ATLAS searches for electroweak supersymmetry with compressed spectra

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On the behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

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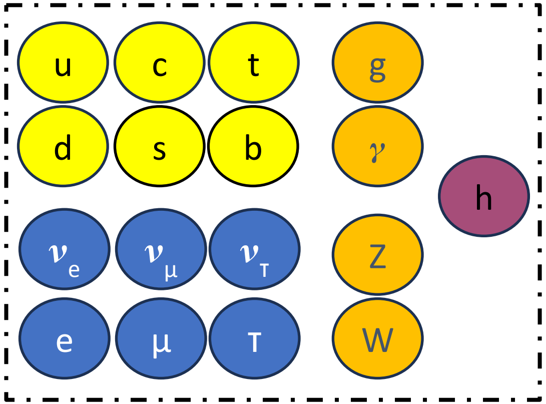
VIRTUTE ET SAPIENTIA

IFIN-HH

The Minimal Supersymmetric Standard Model

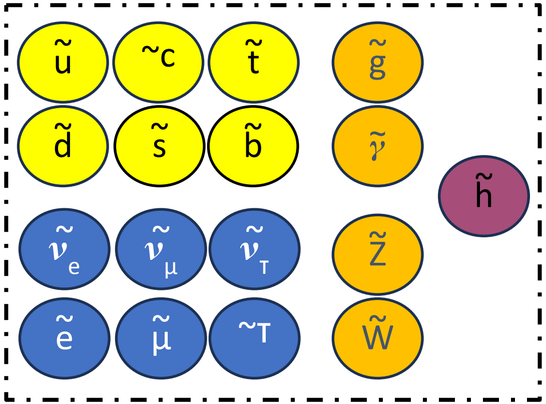
SM Particles

Even under R-parity

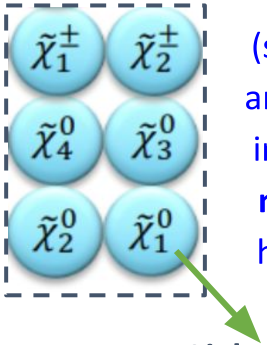


SUSY Particles

Odd Under R-parity



EWK SUSY Sector



Electroweakinos (superpartners of SM Higgs and EWK gauge bosons) mix into **charginos** (C1, C2) and **neutralinos** (N1-N4). SUSY has a complex EWK sector.

Lightest supersymmetric particle is **a viable dark matter candidate**

SUSY: Solution to Higgs hierarchy problem

3 Recent ATLAS Run 2 EWK SUSY searches considered, primarily focus on compressed Higgsinos

Short keys in slides

MET → Missing Transverse Energy

pT → Transverse Momentum

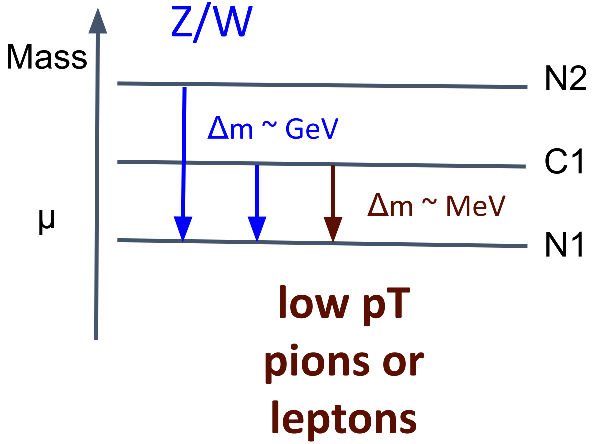
Why compressed Higgsinos?

Importance of Higgsinos:

- The **μ parameter** (controls Higgsino masses) must remain small to to avoid excessive fine-tuning

Compressed Spectrum:

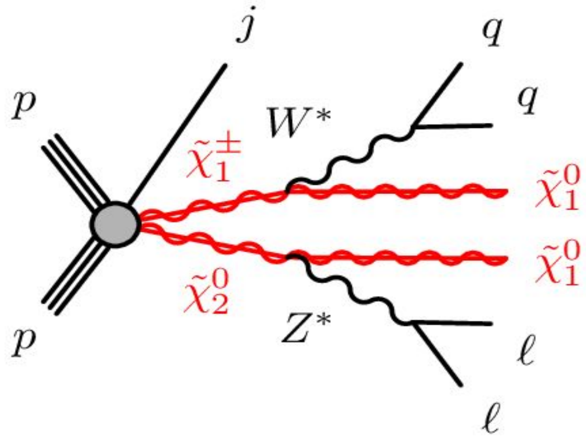
- In **Higgsino-dominated cases**, the **mass splitting** between N1, C1, and N2 is **small**, creating a **compressed spectrum**
- Small mass splitting means **weak signals**, making **detection challenging**
- **Detection** heavily relies on identifying **low pT pions** or **leptons** in the final state



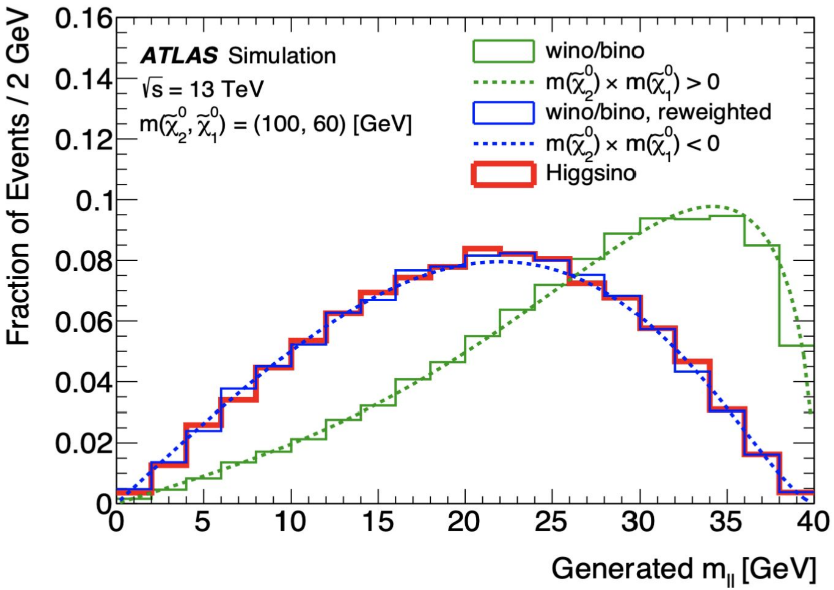
Higgsinos LSP with Soft Leptons

Phys. Rev. D 101, 052005 (2020)

Higgsinos LSP with Soft Leptons



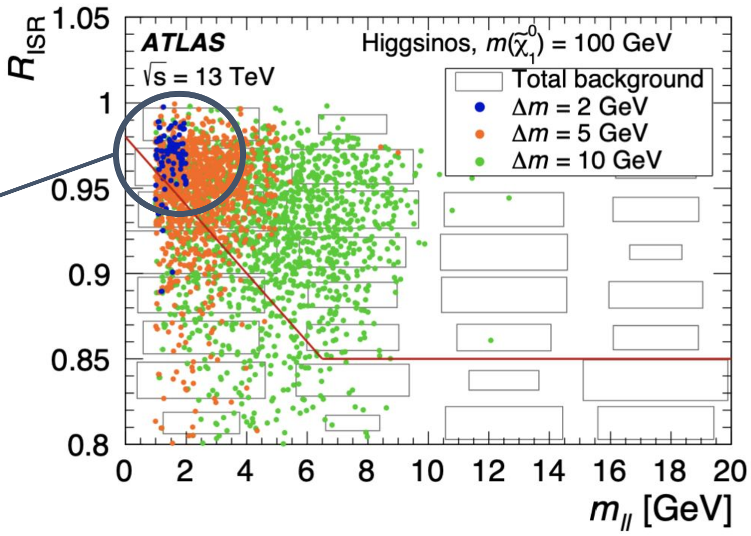
- N2 decay via off-shell Z boson produces low pT leptons
- Dilepton mass (**$m_{\ell\ell}$**) forms a peak at low values
  - A characteristic signature in compressed Higgsino searches



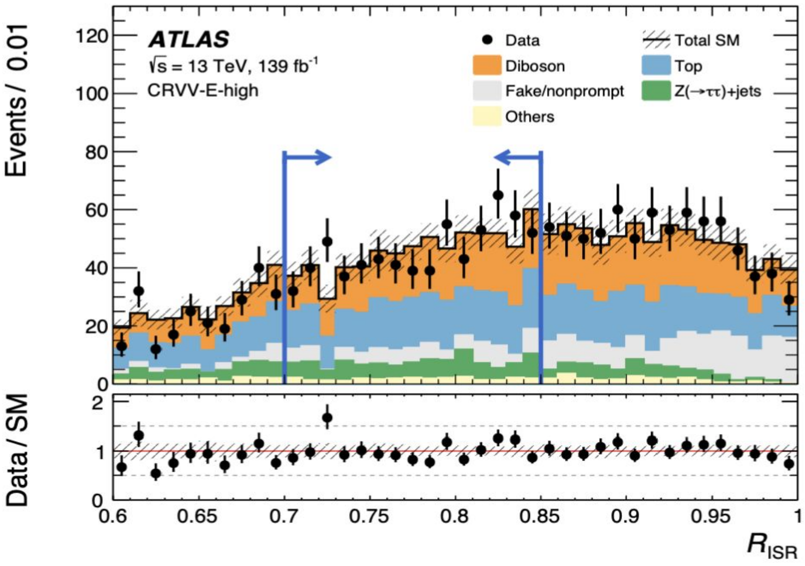
- **$m_{\ell\ell}$** endpoint set by Δm(N2, N1)
- Higgsino-LSP -> Red curve
- Populated regions at low **$m_{\ell\ell}$** values confirm the compressed mass spectrum signature

Analysis Strategy

- **R_{ISR}: Ratio of MET to pT of the Initial State Radiation (ISR)** system
- R_{ISR} variable is sensitive to the mass splitting (**compressed SUSY events**)
- R_{ISR} is higher in signal than background

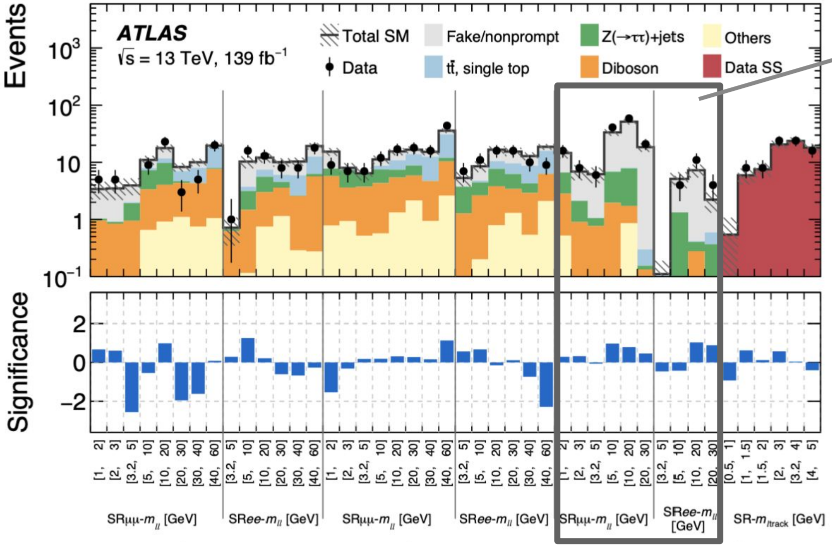


Analysis Strategy



- Cut on $\mathbf{R_{ISR}}$ and fit the $\mathbf{m_{\ell\ell}}$ variable
- Fit is performed in bins of $\mathbf{m_{\ell\ell}}$ distribution
- Separate signal regions are defined based on lepton flavor
- Estimate backgrounds with MC simulation (normalized to data) and the Fake Factor method (JINST 18 (2023) T11004)

Results and Interpretation

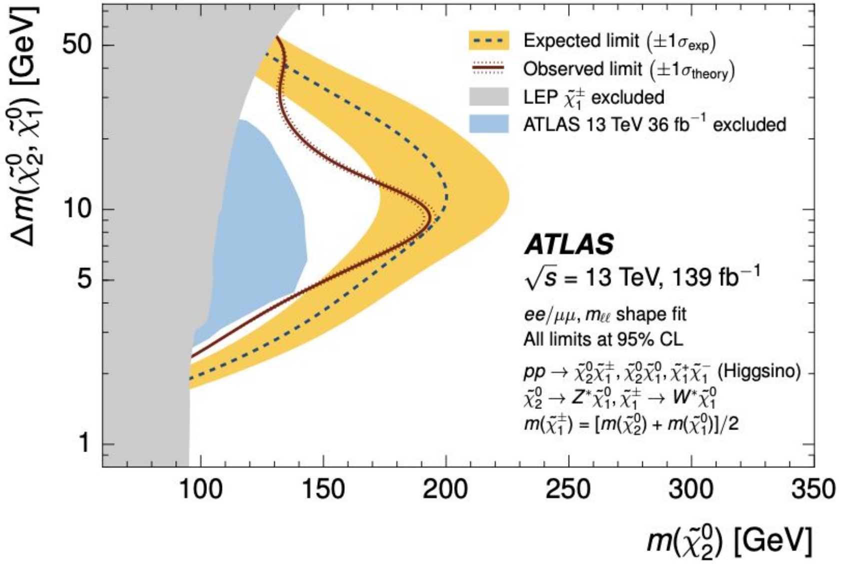


Higgsino-LSP region

Data matches SM predictions

No significant excess or evidence of new physics

Limits are set based on Simplified Models



Exclusion limits set the mass N2 at 193 GeV, with a 9.3 GeV mass splitting from N1

Higgsino-LSP scenarios exclude mass splittings from 2.4 GeV, with sensitivity up to 50 GeV, surpassing LEP limits

Higgsino LSP with Displaced Track

Phys. Rev. Lett. 132 (2024) 221801

Higgsinos LSP with Displaced Track

Mass Splitting:

- With Δm(C1, N1) ≈ 0.3 – 1 GeV, the chargino is nearly degenerate with the neutralino, producing low pT pions

Chargino Travel Distance:

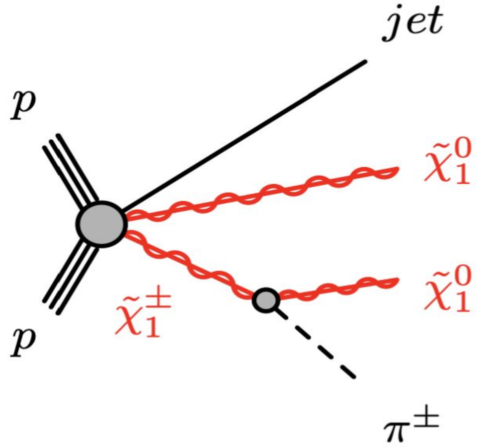
- Chargino travels ~0.1 to 1 mm from the proton collision vertex

Track Inside Inner Detector:

- This distance allows the chargino to decay in the detector, leaving a displaced track

Discrimination Using $S(d_0)$:

- S(d0), the ratio of transverse impact parameter to its resolution, is key discriminator for identifying this decay



Important selections to define the Signal Region:

- ISR leading jet (pT > 250 GeV)
- MET > 600 GeV (rejects SM background)
- S(d0) > 8 (identifies displaced tracks)
- Low pT track: 2 GeV < pT < 5 GeV
- **Two SR in S(d0) (sensitive to Δm changes)**

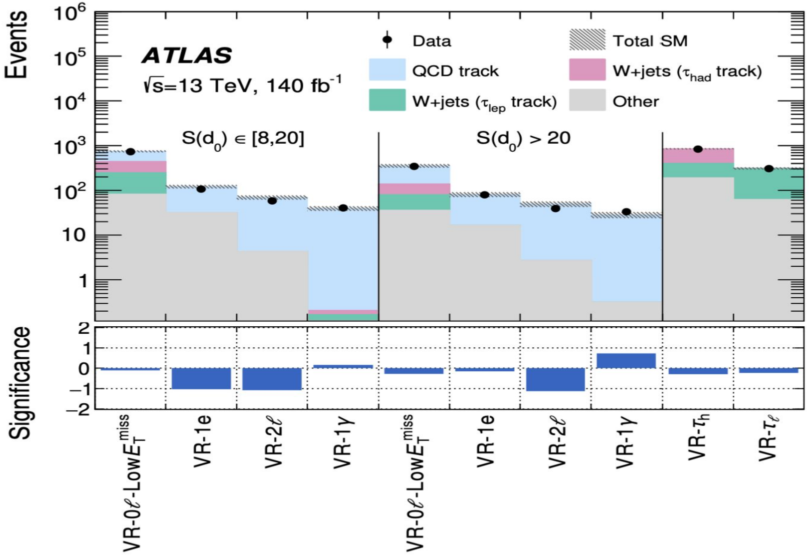
Backgrounds and Validation Regions (VRs)

Most Impactful Standard Model Backgrounds

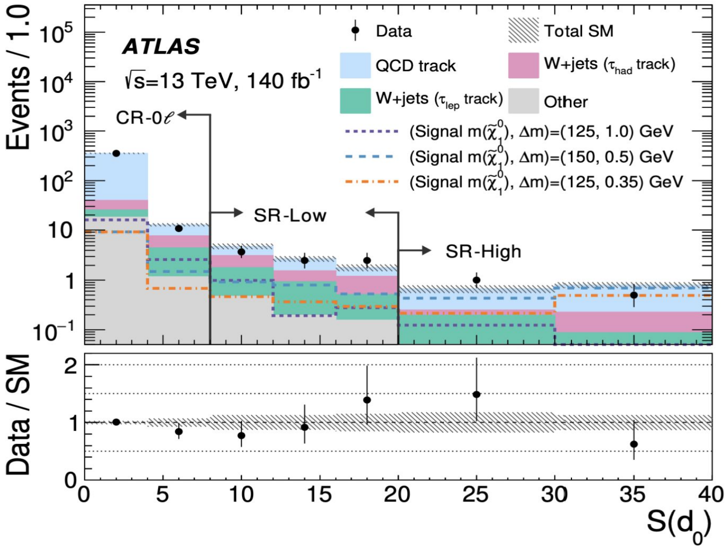
- **QCD Tracks:**
  - Originates from W/Z + jets events where the signal candidate tracks originate from long lived hadrons decays, pileup jets
  - Estimated via data-driven ABCD method.
- **Tau Tracks:**
  - Originates from W($\rightarrow \tau\nu$) + jets events where a pion or lepton from a low pT τ-lepton decay is tagged as the signal candidate track
  - Estimated via MC simulation, normalized to data

Validation Regions:

- Defined with similar backgrounds as the SRs in addition with different lepton or photon content
- A shifted MET range (300 GeV < MET < 400 GeV) increases data yield and reduces signal contamination

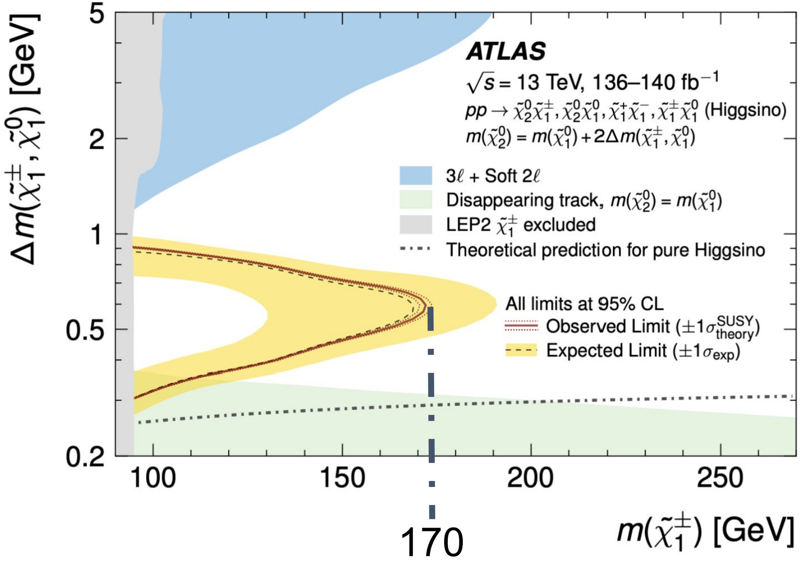


Results and Interpretation



Data matches SM predictions, showing no significant excess or evidence of new physics

Limits set on Higgsino Simplified Models



- Exclusion limits for mass splittings:
  - 0.3 GeV < Δm(C1, N1) < 0.9 GeV
- Search sensitivity peaks at Δm(C1, N1) = 0.6 GeV, excluding m(C1) up to ~170 GeV

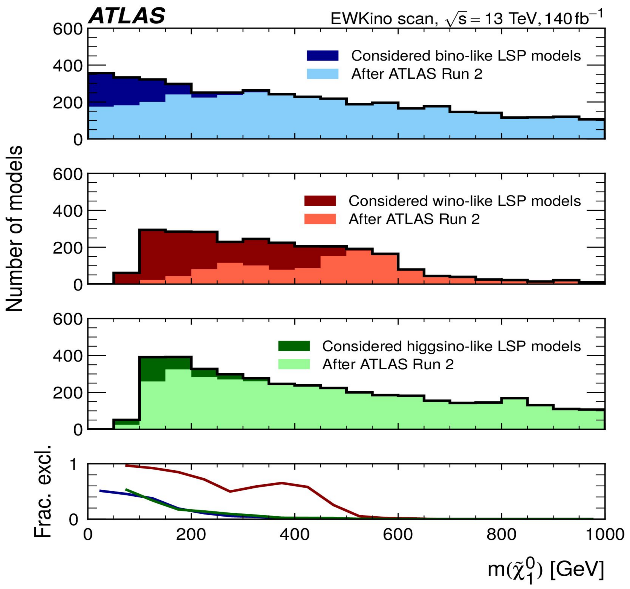
ATLAS Run 2 searches for electroweak SUSY particles interpreted within 19D phenomenological Minimal Supersymmetric Standard Model

JHEP 2024 (2024) 106

Electroweak pMSSM Scan

- **Simplified models** do not capture the full complexity of SUSY phenomenology
- SUSY parameters reduced from 100 in **MSSM** to 19 in **pMSSM**, assuming CP-conservation, RPC, and minimal flavour violation
- **Reinterpreting electroweak ATLAS Run 2 SUSY searches in pMSSM explores electroweakinos,** assuming other sparticles are decoupled
- **LSP assumed as N1**
- This talk only focuses on Higgsino LSP and compressed scenarios results

LSP MASS DISTRIBUTION

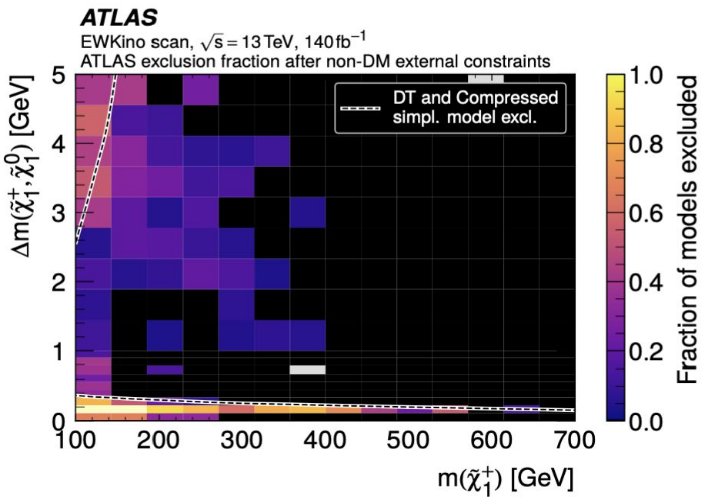


For m(N1) < 200 GeV: Less than 20% of Higgsino-like LSP models are excluded by ATLAS

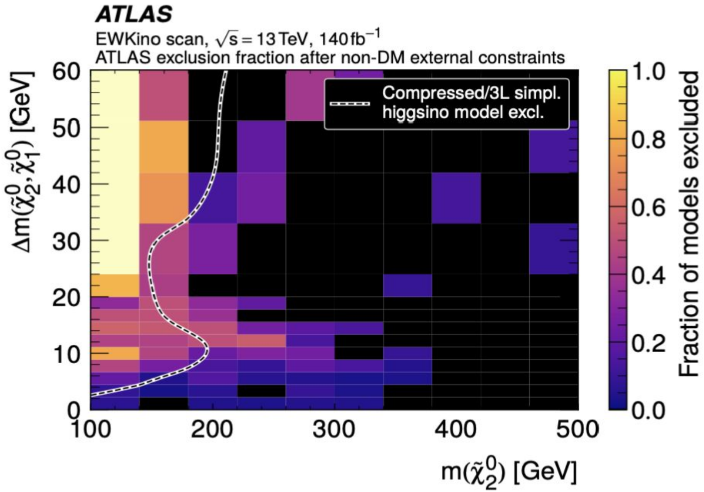
EWkinos Exclusion in Compressed Region

ATLAS shows sensitivity to low Ewkino masses in both Δm(C1,N1) vs. m(N1) and Δm(N2,N1) vs m(N2) plane

Exclusion fractions shown with non-DM constraints: Precision EWK, Flavor measurements



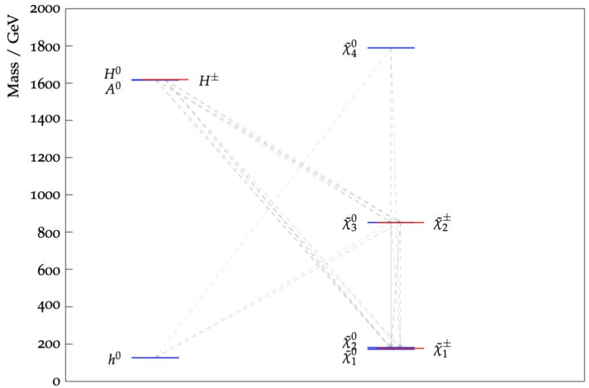
Highest exclusion is seen for Δm(C1,N1) ≈ 0.1– 0.2 GeV the sensitive region for disappearing track analysis

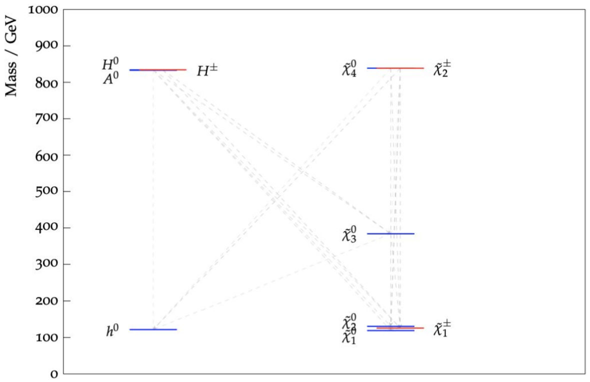


In many bins within the simplified model contours, less than 100% exclusion is observed due to pMSSM models' smaller branching fractions

Benchmark Models with Higgsino-like LSP

- **Models satisfy all constraints and are not excluded**
- N3 and C2 are under 1 TeV with large mass splittings from other electroweakinos
- **Mass spectrum remains within the published compressed ATLAS simplified model contours**
- BR(N2→N1$\ell^+\ell^-$), smaller in pMSSM models
  - N2 also has a radiative decay mode: N2 → N1 + γ, typically suppressed but favoured at small mass splittings
- **In some benchmark models, enhanced radiative decay, heavier electroweakinos and their decay products, interesting for future searches**





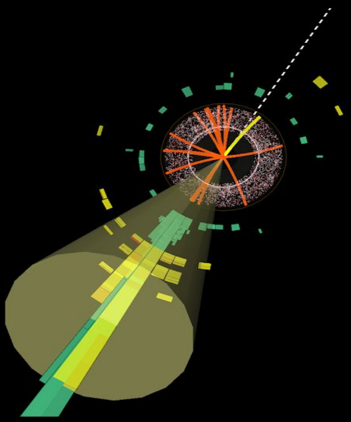
Summary and Outlook

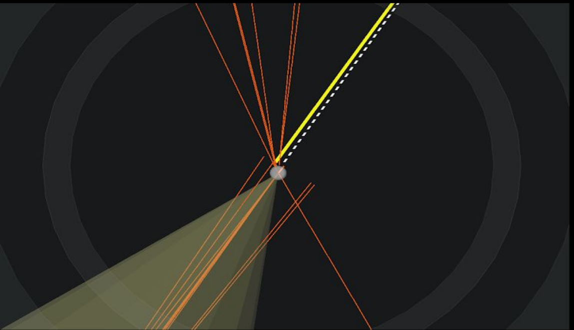
- **Current Status:**
  - **EWK SUSY** searches at the LHC are crucial, particularly in **challenging** compressed scenarios**, necessitating specialized analysis strategies**
  - **Higgsino searches** are motivated by the need to address fine-tuning in the Higgs sector
  - **ATLAS shows data consistent with SM predictions, though SM doesn't explain everything**
- **Key Insights:**
  - **Challenging** final state **signatures** (soft pions) are key, especially in **compressed** Higgsino **scenarios**
  - Exclusion sensitivity peaks at $\Delta m(C1, N1) = 0.6$ GeV, excluding m(C1) up to 170 GeV based on **Displaced track analysis**
  - **pMSSM paper** provides an **excellent overview** of **EWK SUSY Run 2 searches**
- **Future Directions:**
  - Run 3 offers exciting prospects (with more data) to continue the hunt for SUSY signals as well as with new ideas and techniques
  - **Benchmark models** from **pMSSM** results further **motivate** continued exploration

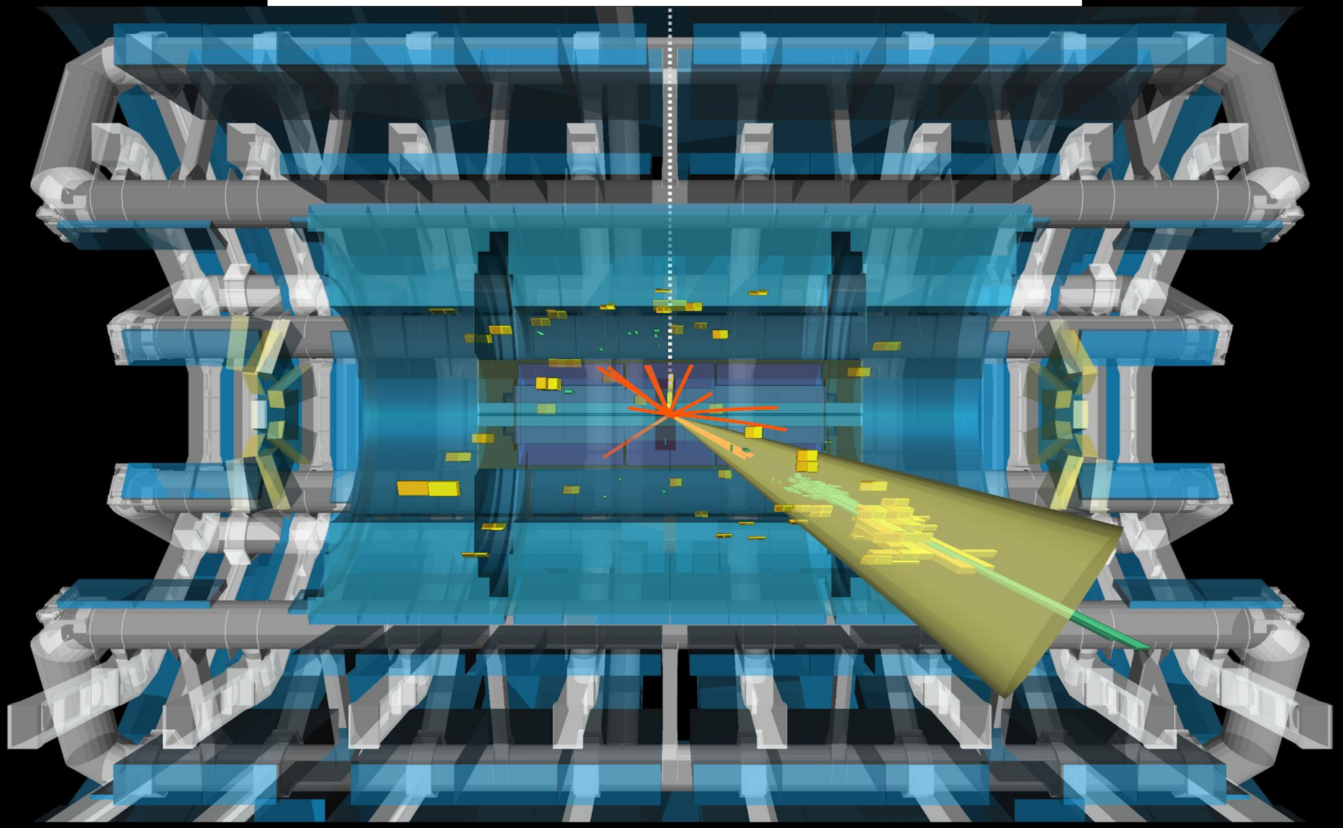
BACKUP SLIDES

ATLAS EXPERIMENT

Run: 349309
Event: 1342904905
2018-05-01 16:21:51 CEST







HIggsino LSP with Soft Leptons

Variable	Preselection requirements: 2ℓ	Preselection requirements: $1\ell 1T$
Number of leptons (tracks)	= 2 leptons	= 1 lepton and ≥ 1 track
Lepton p_T [GeV]	$p_T^{\ell_1} > 5$	$p_T^{\ell} < 10$
$\Delta R_{\ell\ell}$	$\Delta R_{ee} > 0.30$, $\Delta R_{\mu\mu} > 0.05$, $\Delta R_{e\mu} > 0.2$	$0.05 < \Delta R_{\ell\mathrm{track}} < 1.5$
Lepton (track) charge and flavor	$e^\pm e^\mp$ or $\mu^\pm\mu^\mp$	$e^\pm e^\mp$ or $\mu^\pm\mu^\mp$
Lepton (track) invariant mass [GeV]	$3 < m_{ee} < 60$, $1 < m_{\mu\mu} < 60$	$0.5 < m_{\ell\mathrm{track}} < 5$
J/ψ invariant mass [GeV]	veto $3 < m_{\ell\ell} < 3.2$	veto $3 < m_{\ell\mathrm{track}} < 3.2$
$m_{\tau\tau}$ [GeV]	< 0 or > 160	no requirement
E_T^{miss} [GeV]	> 120	> 120
Number of jets	≥ 1	≥ 1
Number of b-tagged jets	= 0	no requirement
Leading jet p_T [GeV]	≥ 100	≥ 100
min($\Delta\phi$(any jet, $\mathbf{p}_T^{miss}$))	> 0.4	> 0.4
$\Delta\phi(j_1, \mathbf{p}_T^{miss})$ †	≥ 2.0	≥ 2.0

Fit Results

SR–E–med ee	Observed			0	4	11	4
	Fitted SM events			0.11 ± 0.08	5.1 ± 1.6	7.3 ± 1.9	2.2 ± 0.9
	Fake/nonprompt			$0.000^{+0.016}_{-0.000}$	3.8 ± 1.3	6.9 ± 2.0	1.6 ± 1.1
	$t\bar{t}$, single top			$0.00^{+0.05}_{-0.00}$	$0.00^{+0.04}_{-0.00}$	$0.01^{+0.06}_{-0.01}$	$0.23^{+0.25}_{-0.23}$
	Diboson			0.10 ± 0.05	0.10 ± 0.09	0.28 ± 0.26	$0.02^{+0.13}_{-0.02}$
	$Z(\to \tau\tau)$+jets			$0.000^{+0.028}_{-0.000}$	1.2 ± 1.2	$0.1^{+0.5}_{-0.1}$	$0.3^{+0.6}_{-0.3}$
	Others			$0.000^{+0.012}_{-0.000}$	–	–	–
SR–E–med $\mu\mu$	Observed	16	8	6	41	59	21
	Fitted SM events	14.6 ± 2.9	6.9 ± 2.1	6.2 ± 1.9	34 ± 4	52 ± 6	18.5 ± 3.2
	Fake/nonprompt	7.9 ± 3.2	4.8 ± 2.1	5.1 ± 2.0	27 ± 5	44 ± 6	18.2 ± 3.2
	$t\bar{t}$, single top	$0.01^{+0.06}_{-0.01}$	$0.01^{+0.06}_{-0.01}$	$0.00^{+0.05}_{-0.00}$	$0.12^{+0.13}_{-0.12}$	0.24 ± 0.08	$0.14^{+0.19}_{-0.14}$
	Diboson	2.3 ± 0.8	0.9 ± 0.4	0.73 ± 0.24	1.9 ± 0.7	0.87 ± 0.26	0.13 ± 0.07
	$Z(\to \tau\tau)$+jets	3.8 ± 1.8	1.2 ± 0.5	$0.3^{+0.6}_{-0.3}$	4.9 ± 1.6	6.1 ± 2.1	$0.02^{+0.29}_{-0.02}$
	Others	0.5 ± 0.4	$0.000^{+0.026}_{-0.000}$	0.036 ± 0.015	0.019 ± 0.017	0.9 ± 0.6	–

Backgrounds

Estimated via Fake Factor method

Estimated via MC

Process	Matrix element	Parton shower	PDF set	Cross-section
V+jets	Sherpa 2.2.1		NNPDF 3.0 NNLO [84]	NNLO [85]
VV	[illegible]		NNPDF 3.0 NNLO	Generator NLO
Triboson	Sherpa 2.2.1		NNPDF 3.0 NNLO	Generator LO, NLO
h (ggF)	Powheg-Box	Pythia 8.212	NLO CTEQ6L1 [86]	N^{3}LO [87]
h (VBF)	Powheg-Box	Pythia 8.186	NLO CTEQ6L1 [86]	NNLO + NLO [87]
$h + W/Z$	Pythia 8.186		NNPDF 2.3 LO [54]	NNLO + NLO [87]
$h + t\bar{t}$	MG5_aMC@NLO 2.2.3	Pythia 8.210	NNPDF 2.3 LO	NLO [87]
$t\bar{t}$	Powheg-Box	Pythia 8.230	NNPDF 2.3 LO	NNLO+NNLL [88–92]
t (s-channel)	Powheg-Box	[illegible]	NNPDF 2.3 LO	NNLO+NNLL [93]
t (t-channel)	Powheg-Box	Pythia 8.230	NNPDF 2.3 LO	NNLO+NNLL [77, 94]
$t + W$	Powheg-Box	[illegible]	NNPDF 2.3 LO	NNLO+NNLL [95]
$t + Z$	MG5_aMC@NLO 2.3.3	Pythia 8.212	NNPDF 2.3 LO	NLO [53]
$t\bar{t}WW$	MG5_aMC@NLO 2.2.2	Pythia 8.186	NNPDF 2.3 LO	NLO [53]
$t\bar{t} + Z/W/\gamma^*$	MG5_aMC@NLO 2.3.3	Pythia 8.210/8.212	NNPDF 2.3 LO	NLO [87]
$t + WZ$	MG5_aMC@NLO 2.3.3	Pythia 8.212	NNPDF 2.3 LO	NLO [53]
$t + t\bar{t}$	MG5_aMC@NLO 2.2.2	Pythia 8.186	NNPDF 2.3 LO	LO [53]
$t\bar{t}t\bar{t}$	MG5_aMC@NLO 2.2.2	Pythia 8.186	NNPDF 2.3 LO	NLO [53]

Also an effective variable

Variable	Electroweakino SR Requirements: SR–E–low	SR–E–med	SR–E–high	SR–E–$1\ell 1T$
E_T^{miss} [GeV]	[120, 200]	[120, 200]	> 200	> 200
E_T^{miss}/H_T^{lep}	< 10	> 10	–	> 30
$\Delta\phi(\mathrm{lep}, \mathbf{p}_T^{miss})$	–	–	–	< 1.0
Lepton or track p_T [GeV]	$p_T^{\ell_2} > 5 + m_{\ell\ell}/4$	–	$p_T^{\ell_2} > \min(10, 2 + m_{\ell\ell}/3)$	$p_T^{track} < 5$
M_T^S [GeV]	–	< 50	–	–
$m_T^{\ell_1}$ [GeV]	[10, 60]	–	< 60	–
R_{ISR}	[0.8, 1.0]	–	[max(0.85, 0.98 − 0.02 × $m_{\ell\ell}$), 1.0]	–

Displaced Track

Event level Selection:

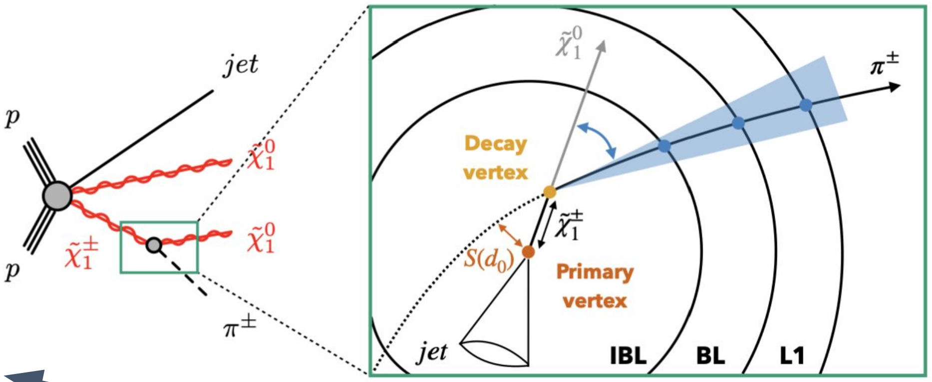
- MET > 600 GeV
- Leading jet: pT > 250 GeV ,|η | < 2.5
- min[Δϕ(any jet, MET)] > 0.4
- No leptons or photons
- Njets ≤ 4

Track level Selection:

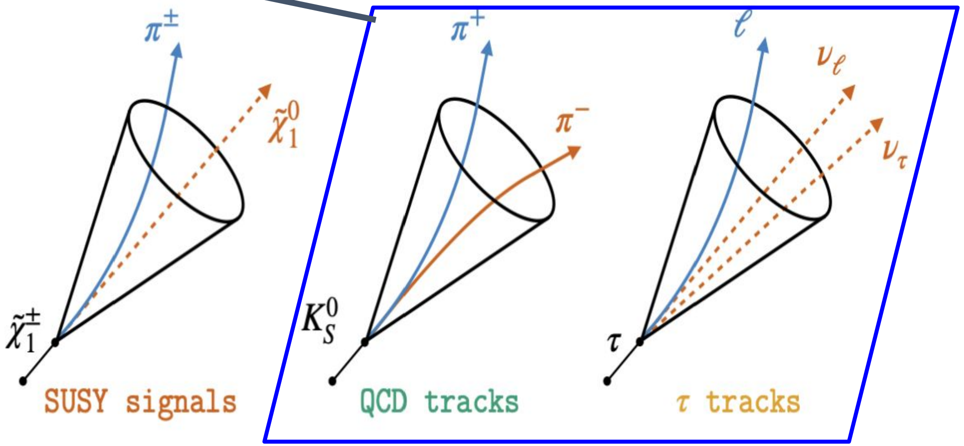
- pT ∈ [2GeV,5GeV], |η| < 1.5
- |d0| < 10 mm, |z0sinθ| < 3 mm
- Δϕ(track, MET) < 0.4
- No other track with pT > 1 GeV within ΔR=0.4
- TightPrimary WP + N_{IBL} hits > 0
- $S(d_0)>8$

SRs binned in $S(d_0)$:

- **SR-low:** $S(d_0) \in [8,20]$
- **SR-high:** $S(d_0) > 20$



BKGs



From Sala, Alessandro

pMSSM Scans

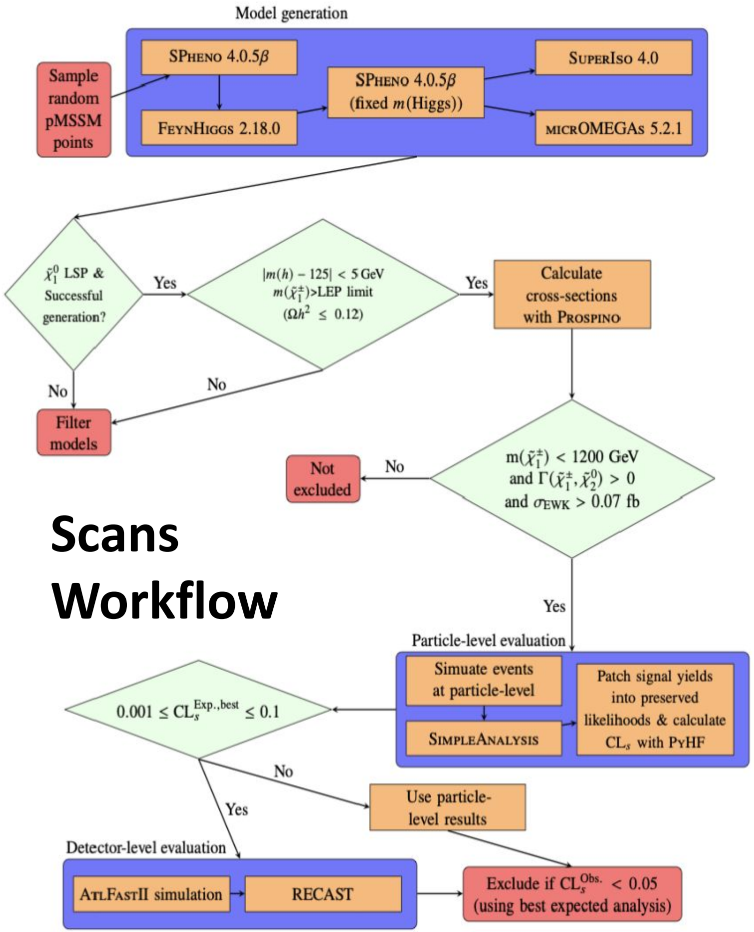
Run1 pMSSM Scans: [JHEP 10 (2015) 134]

Assumptions:

- No new sources of CP-violation (beyond CKM matrix)
- No flavour-changing neutral currents (FCNCs)
- Universality of 1st and 2nd generation sfermions
- R-parity conserved
- Lightest SUSY particle (LSP) is the lightest neutralino

Analysis Considered:

Analysis	Relevant simplified models targeted
FullHad [24]	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 [15]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh
2L0J [19]	Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ via WW, slepton pairs
2L2J [25]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ
3L [23]	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 [22]	Higgsino GGM
Compressed [20]	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 [27]	Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$



Scans Workflow

pMSSM Scans

Constraints Considered:

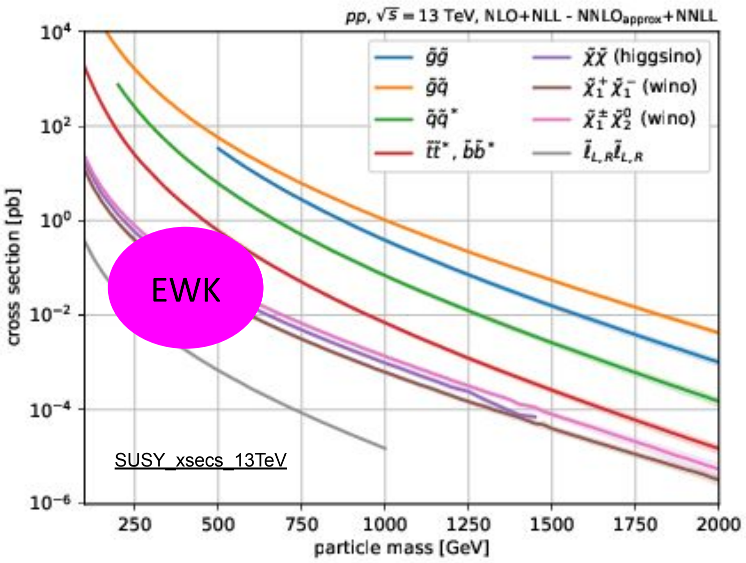
Category	Constraint	Lower bound	Upper bound	Notes
Flavour	$\mathcal{B}(b \to s\gamma)$	3.11×10^{-4}	3.87×10^{-4}	2022 PDG average (2σ window) [58].
	$\mathcal{B}(B_s \to \mu\mu)$	1.87×10^{-9}	4.31×10^{-9}	Most recent LHCb result (2σ window) [59].
	$\mathcal{B}(B^+ \to \tau\nu)$	6.10×10^{-5}	1.57×10^{-4}	2022 PDG average (2σ window) [58].
Precision electroweak	$\Delta\rho$	-0.0004	0.0018	Updated global electroweak fit by GFITTER group [60] (not including CDF W mass measurement [61]).
	$\Gamma_{\text{inv}}^{\text{BSM}}(Z)$	–	2 MeV	Beyond-the-Standard Model contributions to precision electroweak measurements on the Z-resonance from experiments at the SLC and LEP colliders [62].
	$m(W)$	80.347 GeV	80.407 GeV	2022 PDG result (excluding CDF W mass measurement [61]) [58] but with the 2σ window expanded by 6 MeV to allow for uncertainty due to the top-quark mass in the MSSM Higgs calculation [63].
DM	Relic density	–	0.12	Latest bound from Planck [64].
	$\sigma_{\text{Spin-independent}}$			Exclusion contour on direct detection of DM from the LZ Collaboration [65].
	$\sigma_{\text{Spin-dependent}}$			Exclusion contour on direct detection of DM from PICO-60 [66].

19 Parameters Ranges

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

Electroweak Supersymmetry at LHC

- Smaller production cross sections at the LHC make electroweak SUSY searches particularly challenging
- These rare processes demand large amounts of data to uncover and achieve discovery



Fine Tuning Equation

At this stage, we can already see the tension with naturalness, if the SUSY parameters are significantly larger than the scale of electroweak symmetry breaking. In this case, m_Z^2 will be the difference of two large numbers,

$$\tfrac{1}{2}m_Z^2 = -|\mu|^2 + \frac{m_1^2 - m_2^2\tan^2\beta}{\tan^2\beta - 1},$$

requiring some fine-tuning of the SUSY parameters in order to produce the correct Z boson mass. In the literature, this tension is referred to as the *little hierarchy problem*.

In the above equation, μ, m_1^2 and m_2^2 are parameters defined at the electroweak scale. The question of fine-tuning should really be addressed to the fundamental SUSY-breaking parameters at some high energy scale, which ultimately determine the low-energy parameters appearing the above expression.

ATLAS SUSY Searches

SUSY group at ATLAS never give up!