Cambridge HEP extravaganza ATLAS results- Run 2 EWK pMSSM reinterpretation effort

Above: My top Christmas movie recommendations for 2023 (so far)…

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Introduction

https://cds.cern.ch/record/2870222

- I'll aim to give a quick walk-through of one of the ATLAS SUSY results from this year that had significant Cambridge involvement.
- My aim is NOT to summarise all of the results in lots of detail but to give you an overview of the aims and key results, in the hope that you all then read the CONF note (and anticipated paper).

ATLAS CONF Note

ATLAS-CONF-2023-055

30th August 2023

ATLAS Run 2 searches for electroweak production of supersymmetric particles interpreted within the pMSSM

The ATLAS Collaboration

A summary of the constraints from searches performed by the ATLAS experiment for the electroweak production of charginos and neutralinos is presented. Results from eight separate ATLAS searches are considered, each using 140 fb^{-1} of proton-proton data at a center-of-mass energy of $\sqrt{s}$ = 13 TeV collected by the Large Hadron Collider (LHC) during its second data-taking run. The results are interpreted in the context of the 19-parameter phenomenological minimal supersymmetric standard model, where R-parity conservation is assumed and the lightest supersymmetric particle is assumed to be the lightest neutralino. Constraints from previous electroweak, flavour and dark matter related measurements are also considered. The results are presented in terms of constraints on supersymmetric particle masses and are compared to limits from simplified models. Also shown is the impact of ATLAS searches on parameters such as the dark matter relic density and the spin-dependent and spin-independent scattering cross-sections targeted by direct dark matter detection experiments. The Higgs boson and Z-boson "funnel regions" where a low-mass neutralino would not oversaturate the dark matter relic abundance are almost completely excluded by the ATLAS constraints. Example spectra for non-excluded supersymmetric models with light charginos and neutralinos are also presented.

An alternative title to this talk

SUSY could still exist….

…reason to keep searching for SUSY

Starring…

This project provides a legacy reinterpretation of the run 2 EWK SUSY programme in broader SUSY parameter space

Analysis	Simplified models targeted
1Lbb [10]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh
Compressed [15]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, Higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\tilde{\chi}_1^0$
FullHad [19]	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, Higgsino GGM
2L0J [14]	Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ via WW, slepton pairs
3L [18]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh, Higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\tilde{\chi}_1^0$, Higgsino GGM
2L2J [20]	Wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ, Higgsino GGM
4L [17]	Higgsino GGM
Disappearing Track [22]	Wino $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0$

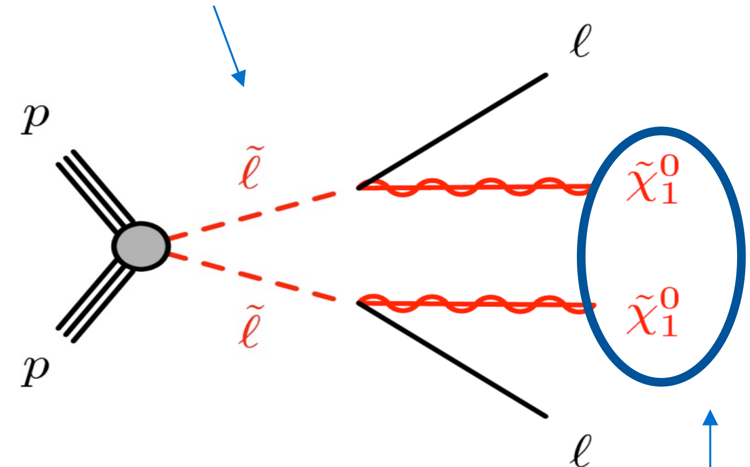
Supersymmetry and collider searches

Invoke a symmetry between fermions and bosons such that every SM particle has a corresponding "super-partner". Can address several problems in the SM:

- Dark matter candidate?
- Plus (natural?) solution to the hierarchy problem and gauge coupling unification…

Searches for SUSY at the LHC typically involve looking for statistically significant deviations from the Standard Model predictions in event topologies designed to enhance signal acceptance and strongly suppress the SM backgrounds…

R-parity conservation:
pair produced sparticles at LHC!



Plus **missing transverse momentum** associated with LSPs

Undiscovered particles in the MSSM

MSSM= ”Minimal Supersymmetric Standard Model”

Name	Spin	Gauge eigenstates	Mass eigenstates
Higgs bosons	0	$H_u^0, H_d^0, H_u^+, H_d^-,$	$h^0\ (*), H^0, A^0, H^{\pm}$
Squarks	0	$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$ $\tilde{s}_L, \tilde{s}_R, \tilde{c}_L, \tilde{c}_R$ $\tilde{t}_L, \tilde{t}_R, \tilde{b}_L, \tilde{b}_R$	same same $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$
Sleptons	0	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_e$ $\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_\mu$ $\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_\tau$	same same $\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau$
Neutralinos	½	$\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
Charginos	½	$\tilde{W}^{\pm}, \tilde{H}_u^+, \tilde{H}_d^-$	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$
Gluinos	½	$\tilde{g}$	same

=> A wealth of new particles to search for experimentally!

=> “Gauginos”

(*) Note: typically assume h^0 is the 125 GeV “SM” Higgs boson

The “phenomenological” MSSM

In bold are the parameters most relevant to the EWK sector

Apply set of theoretical and experimental constraints on the general MSSM-> reduce number of parameters from 105 to 19:

pMSSM parameter	Meaning
$\boldsymbol{\tan\beta}$	Ratio of VEVs of the two Higgs doublets
$\boldsymbol{M_A}$	CP-odd Higgs boson mass parameter
$\boldsymbol{\mu}$	Higgsino mass parameter
$\boldsymbol{M_1}, \boldsymbol{M_2}, M_3$	Bino, wino and gluino mass parameters
A_t, A_b, A_τ	Third generation trilinear couplings
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}$	First/second generation sfermion masses
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}$	Third generation sfermion masses

Most LHC searches present interpretation of results using “simplified models” within the pMSSM.

Once upon a time there was a bino, wino and higgsino…

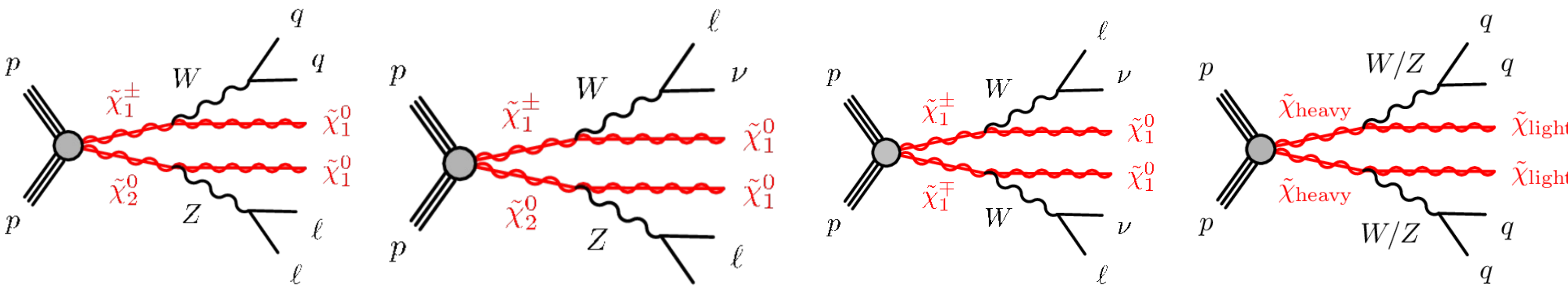
For models that *assume* the gauginos masses unify at high energies, expect $M_1 \approx 0.5M_2$ at EW scale. Within pMSSM can then get three distinct phenomenologies…

	pMSSM parameters	LSP nature	Particle spectrum
(1)	$\|\mu\| \gg \|M_1, M_2\| \gg M_Z$	Bino	**Bino-like** $\tilde{\chi}_1^0$, **wino-like** $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ m($\tilde{\chi}_1^0$) <m($\tilde{\chi}_1^{\pm}$)~m($\tilde{\chi}_2^0$)
(2)	$\|\mu\| \ll \|M_1, M_2\|$	Higgsino	**Higgsino-like** $\tilde{\chi}_1^0, \tilde{\chi}_1^{\pm}$,$\tilde{\chi}_2^0$ m($\tilde{\chi}_1^0$)~m($\tilde{\chi}_1^{\pm}$)~m($\tilde{\chi}_2^0$)
(3)	$\|\mu\| \sim \|M_1\|$ or $\|M_2\|$	Mixed	Mixed states

=> Even with a small number of starting ingredients, these different possible "mixtures" of gaugino states would give very different signatures if produced at the LHC. There are also significant implications for dark matter!

Searching for SUSY at the LHC- run 2 searches

Signature driven approach to target simplified models in dedicated channels…



2l+ jets+ $\vec{p}_T^{\,miss}$ **3l+ $\vec{p}_T^{\,miss}$** **2l+0jets+ $\vec{p}_T^{\,miss}$** **0l + jets + $\vec{p}_T^{\,miss}$**

- Different search channels=> complementary sensitivity to different areas of the SUSY mass plane, and different dominant backgrounds.

- Legacy results of the search programme involve combinations and reinterpretations to understand the overall constraints and any gaps.

Analysis in a nutshell

Note- developing and validating the framework to do this reliably was a significant task!

1. Generate pMSSM points in two scan configurations:
   - ”EWKino” scan
   - “Bino” scan
2. Apply a set of pre-filters.
3. Use particle-level and reco-Level analysis to assess the fraction of models excluded by the ATLAS results with and without applying external constraints…

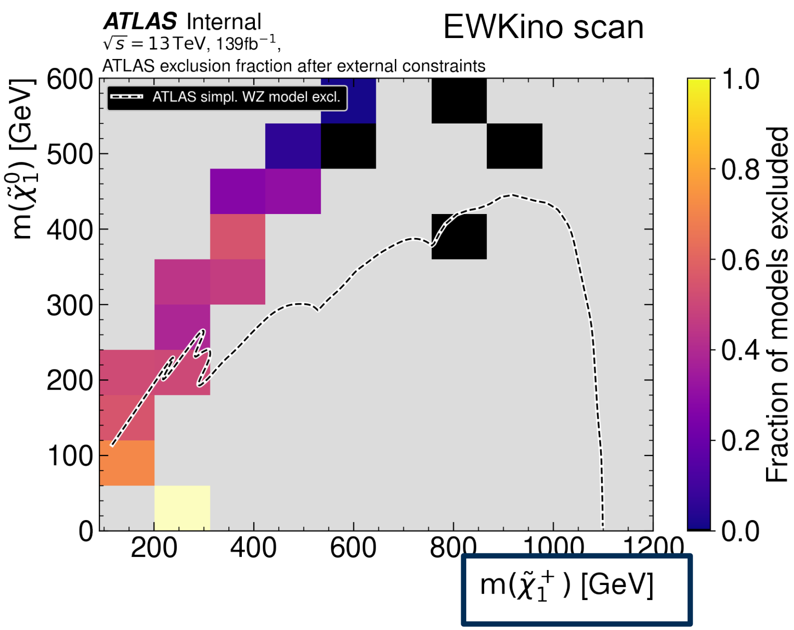
Table 4: Set-ups for the two pMSSM scans performed and number of models passing each step.

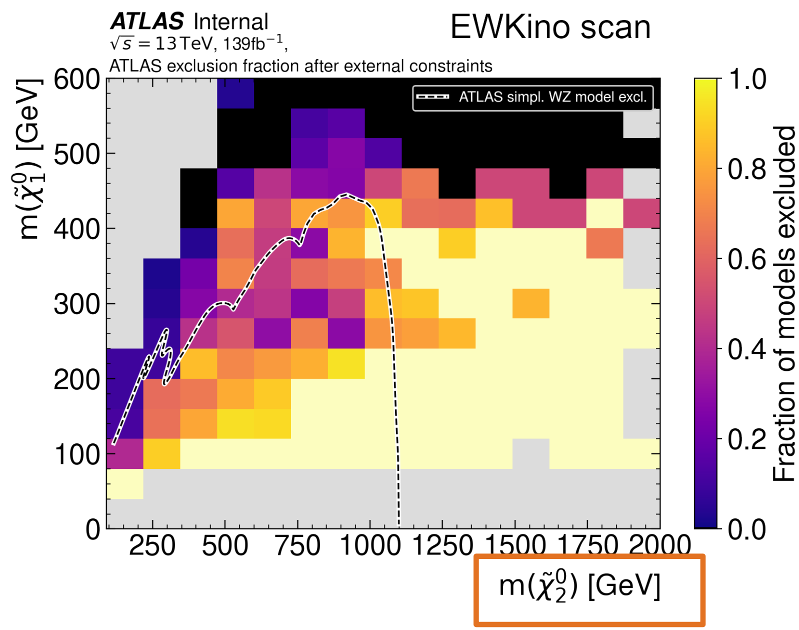
Scan name	EWKino	Bino-DM
$\lvert M_1 \rvert$ range	0 – 2 TeV	0 – 500 GeV
LSP type	Neutralino	Bino-like neutralino
Number of models generated:		
Sampled	20,000	437,500
Successful generation	16,883	370,058
Correct LSP type	15,537	286,308
Pass DM relic density constraint $\Omega h^2 \leq 0.12$	N/A	11,163
Pass LEP chargino mass constraint	13,931	10,165
120 GeV $<$ m(h) $<$ 130 GeV	12,280	8,897
Number of models processed:		
$m(\tilde{\chi}_1^{\pm}) < 1200$ GeV and $\sigma_{\mathrm{EW}} > 7 \times 10^{-5}$ pb	10,063	8,771
Successful truth-level evaluation	9,726	8,725
Reco-level evaluation	699	733

Results- EWKino masses (EWKino scan)

- External constraints remove most models inside contour.
- Improved sensitivity to compressed models relative to run 1

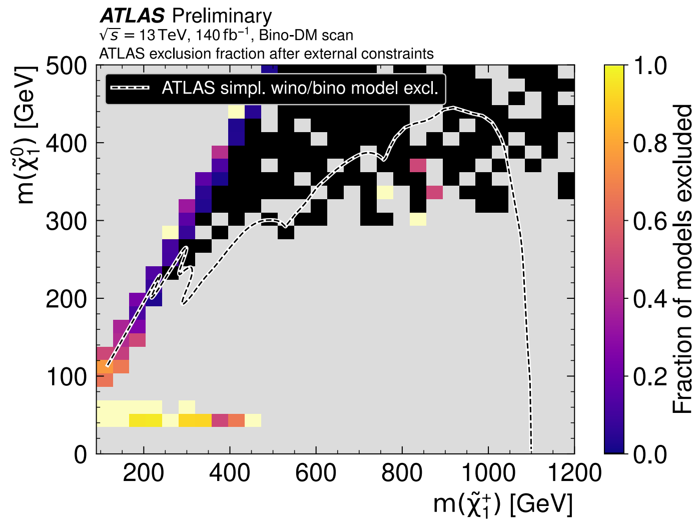
- Large exclusion fraction outside contour driven by wino-like LSP models with a bino/higgsino-like $\tilde{\chi}_2^0$

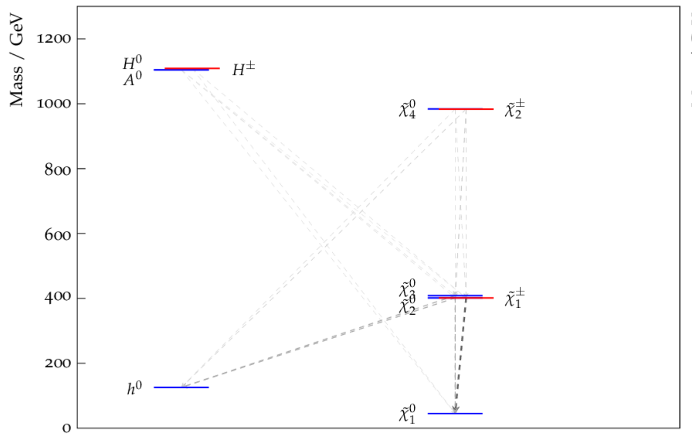




Key messages of this work

- Significant extension of the run 1 constraints on (EWK) pMSSM parameter space.
- The Higgs and Z-boson ”funnel regions” where a low-mass neutralino would not over-saturate the relic density are almost completely excluded.
- Models that survive the ATLAS search programme include spectra that deviate from simplified models- due to different hierarchies and/or mixed decay modes.





Conclusions

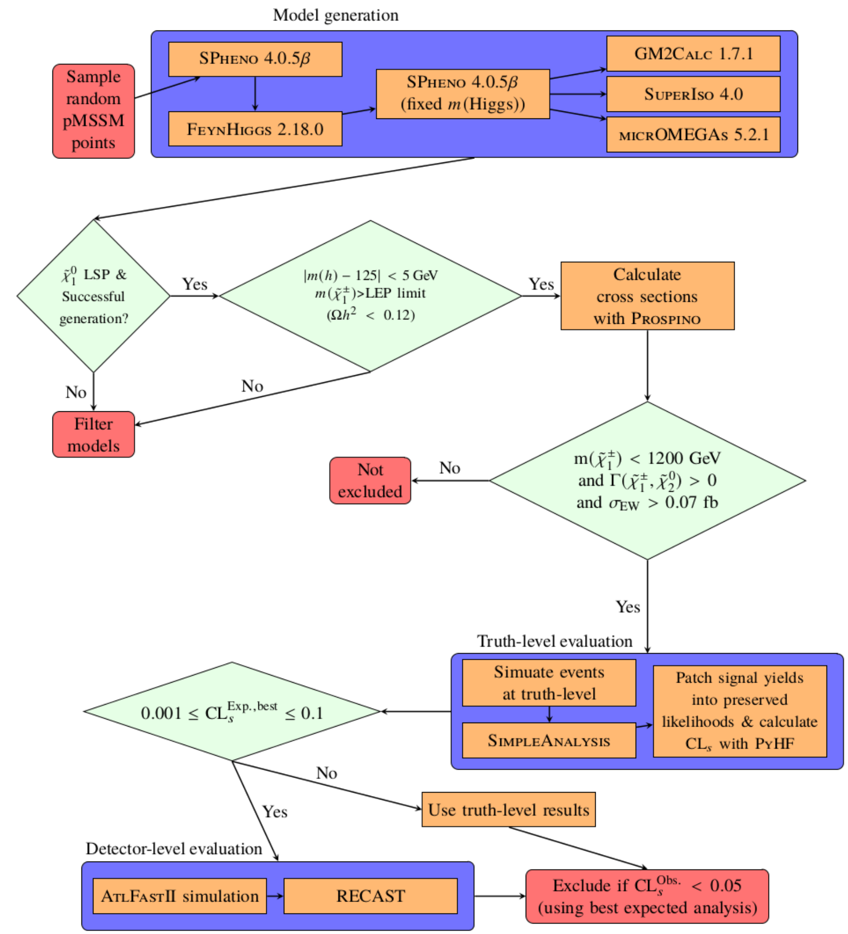
p.s. Die hard is not a Christmas movie…

- When simplified model assumptions are relaxed exclusion constraints are typically weaker.
- First (EWK) pMSSM reinterpretation effort from run 2 aims to quantify the sensitivity of ATLAS searches in broader SUSY parameter space and demonstrate complementarity with external constraints.
- Further reinterpretation efforts planned, and results will be used to design new searches for run 3 (and beyond).

Have a great Christmas break!

Scanning the pMSSM …

- **pMSSM** = 19-dimensional space of viable SUSY models
- **Randomly sample** pMSSM parameters (flat prior)
- **Re-interpret** Run-2 analyses on pMSSM models
- **EWK scan** targets electroweakinos (with other sparticles decoupled) which are the sparticles most relevant to dark matter phenomenology.
- **Summarises** ATLAS Run-2 sensitivity to EWKinos and highlights areas to be targeted with future searches



External constraints considered

Note- when applying DD constraints- all cross-sections are scaled by $\Omega h^2/0.12$

When referring to external constraints throughout the paper:

1. All models = all models generated passing the LEP chargino mass constraint and the Higgs mass window.

2. All non-DM external constraints= flavour and precision EWK constraints (note for the bino-DM scan this is essentially all constraints except the direct-detection constraints).

3. All external constraints= flavour + precision EWK + dark matter (relic density + DD)

(2)

(3)

Category	Constraint	Lower bound	Upper bound	Notes
Flavour	$\mathrm{BR}(b \to s\gamma)$	3.11×10^{-4}	3.87×10^{-4}	2022 PDG average [46]
	$\mathrm{BR}(B_s \to \mu\mu)$	1.87×10^{-9}	4.31×10^{-9}	Most recent LHCb result [47]
	$\mathrm{BR}(B^+ \to \tau\nu)$	6.10×10^{-5}	1.57×10^{-4}	2022 PDG average [46]
Precision EW	$\Delta\rho$	-0.0004	0.0018	Updated global electroweak fit by `GFitter` group [48] (not including CDF W-mass measurement [49])
	$\Gamma_{\mathrm{inv}}(Z)$	$--$	2 MeV	Precision electroweak measurements on the Z-resonance from experiments at the SLC and LEP colliders [50].
	$\mathrm{m}(W)$	80.347 GeV	80.407 GeV	2022 PDG result (excluding CDF W-mass measurement [49]) [46] but with the 2σ window expanded by 6 MeV to allow for uncertainty due to the top-quark mass in the MSSM Higgs calculation [51]
Dark matter	DM relic density	$--$	0.12	Latest bound from Planck [52]
	DD $\sigma_{\text{Spin-independent}}$			Exclusion contour on direct-detection of DM from the LZ collaboration [53]
	DD $\sigma_{\text{Spin-dependent}}$			Exclusion contour on direct-detection of DM from PICO-60 [54]

In most cases the constraints are the $\pm 2\sigma$ bounds from the published values- we plan to add this to the paper.