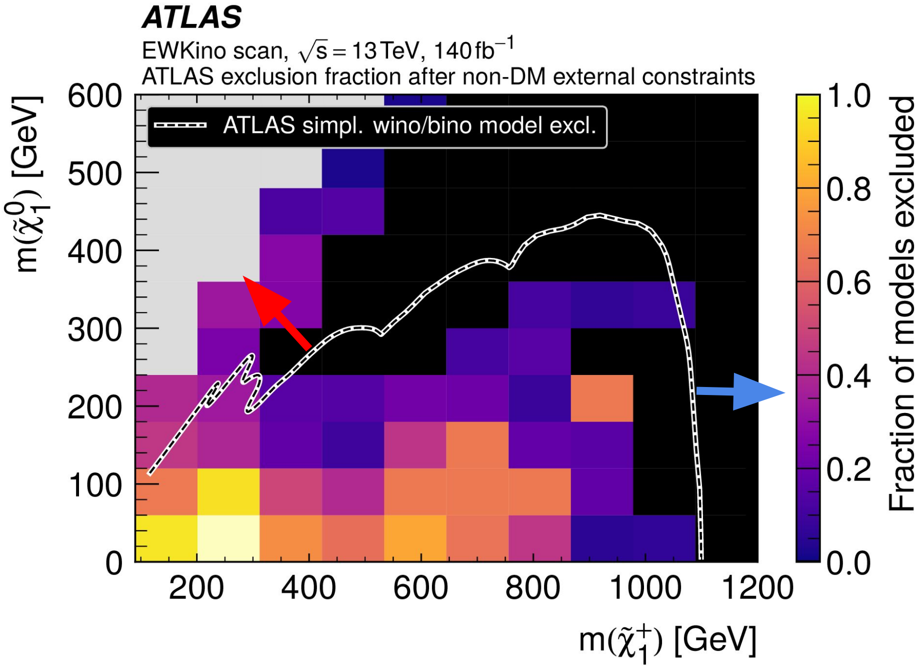
Recent ATLAS search results

Increased sensitivity to compressed scenarios

- ➢ Unique topologies: VBF
- ➢ Unique signatures: Displaced tracks

Increase sensitivity to higher masses

- ➢ Hadronic final states
- ➢ Deploy improvements to b-tagging and boosted large-R jet reconstruction

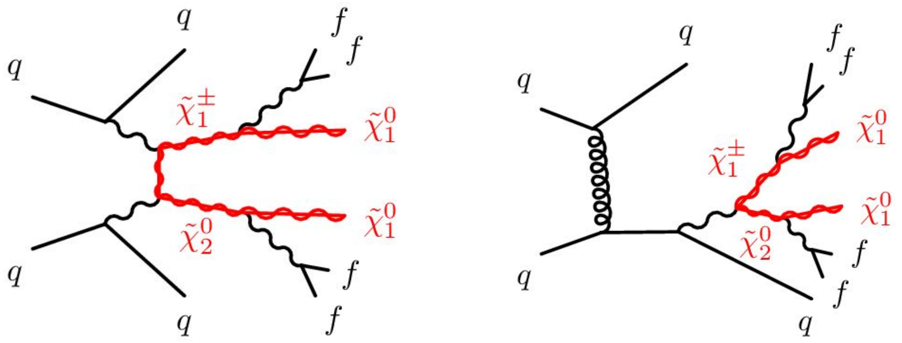


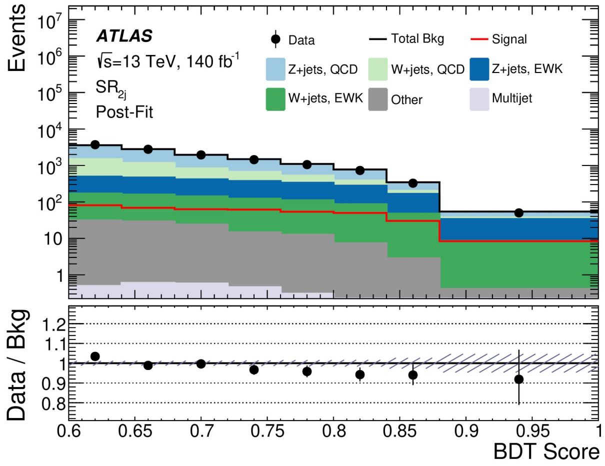
Also interesting long-lived signatures ➔ see [Ian's talk]

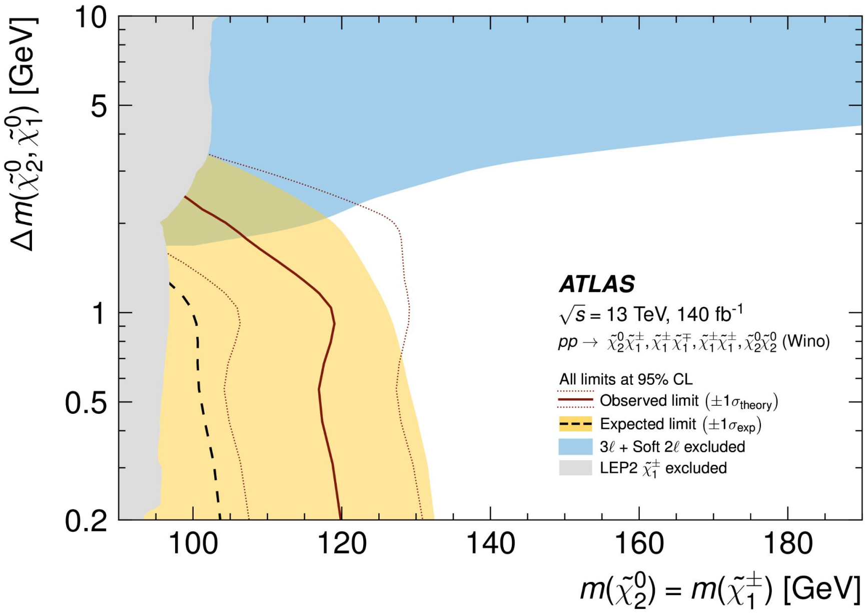
VBF topologies

arXiv:2409.18762

- Large MET + two forward jets
- Targeting ~ 2 GeV mass splittings
- Agnostic to branching ratios of N2/C1 decays
  - ➢ Decay products too soft to be reconstructed
- BDT to discriminate large backgrounds



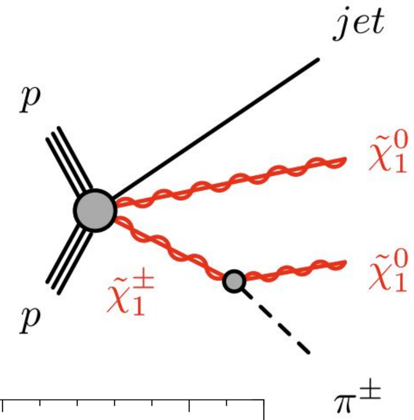


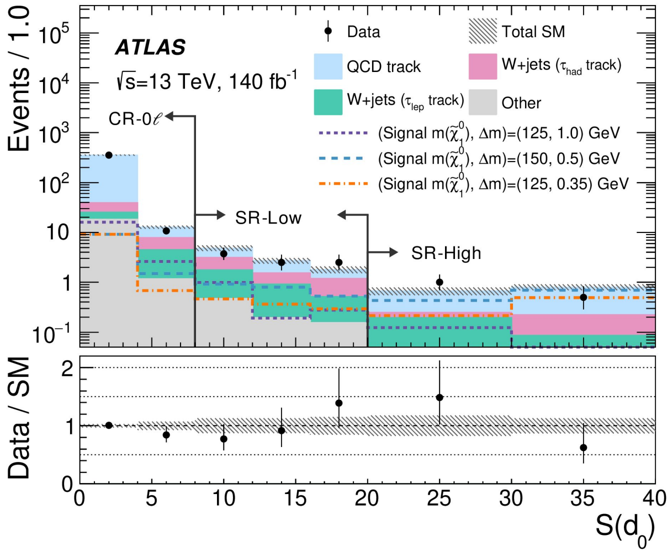


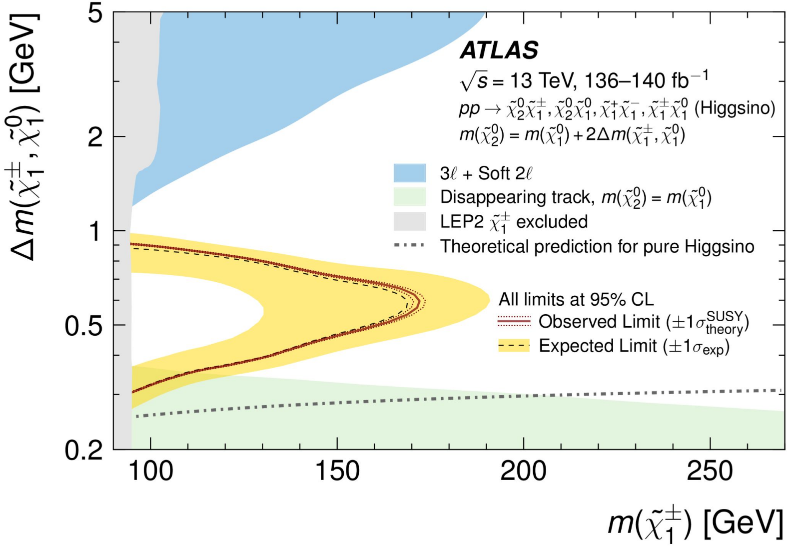
Mildly-displaced tracks

Phys. Rev. Lett. 132 (2024) 221801

- Targets gap between soft-2L and disappearing track signatures
- Chargino flight length reaches 0.1 – 1 mm
- “Mildly” displaced-track identified using transverse impact parameter
    - ➢ Unique signature, significantly reduces backgrounds







One lepton + boosted jets

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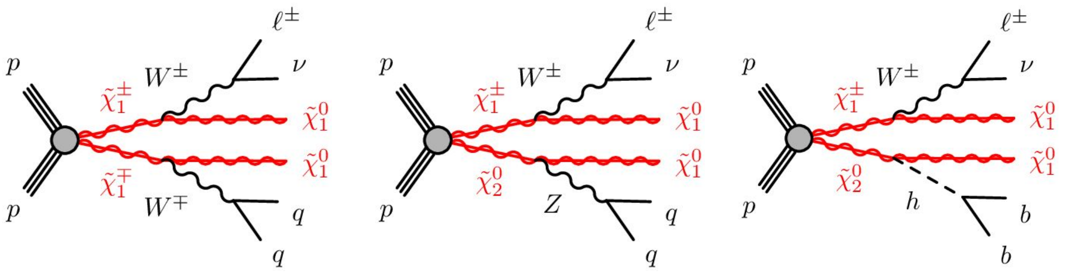
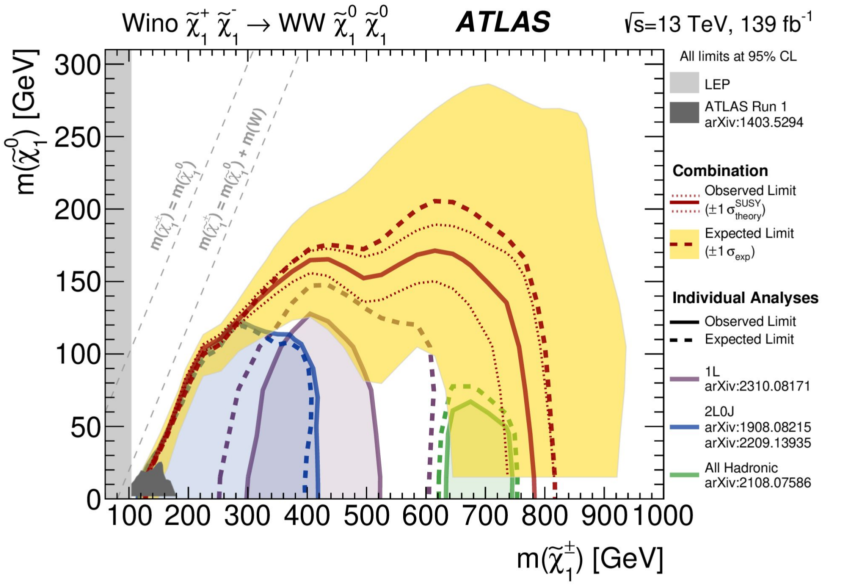
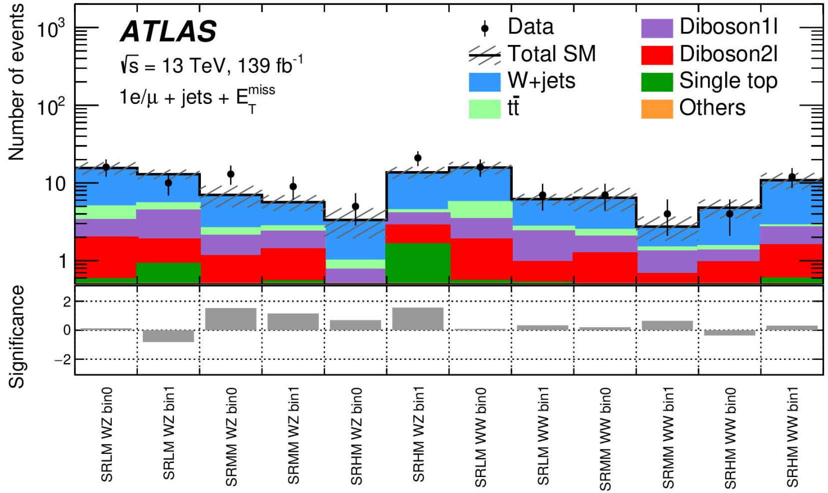
- 1 lepton + 1-3 signal jets + large MET
- Jet substructure information used to tag large-R W/Z jets and b-jets
- Combination with existing 0L/1L/2L/3L searches performed in SUSY-2023-26



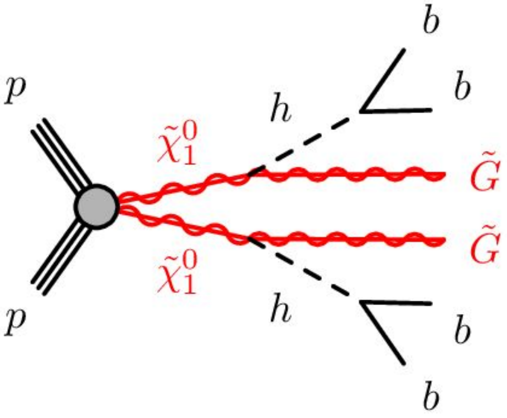


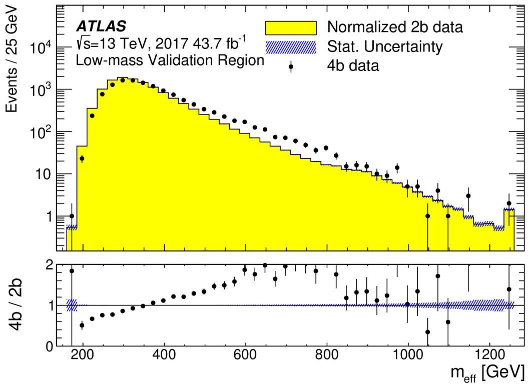


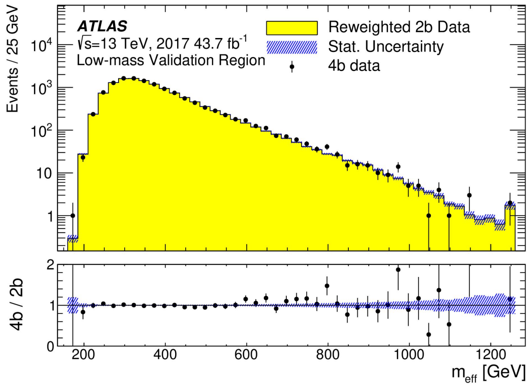
Multiple b-jets

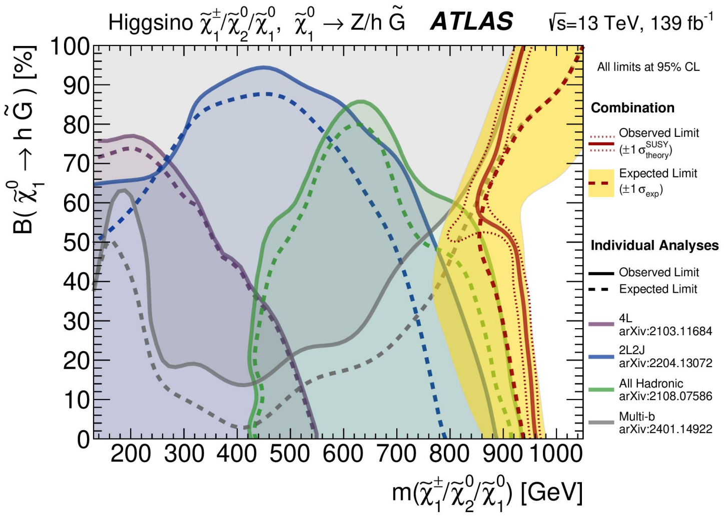
Phys. Rev. D 109 (2024) 112011

- Targeting GGM and GMSB Higgsino scenarios
- Improvements on partial Run 2 search:
  - ➢ Delta-R-based b-jet pairing method
  - ➢ Improved jet reconstruction and b-tagging
  - ➢ ML techniques for discrimination
- Data-driven background estimate
  - ➢ 2 b-jet events reweighted to model 4 b-jet events
- Combination with existing 0L/2L/4L searches performed in SUSY-2023-26









Summary & Outlook

SUSY Physics Report 2024

- EW SUSY is challenging
  - ➢ Good coverage of pMSSM scenarios with early Run 2 analyses
  - ➢ Room to improve depth of sensitivity and target compressed scenarios
- Recent analyses provide unique sensitivity to compressed and hadronic signatures
  - ➢ Novel final states and analysis techniques
  - ➢ Improved reconstruction and object identification
- Reinterpretation material published on HEPData
  - ➢ Preserved likelihoods, SimpleAnalysis and efficiencies
  - ➢ Enables interpretation of the ATLAS search programme in non-simplified models
- Run 3 searches are in development

Backup

pMSSM assumptions

Based on experimental constraints and general features of SUSY breaking mechanisms.

1) No new sources of CP-violation (beyond CKM matrix)
2) No flavour-changing neutral currents (FCNCs)
3) Universality of 1st and 2nd generation sfermions
4) R-parity conserved $P_R = (-1)^{3B+L+2s}$
5) Lightest SUSY particle (LSP) is the lightest neutralino

pMSSM parameters

Parameter	Min	Max	Note
$M_{\tilde{L}_1}$ $(=M_{\tilde{L}_2})$	10 TeV	10 TeV	Left-handed slepton (first two gens.) mass
$M_{\tilde{e}_1}$ $(=M_{\tilde{e}_2})$	10 TeV	10 TeV	Right-handed slepton (first two gens.) mass
$M_{\tilde{L}_3}$	10 TeV	10 TeV	Left-handed stau doublet mass
$M_{\tilde{e}_3}$	10 TeV	10 TeV	Right-handed stau mass
$M_{\tilde{Q}_1}$ $(=M_{\tilde{Q}_2})$	10 TeV	10 TeV	Left-handed squark (first two gens.) mass
$M_{\tilde{u}_1}$ $(=M_{\tilde{u}_2})$	10 TeV	10 TeV	Right-handed up-type squark (first two gens.) mass
$M_{\tilde{d}_1}$ $(=M_{\tilde{d}_2})$	10 TeV	10 TeV	Right-handed down-type squark (first two gens.) mass
$M_{\tilde{Q}_3}$	2 TeV	5 TeV	Left-handed squark (third gen.) mass
$M_{\tilde{u}_3}$	2 TeV	5 TeV	Right-handed top squark mass
$M_{\tilde{d}_3}$	2 TeV	5 TeV	Right-handed bottom squark mass
M_1	−2 TeV	2 TeV	Bino mass parameter
M_2	−2 TeV	2 TeV	Wino mass parameter
μ	−2 TeV	2 TeV	Bilinear Higgs boson mass parameter
M_3	1 TeV	5 TeV	Gluino mass parameter
A_t	−8 TeV	8 TeV	Trilinear top coupling
A_b	−2 TeV	2 TeV	Trilinear bottom coupling
A_τ	−2 TeV	2 TeV	Trilinear τ-lepton coupling
M_A	0 TeV	5 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

Dark matter relic density of models

We allow LSP to be a sub-dominant DM component

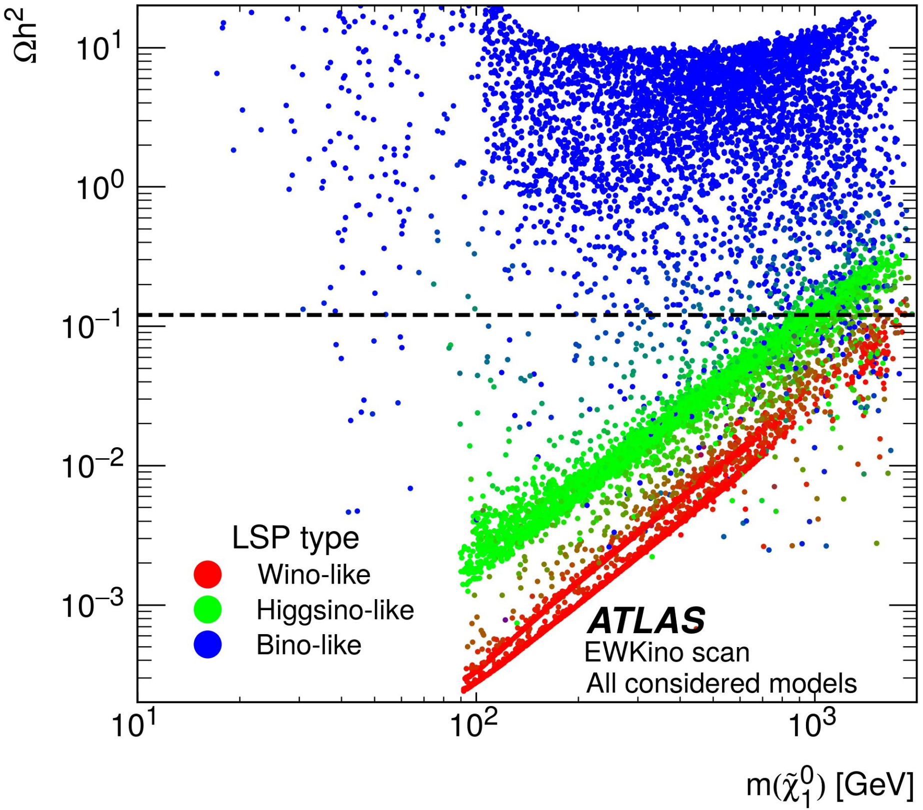
- Require $\Omega h^2 \leq 0.12$

Higgsino/Wino-like LSP:

- Mass near to chargino / 2nd neutralino
- Enhanced co-annihilation with chargino / 2nd neutralino
- Underestimates relic density unless m(LSP)~TeV

Bino LSP:

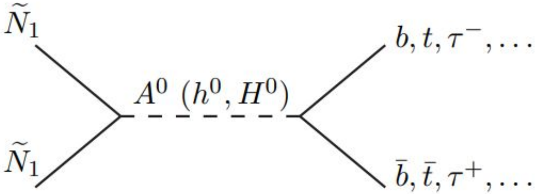
- In general overestimates relic density
- Flat scanning strategy doesn't sample many models with satisfactory relic density



Bino-LSP models: DM relic density

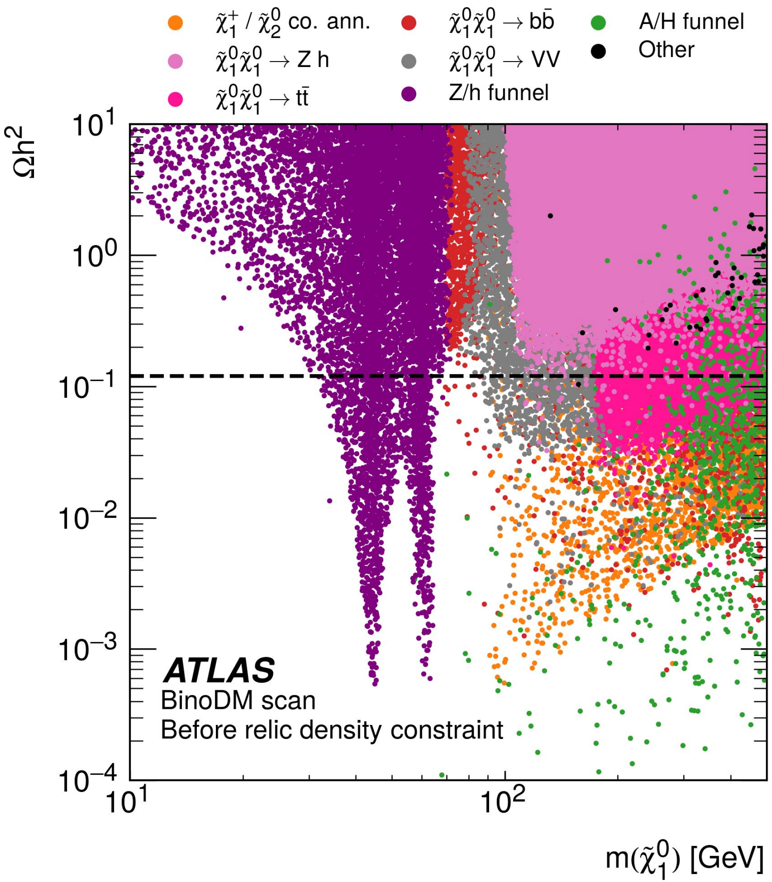
Regions with satisfactory DM relic density for bino-LSP models:

- Z/h/A funnel



- Enhanced co-annihilation with 2nd neutralino or chargino
  - ➢ Wino-like C1/N2 close in mass
  - ➢ Significant higgsino component

Targeted scan performed to oversample these regions



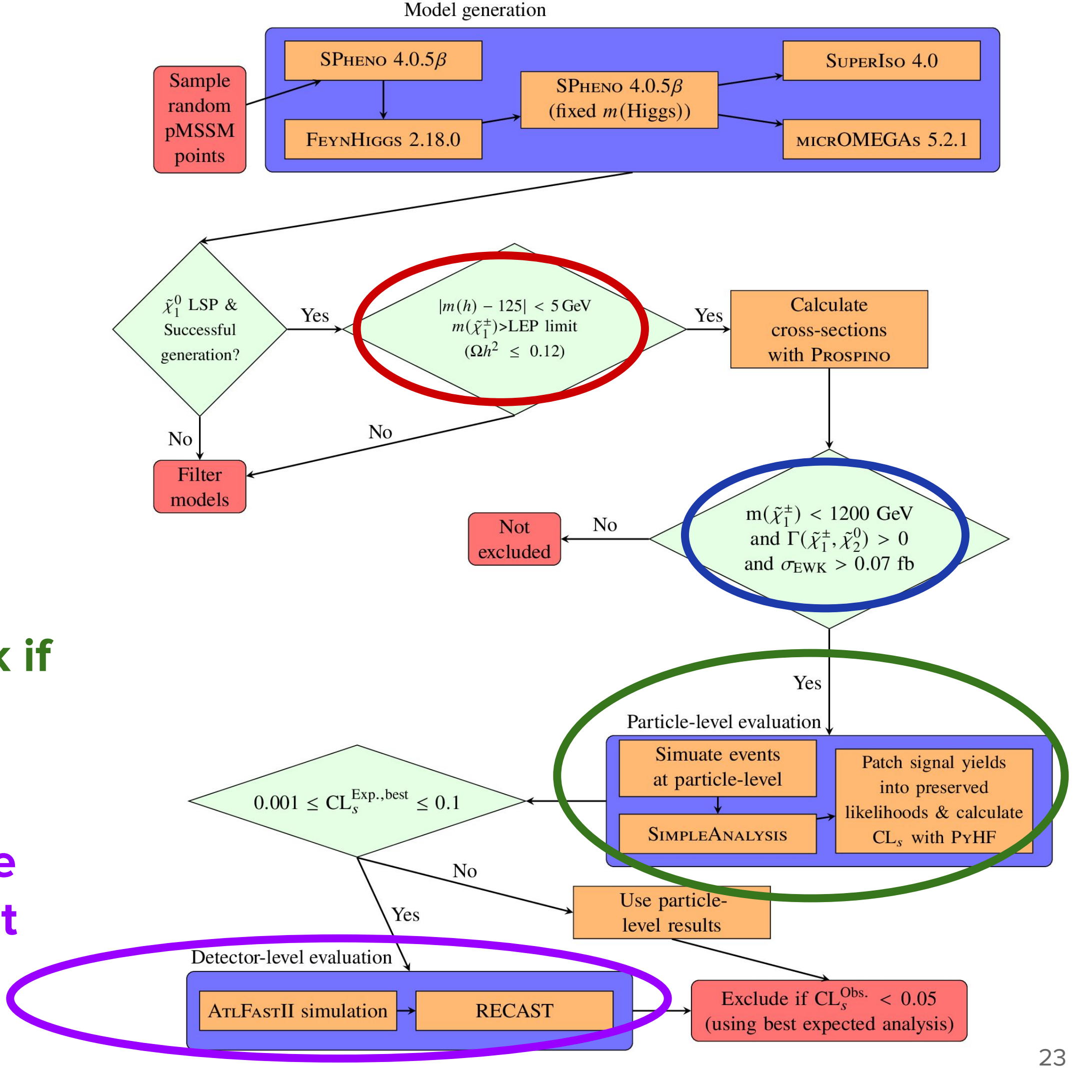
Workflow

Initial constraints applied

Only simulate models where we expect some sensitivity

Particle-level evaluation first to check if model is likely to be excluded or not

Detector simulation for models where particle-level evaluation is insufficient
→ This is what separates this from non-ATLAS pheno studies



ATLAS pMSSM sensitivity

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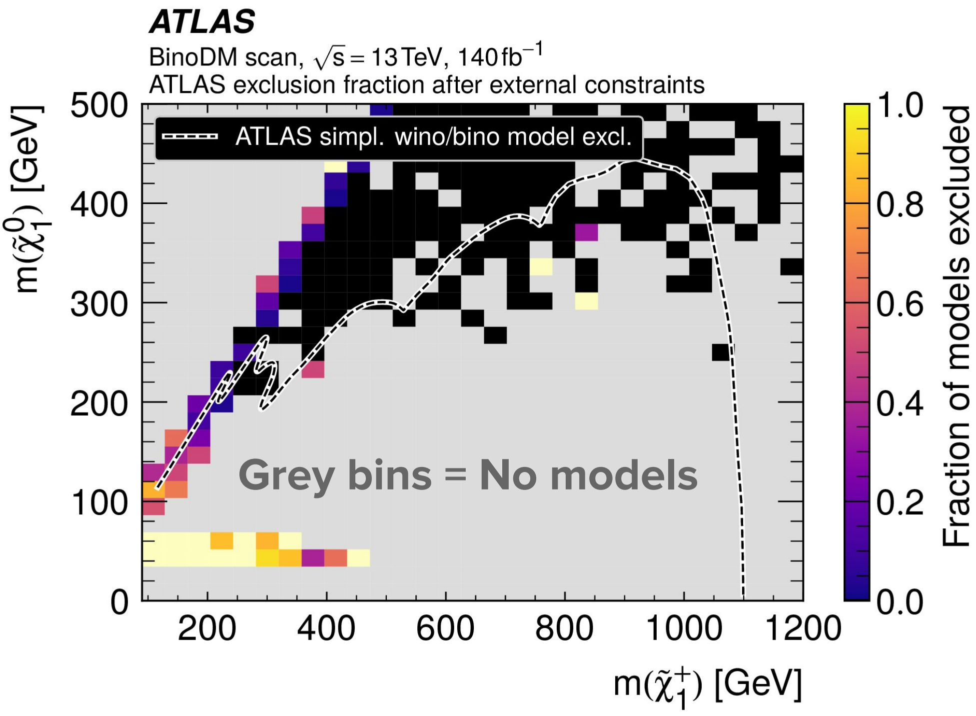

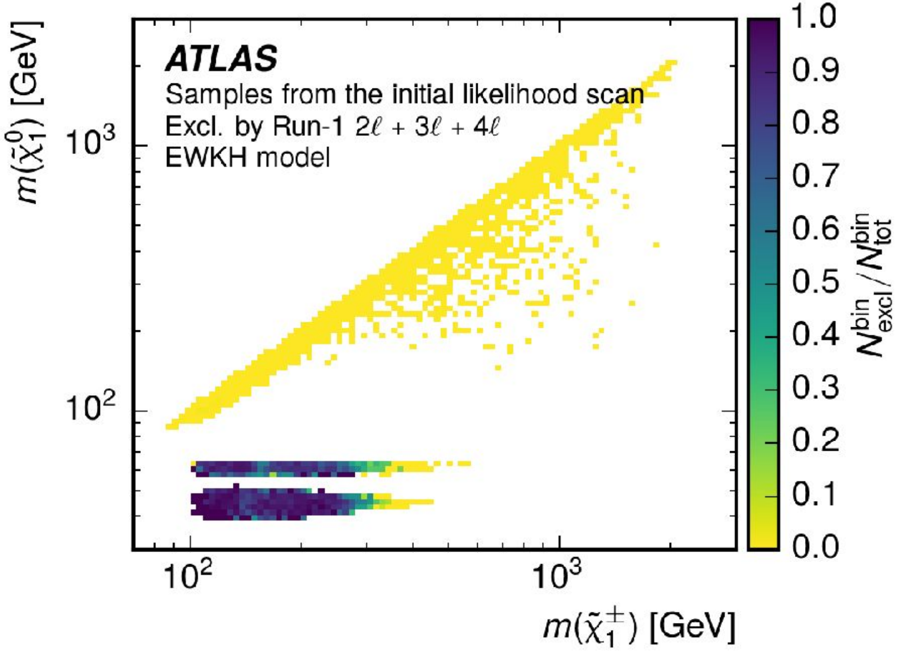

Run 2 EW pMSSM scan

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Run 1 EW pMSSM scan

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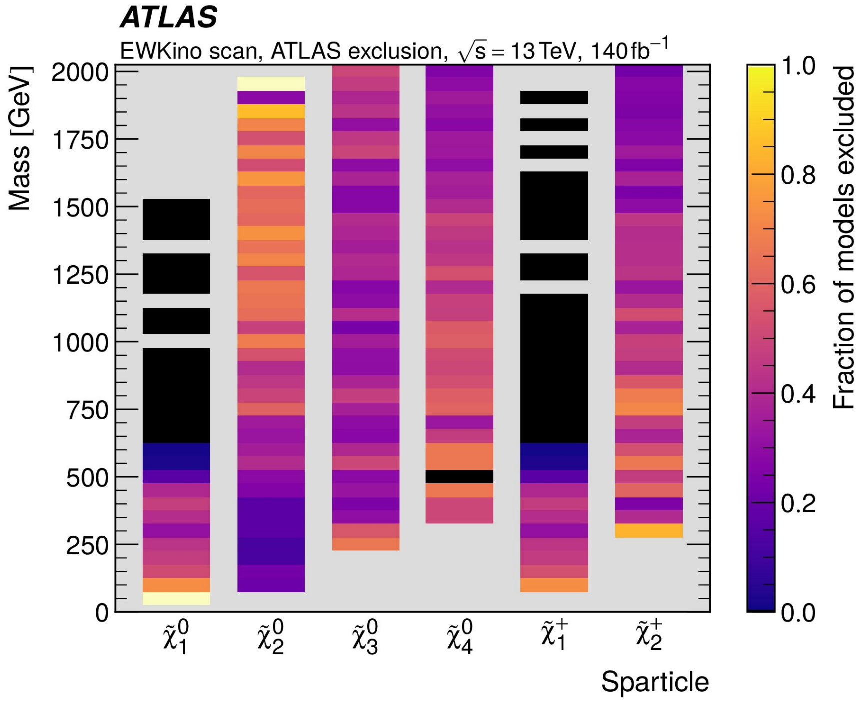
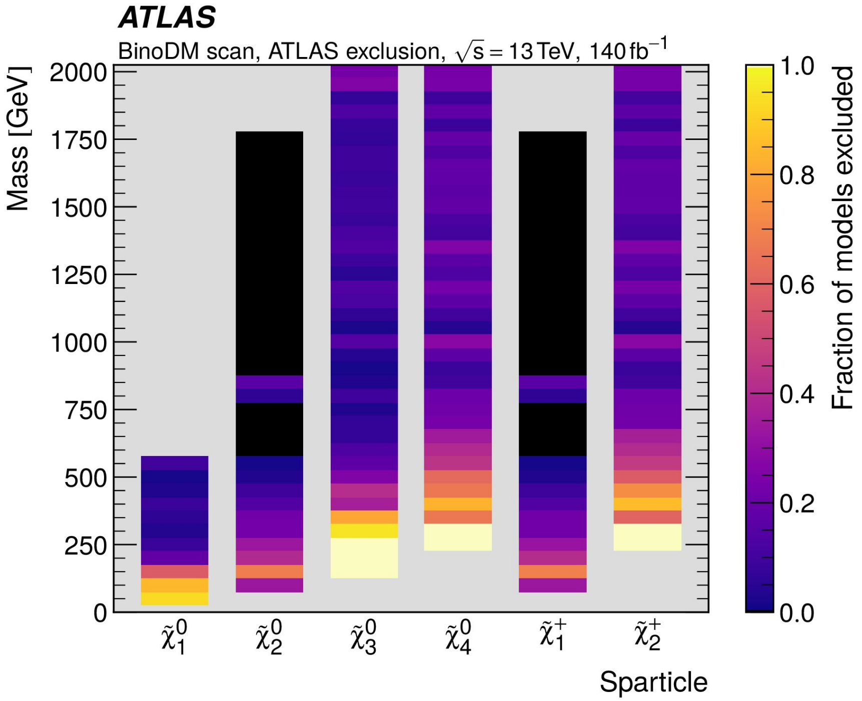
Overall exclusion

ATLAS exclusion of each sparticle (after all external and dark matter constraints)

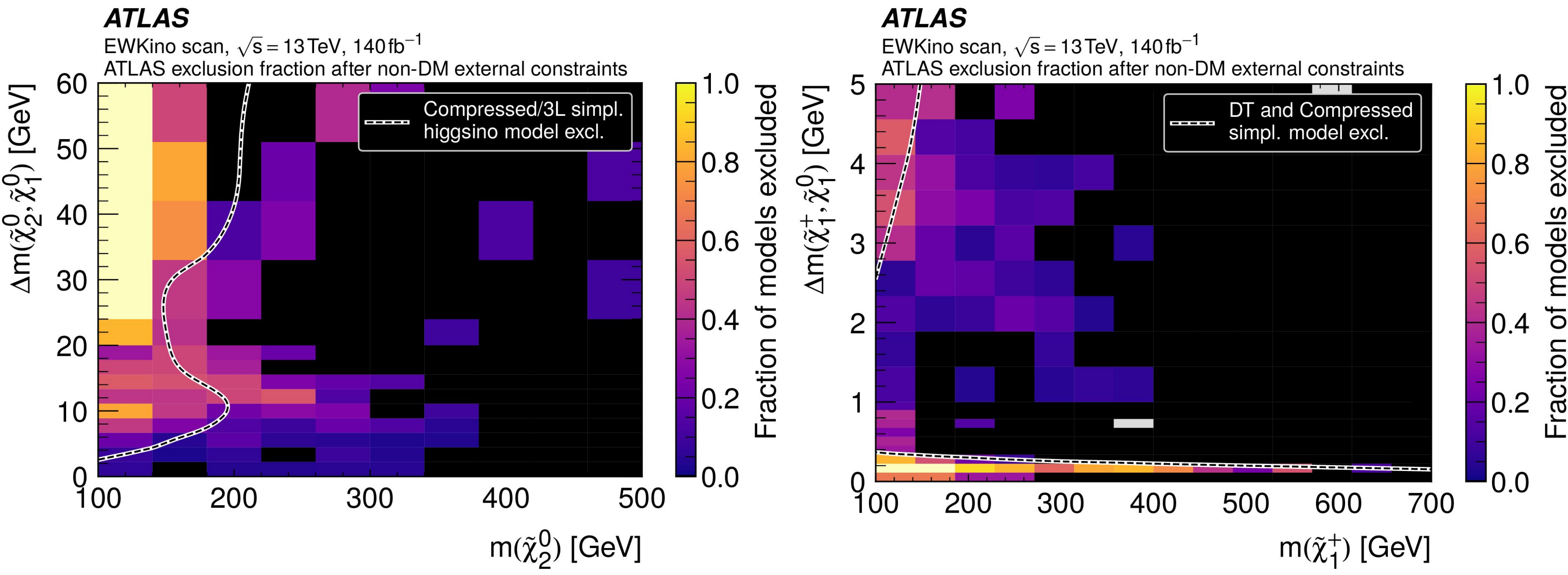


Flat scan (mostly wino/higgsino LSP)



Bino dark matter scan

EW pMSSM scan – small mass splittings

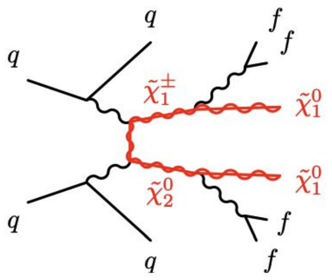


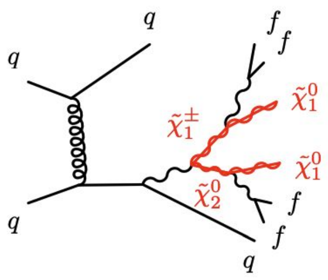
EW pMSSM scan – analyses included

Analysis	Relevant simplified models targeted
FullHad	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh, Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ via WW
1Lbb	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh
2L0J	Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ via WW, slepton pairs
2L2J	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ
3L	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh, higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\tilde{\chi}_1^0$
4L	Higgsino GGM
Compressed	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\tilde{\chi}_1^0$
Disappearing-track	Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$

VBF compressed

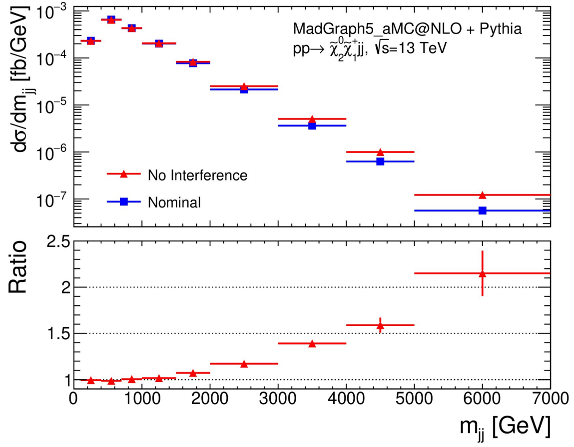
arXiv:2409.18762





Uncertainties

- Largest exp u/c is muon reco efficiency
- Bkg modelling, experimental, and statistical u/c all contribute roughly equally



Feature	CR−Z	VR−Z	CR−W	VR−W	VR−0L	Multi-bin SR	Single-bin SR
N_{leptons}	2		1			0	
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 30$ GeV		–			–	
$E_T^{\text{miss}}/\sqrt{\Sigma E_T}$	–		$E_T^{\text{miss}}/\sqrt{\Sigma E_T} > 5\ \sqrt{\text{GeV}}$			–	
BDT score	[0.50, 0.84)	[0.84, 1.0]	[0.50, 0.84)	[0.84, 1.0]	[0.4, 0.6)	[0.6, 1.0]	[0.88, 1.0]
BDT score bins	1	2	1	2	5	8	1

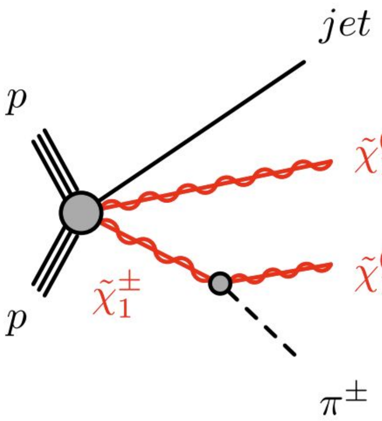
Important to account for interference in EW and QCD diagrams

Mildly-displaced track

Phys. Rev. Lett. 132 (2024) 221801

Variable	SR (CR-0ℓ)	CR-1μ	VR(CR)-0ℓ–lowE_T^{miss}	VR(CR)-1e	VR(CR)-2ℓ	VR(CR)-1γ
Trigger	E_T^{miss}	E_T^{miss}	E_T^{miss}	Single-e	E_T^{miss} or Single-e	Single Photon
$N(e)$	$= 0$	$= 0$	$= 0$	$= 1$	–	$= 0$
$N(\mu)$	$= 0$	$= 1$	$= 0$	$= 0$	–	$= 0$
$N(e$ or $\mu)$	$= 0$	$= 1$	$= 0$	$= 1$	$= 2$	$= 0$
N_γ	$= 0$	$= 0$	$= 0$	$= 0$	$= 0$	$= 1$
$p_T(\ell_1)$ [GeV]	–	> 10	–	> 30	$p_T(\mu) > 10$ ($p_T(e) > 30$)	–
$p_T(\ell_2)$ [GeV]	–	–	–	–	> 10	–
m_{ll} [GeV]	–	–	–	–	[66.2, 116.2]	–
m_T [GeV]	–	[56, 106]	–	[56, 106]	–	–
p_T^{recoil} [GeV]	> 600	> 300	[300, 400]	> 300	> 300	> 600
Track $S(d_0)$	> 8 (< 8)	–	> 8 (< 8)			

Variable	SR	CR-τ_h	CR-τ_ℓ	VR(CR2)-τ_h	VR(CR2)-τ_ℓ
N_ℓ	$= 0$	$= 0$	$= 1$	$= 0$	$= 1$
m_T [GeV]	–	–	< 50	–	< 50
p_T^{recoil} [GeV]	> 600	> 600		[300,400]	
Track p_T	[2,5]	[8,20]		[5,8] ([8,20])	
Track $S(d_0)$	> 8	> 3		> 3	



One lepton + boosted jets

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Variable	C1C1-WW model			C1N2-WZ model		
	SRLM	SRMM	SRHM	SRLM	SRMM	SRHM
N_{lep} ($p_T > 25$ GeV)	1					
N_{jet} ($p_T > 30$ GeV)	1–3					
$N_{large-Rjet}$ ($p_T > 250$ GeV)	≥ 1					
E_T^{miss} [GeV]	> 200					
$\Delta\phi(\ell, E_T^{miss})$	< 2.6					
Large-R jet type	W tagged			Z tagged		
m_T [GeV]	120–200	200–300	> 300	120–200	200–300	> 300
	Exclusion SR					
m_{eff} [GeV] (excl.)	[600–850, > 850]			[600–850, > 850]		
m_{jj}[GeV] (excl.)	[70–90, –]			[80–100, –]		
$\sigma_{E_T^{miss}}$ (excl.)	[> 12, > 15]			[> 12, > 12]		
	Discovery SR					
m_{eff} [GeV] (disc.)	> 600	> 600	> 850	> 600	> 850	> 850
m_{jj}[GeV] (disc.)	-	-	-	80–100	-	-
$\sigma_{E_T^{miss}}$ (disc.)	> 15	> 15	> 15	> 12	> 12	> 12

C1N2-Wh model

Variable	Regions		
E_T^{miss} [GeV]	> 50		
N_{lep} ($p_T > 27$ GeV)	1		
N_{jet} ($p_T > 30$ GeV)	2–3		
N_{b-jet} ($p_T > 30$ GeV)	2		
m_{bb} [GeV]	$\in [50, 200]$		
$\sigma_{E_T^{miss}}$	> 5		
	CR$t\bar{t}$ (**CRttXGB**)	CR single-top (**CRstXGB**)	CR W+jets (**CRWXGB**)
w_{sig}	$\in [0.2, 0.3]$	$\in [0, 0.2]$	$\in [0.0, 0.2]$
$w_{t\bar{t}}$	> 0.73	–	–
w_{st}	< 0.2	> 0.45	< 0.2
w_{W+jets}	< 0.4	–	> 0.65
	VR $t\bar{t}$ (**VRttXGB**)	VR single-top (**VRstXGB**)	VR W+jets (**VRWXGB**)
w_{sig}	$\in [0.4, 0.9]$	$\in [0.2, 0.9]$	$\in [0.2, 0.9]$
$w_{t\bar{t}}$	> 0.4	–	–
w_{st}	< 0.2	> 0.2	< 0.2
w_{W+jets}	< 0.4	–	> 0.4

Multiple b-jets

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High mass channel

Region name	Fixed Requirements			Boundary Conditions		
	Preselection	$m_{\mathrm{T,min}}^{b\text{-jets}}$	$N_{b\text{-jets}}$	Z	n_{bkg}	S/B
SR_i_M	Standard	–	–	max.	≥ 0.5	–
VR_tt_M	Standard	< 200 GeV	–	–	≥ 25	< 0.2
VR_hmTb_M	Standard	> 200 GeV	–	–	≥ 25	< 0.2
VR_Z_M	Z+jets	–	–	–	≥ 25	< 0.2
CR_tt3b_M	Standard	< 200 GeV	$= 3$	–	≥ 100	< 0.1
CR_tt4b_M	Standard	< 200 GeV	≥ 4	–	≥ 100	< 0.1
CR_hmTb_M	Standard	> 200 GeV	–	–	≥ 100	< 0.1
CR_Z_M	Z+jets	–	–	–	≥ 100	< 0.1

Low mass channel

Region	$E_{\mathrm{T}}^{\mathrm{miss}}$	m_{eff}
SR_LM_150	> 20 GeV	> 560 GeV
SR_LM_300	> 150 GeV	> 340 GeV

Displaced leptons

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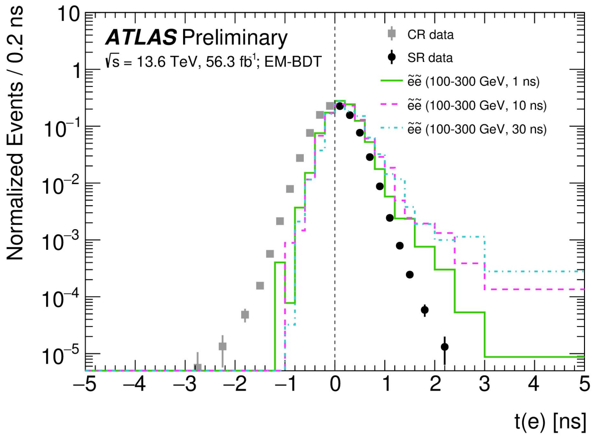
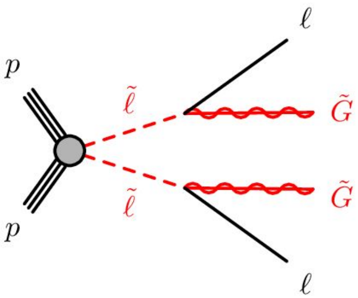
- Targeting slepton lifetimes from o(1) ps ➔ o(100) ps
- Inclusive selection criteria for broad sensitivity to LLPs
- Improvements on previous analysis
  - ➢ Partial Run 3 data
  - ➢ Large radius tracking triggers
  - ➢ Precision pointing and timing resolution from LAr calorimeter
  - ➢ BDT discriminant





Benchmark GMSB SUSY model