Seeking a coherent explanation of LHC excesses for compressed spectra

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Based on arXiv:2404.12423
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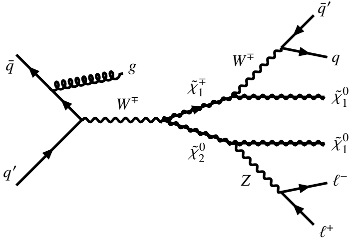
SMALL EXCESSES IN $2\ell + E_{\mathrm{T}}^{\mathrm{MISS}}$...

- ATLAS and CMS target compressed EWinos in soft leptons $(2/3\ell) + E_{\mathrm{T}}^{\mathrm{miss}}$ channels [1, 2, 3, 4, 5]



- Results interpreted for pure higgsino or wino LSP
- 2ℓ analyses show 1–2σ excesses corresponding to $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 10\text{–}30$ GeV
  - Overlapping excesses in the monojet channel [6, 7, 8]?

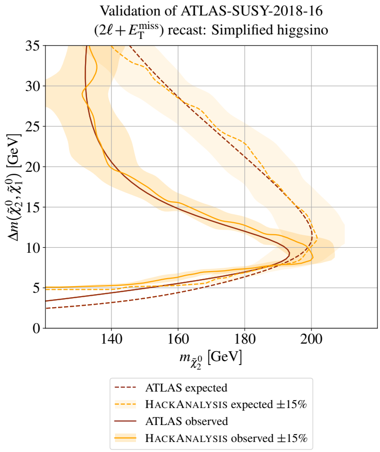
Recasting the ATLAS $2/3\ell$ analyses

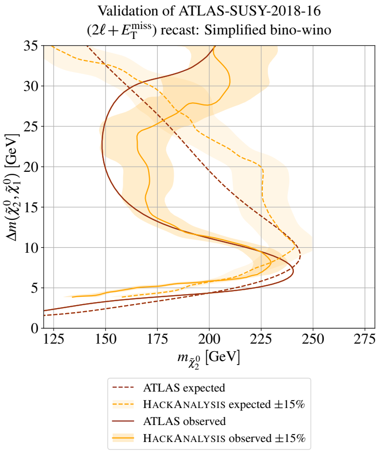
- ATLAS-SUSY-2018-16: 2ℓ and $1\ell 1T$ electroweakino channels are recast in HackAnalysis (HA) v2
- Multiple technical challenges:
  - RJR variables require RestFrames [9], thus `root`
  - Results are sensitive to $m_{\ell\ell}$ distributions so that Pythia 8 cannot be used to handle the three-body electroweakino decays
  - Signal efficiencies are of $\mathcal{O}(10^{-5})$, requiring large samples
- ATLAS-SUSY-2019-09: off-shell WZ 3ℓ selection is recast in HA
  - Lepton reconstruction efficiencies are scraped
  - Object-based $E_{\mathrm{T}}^{\mathrm{miss}}$ significance computed in HA using momentum resolution uncertainties taken from ATLAS [10, 11]
- Validations use ATLAS cutflows and reproduced exclusion plots; agreement is excellent

Simulation and analysis toolchain

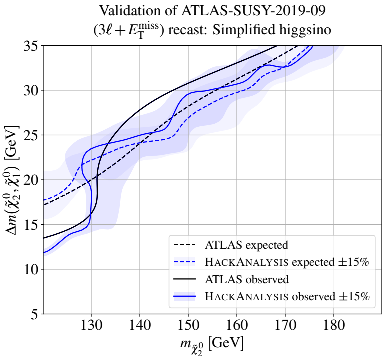
- Relevant processes simulated in each model as follows:
  - Hard events with ≤ 2 hard jets generated using MG5_aMC, including full decay chains in matrix elements
  - Matching, showering, and hadronization performed with Pythia 8
  - Normalizations computed at best available accuracy; for MSSM we use Resummino [12] at NLO + NLL
- Samples range in size from 3.2 M to 20 M events per parameter point, with $\mathcal{O}(10)$–$\mathcal{O}(100)$ points considered for each model
- ATLAS and CMS monojet searches implemented in MadAnalysis 5 and available on the Public Analysis Database (PAD), but ported to HA v2 to streamline the workflow
- Efficiencies computed by HA; statistical analysis performed by Spey [13]

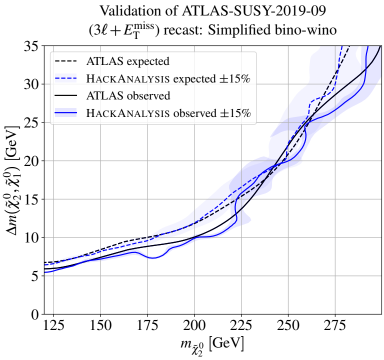
ATLAS-SUSY-2018-16 VALIDATION





ATLAS-SUSY-2019-09 VALIDATION





What's the plan?

- With validated ATLAS $2/3\ell$ recasts (and monojets, with caveats), we can try to find suitable models
  - Why not also try to produce a dark matter candidate?
  - Other minimal(ish) SUSY scenarios seem like good candidates
  - What about non-SUSY models with different topologies? $m_{\ell\ell}$ distributions should differ
- Four candidate models: scan parameter spaces to find suitable spectra, compute LHC cross sections and (where applicable) Ωh^2, apply recasts
- For each model and each analysis compute expected/observed limits at 95% CL
- Identify a best-fit point ($\hat{\mu} \approx 1$) and a significant point (lowest p-value); if we get lucky, we can find points with good fit and significance for all analyses

Candidate 1: MSSM with decoupled higgsinos

- Already looked at simplified (pure) higgsinos; ATLAS interpreted soft leptons for simplified bino-wino LSP
  - Bino-winos not symmetric like higgsinos; instead $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$
  - Mixing and decays fixed, curiously with 2–10% higgsino admixture; physical masses changed by hand
- (Mostly) bino LSP is a viable DM candidate, with coannihilations important in the parameter space relevant to soft-lepton analyses
- Straighforward to perform a “realistic” scan over (M_1, M_2)
- Higgsinos decoupled with $\mu = 2$ TeV; first- and second-generation sfermions taken to $\mathcal{O}(10)$ TeV for simplicity

Candidate 2: NMSSM with singlino LSP

- MSSM + singlet superfield → five neutralinos:

$$\mathcal{W} \supset \mu \mathcal{H}_\mathrm{u} \mathcal{H}_\mathrm{d} \to \mathcal{W}_\mathrm{NMSSM} \supset \lambda \mathcal{S} \mathcal{H}_\mathrm{u} \mathcal{H}_\mathrm{d} + \frac{1}{3}\kappa \mathcal{S}^3$$

- Light S a bit lighter than light higgsinos (with small mixing) solves higgsino underabundance problem
- Singlino-higgsino compression and mixing tuned with λ, κ
- Light $\tilde{\chi}_3^0$ offers additional signal processes
- More parameters impose greater computing needs for scanning—in the end we want

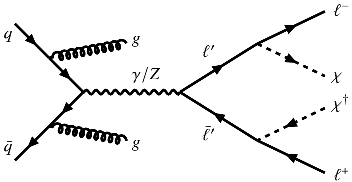
$$\lambda\langle S\rangle \in [100, 250]\ \mathrm{GeV}, \quad \kappa \in [0.001, 0.02], \quad \lambda \approx 2\kappa + \epsilon$$

Candidate 3: VLL doublet

- SM + scalar DM χ + weak doublet $\Psi^\intercal = (\nu', \ell')$ of vector-like leptons:

$$\mathcal{L} \supset \lambda_I\, \chi(\bar{\nu}'\nu_{\mathrm{L}I} + \bar{\ell}'\ell_{\mathrm{L}I}) + \mathrm{H.c.}$$

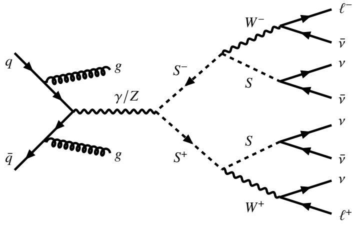
- VLL pair production produces 2ℓ/monojet signals



- VLL and DM masses independently tuned, look for $\Delta m \sim 0$–30 GeV
- χ annihilates to ν, ℓ and coannihilates with ν', ℓ'

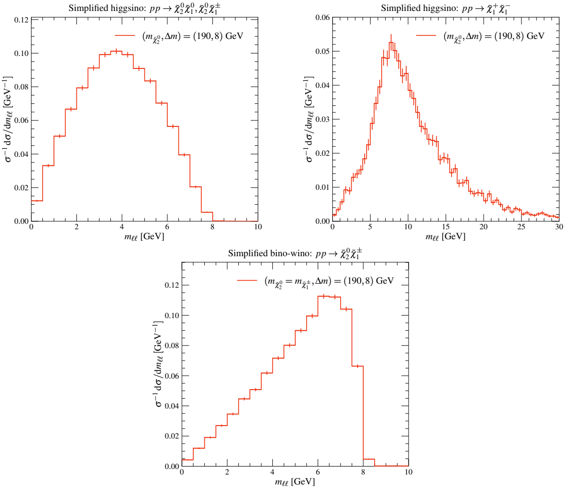
Candidate 4: Type-II seesaw

- SM + $Y = 1$ weak triplet $\Delta \to h, S, S^{\pm}, S^{\pm\pm}$
- Tree-level generation of Majorana neutrino masses
- If $m_S < m_{S^{\pm}} < m_{S^{\pm\pm}}$, $v_{\Delta} \ll 1$ GeV, and h is SM like, $S \to \nu\bar{\nu}$
- Charged scalar decays via off-shell W bosons produce 2ℓ/monojet signals

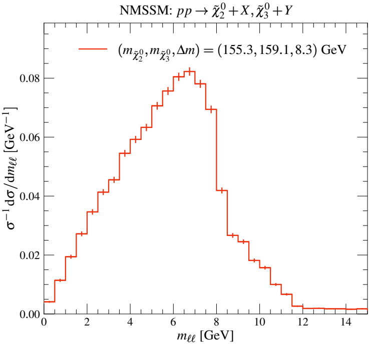


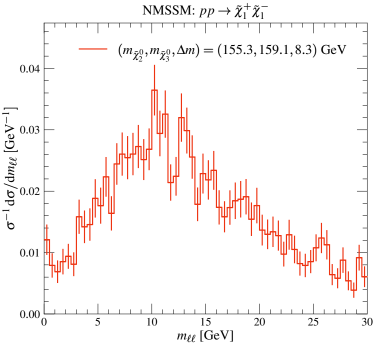
- Triplet scalar splitting controlled by $\mathcal{L} \supset -\lambda_4\, \Phi^{\dagger}\Delta\Delta^{\dagger}\Phi$
- Scalars known to be weakly constrained for small $\lambda_4 < 0$

$m_{\ell\ell}$ distributions: simplified MSSM



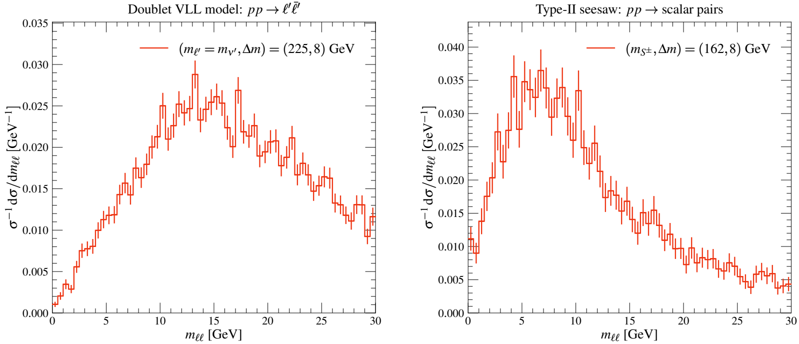
$m_{\ell\ell}$ DISTRIBUTIONS: NMSSM





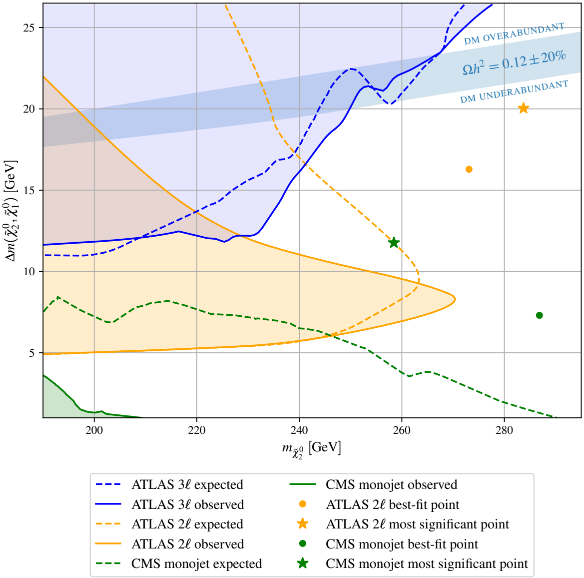
- $X \in \{\tilde{\chi}_1^\pm, \tilde{\chi}_3^0\}$, $Y \in \{\tilde{\chi}_1^\pm, \tilde{\chi}_2^0\}$
- $\tilde{\chi}^+ \tilde{\chi}^-$ similar to higgsinos but $\tilde{\chi}^0$ processes have higgsino and bino-wino features

$m_{\ell\ell}$ DISTRIBUTIONS: NON-SUSY



- Much harder leptons from direct $\ell' \to \chi\ell$ decays
- Type-II seesaw somewhat similar to $\tilde{\chi}^+\tilde{\chi}^-$ since $\ell^+\ell^-$ come from off-shell $W^\pm$

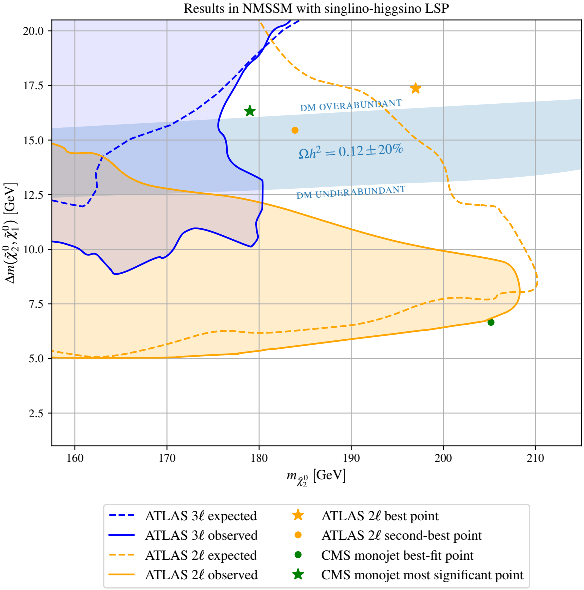
Results in MSSM with decoupled higgsinos



MSSM SIGNIFICANT POINTS

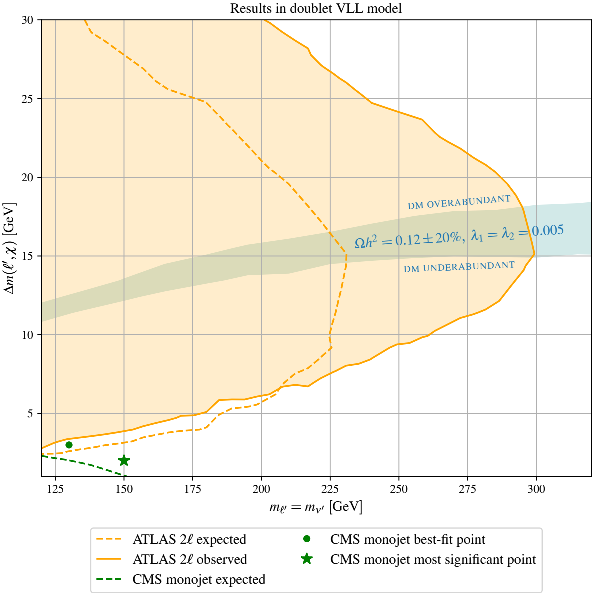
Point $(m_{\tilde{\chi}_2^0}, \Delta m)$ [GeV]	● ATLAS 2ℓ best fit $(273, 16.3)$	★ ATLAS 2ℓ most significant $(284, 20.0)$	● CMS monojet best fit $(287, 7.30)$	★ CMS monojet most significant $(258, 11.8)$
$(p, \hat{\mu})$ [ATLAS 2ℓ]	$(0.047, 1.12)$	$(0.041, 1.26)$	$(> 0.5, < 0.1)$	$(0.290, 0.30)$
$(p, \hat{\mu})$ [ATLAS 3ℓ]	$(> 0.5, < 0.1)$	$(0.426, < 0.1)$	$(> 0.5, < 0.1)$	$(> 0.5, < 0.1)$
$(p, \hat{\mu})$ [CMS monojet]	$(0.098, 1.58)$	$(0.065, 2.33)$	$(0.049, 1.15)$	$(0.044, 1.40)$
$(p, \hat{\mu})$ [ATLAS monojet]	$(0.277, 1.21)$	$(0.163, 2.44)$	$(0.127, 1.53)$	$(0.277, 0.879)$
M_1 [GeV]	248.0	254.6	269.9	238.2
M_2 [GeV]	241.7	251.3	254.0	228.6
m_h [GeV]	127.0	126.5	126.8	126.8
$m_{\tilde{\chi}_1^0}$ [GeV]	256.8	263.7	279.5	246.7
$m_{\tilde{\chi}_2^0}$ [GeV]	273.1	283.7	286.8	258.4
$m_{\tilde{\chi}_1^\pm}$ [GeV]	273.3	283.9	287.0	258.6
$(N_{11}, N_{12}, N_{13}, N_{14})$	$(0.9995, -0.0211, 0.0232, -0.0038)$	$(0.9996, -0.0175, 0.0231, -0.0039)$	$(0.9984, -0.0501, 0.02443, -0.0043)$	$(0.9993, -0.0284, 0.0235, -0.0038)$
$(N_{21}, N_{22}, N_{23}, N_{24})$	$(0.0220, 0.9990, -0.0392, 0.0066)$	$(0.0184, 0.9990, -0.0394, 0.0068)$	$(0.0511, 0.9979, -0.0386, 0.0068)$	$(0.0293, 0.9988, -0.0390, 0.0063)$

- 2ℓ best fit ● shows modest overlap with CMS monojet
- Most significant ★ in vicinity of correct Ωh^2
- Monojet best fit ● with $\Delta m < 10$ GeV invisible to 2ℓ analysis


Results in NMSSM with singlino-higgsino LSP
DM OVERABUNDANT
$\Omega h^2 = 0.12 \pm 20\%$
DM UNDERABUNDANT
$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ [GeV]
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
160
170
180
190
200
210
$m_{\tilde{\chi}_2^0}$ [GeV]
ATLAS 3ℓ expected
ATLAS 3ℓ observed
ATLAS 2ℓ expected
ATLAS 2ℓ observed
ATLAS 2ℓ best point
ATLAS 2ℓ second-best point
CMS monojet best-fit point
CMS monojet most significant point

NMSSM SIGNIFICANT POINTS

Point	★ ATLAS 2ℓ best	● ATLAS 2ℓ second best	● CMS monojet best fit	★ CMS monojet most significant
$(m_{\tilde{\chi}_2^0}, \Delta m)$ [GeV]	$(197, 17.4)$	$(184, 15.5)$	$(205, 6.66)$	$(179, 16.3)$
$(p, \hat{\mu})$ [ATLAS 2ℓ]	$(0.041, 0.97)$	$(0.044, 0.80)$	$(0.435, < 0.1)$	$(0.071, 0.64)$
$(p, \hat{\mu})$ [ATLAS 3ℓ]	$(0.446, 0.12)$	$(> 0.5, 0.12)$	$(> 0.5, 0.71)$	$(> 0.5, 0.13)$
$(p, \hat{\mu})$ [CMS monojet]	$(0.132, 3.00)$	$(0.129, 2.65)$	$(0.712, 1.91)$	$(0.051, 3.79)$
$(p, \hat{\mu})$ [ATLAS monojet]	$(0.277, 2.44)$	$(0.277, 2.02)$	$(0.127, 2.96)$	$(0.277, 2.08)$
μ_{eff} [GeV]	189.3	177.0	199.1	172.6
κ	0.0157	0.0108	0.0025	0.0146
λ	0.0330	0.0226	0.0050	0.0309
$\tan\beta$	19.71	25.94	10.70	12.82
$M_{\tilde{t}}^2$ [GeV^2]	8.06×10^7	7.20×10^7	3.42×10^7	9.12×10^7
A_t [GeV]	2.61×10^3	-1.28×10^3	2.07×10^3	-2.64×10^3
A_λ [GeV]	-34.60	-92.77	189.4	192.0
A_κ [GeV]	-43.01	-8.771	-161.3	-55.91
m_h [GeV]	124.0	123.4	123.0	122.6
$m_{\tilde{\chi}_1^0}$ [GeV]	179.6	168.5	198.5	162.7
$m_{\tilde{\chi}_2^0}$ [GeV]	197.0	183.9	205.2	179.0
$m_{\tilde{\chi}_1^\pm}$ [GeV]	198.1	185.5	207.1	180.3
$m_{\tilde{\chi}_3^0}$ [GeV]	199.9	187.3	209.0	182.1
$(N_{11}, N_{12}, N_{13}, N_{14}, N_{15})$	$(0.0042, -0.0070, 0.1547, -0.1683, 0.9735)$	$(0.0032, -0.0053, 0.1201, -0.1299, 0.9841)$	$(0.0016, -0.0026, 0.0580, -0.0597, 0.9965)$	$(0.0041, -0.0069, 0.1479, -0.1622, 0.9756)$
$(N_{21}, N_{22}, N_{23}, N_{24}, N_{25})$	$(-0.0173, 0.0289, -0.6932, 0.6827, 0.2284)$	$(-0.0172, 0.0287, -0.7004, 0.6907, 0.1767)$	$(-0.0184, 0.0312, -0.7077, 0.7006, 0.0832)$	$(-0.0176, 0.0294, -0.6951, 0.6838, 0.0219)$
$\text{Im}\,(N_{31}, N_{32}, N_{33}, N_{34}, N_{35})$	$(-0.0134, 0.0226, 0.7039, 0.7097, 0.0110)$	$(-0.0137, 0.0231, 0.7036, 0.7101, 0.0080)$	$(-0.0126, 0.0216, 0.7041, 0.7097, 0.0016)$	$(-0.0131, 0.0220, 0.7035, 0.7100, 0.0116)$


Results in doublet VLL model
30
25
20
15
10
5
125
150
175
200
225
250
275
300
$\Delta m(\ell', \chi)$ [GeV]
$m_{\ell'} = m_{\nu'}$ [GeV]
DM OVERABUNDANT
$\Omega h^2 = 0.12 \pm 20\%,\ \lambda_1 = \lambda_2 = 0.005$
DM UNDERABUNDANT
ATLAS 2ℓ expected
ATLAS 2ℓ observed
CMS monojet expected
CMS monojet best-fit point
CMS monojet most significant point

Non-SUSY significant points

Point ($m_{\ell'} = m_{\nu'}, \Delta m(\ell', \chi)$) [GeV]	● CMS monojet best fit (273, 16.3)	★ CMS monojet most significant (284, 20.0)
Significance (p-value)	0.047	0.041
Signal strength $\hat{\mu}$	1.12	1.26

- VLL model has no points with $2/3\ell$ discovery potential: 2ℓ observed limits stronger than expected
- Monojet points correspond to underabundant DM
- Type-II seesaw unconstrained by all searches:

	$\mathrm{CL}_s^{\mathrm{exp}}$	$\mathrm{CL}_s^{\mathrm{obs}}$	p-value	$\hat{\mu}$
ATLAS 2ℓ	0.387	0.620	0.050	2.06
ATLAS 3ℓ	0.611	0.615	≥ 0.5	0.62
CMS monojet	0.270	0.395	0.081	1.17
ATLAS monojet	0.553	0.399	0.277	0.72

- $(m_{S^\pm}, \Delta m(S^\pm, S)) = (95, 5)$ GeV
- Excesses still visible ($\mathrm{CL}_s^{\mathrm{obs}} > \mathrm{CL}_s^{\mathrm{exp}}$)

Outlook

- We explored excesses in the soft lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ channel for four well motivated models
- Excesses might have some overlap with monojets for pure higgsinos [8]; we now find modest compatibility in bino-wino MSSM and singlino-higgsino NMSSM, but poor fits for two non-SUSY models
- With this puzzle unresolved and a workflow worked out, we have choices for future work:
  - Detailed scans of other popular models (go ahead, call them out)
  - Cook up model(s) specifically for these excesses
  - Improved statistical treatments (combined likelihood, allowed signal strengths)

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Thank you for your attention

I am happy to answer questions if we have time

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Bonus material

ATLAS-SUSY-2018-16 YIELDS

		SR $m_{\ell\ell}$ bin [GeV]							
		[1,2]	[2,3]	[3.2,5]	[5,10]	[10,20]	[20,30]	[30,40]	[40,60]
SR–E high ee	Observed			1	**16**	13	8	8	18
	Fitted SM events			0.7 ± 0.4	10.3 ± 2.5	12.1 ± 2.2	10.1 ± 1.7	10.4 ± 1.7	19.3 ± 2.5
SR–E high $\mu\mu$	Observed	5	5	*0*	9	23	*3*	*5*	20
	Fitted SM events	3.4 ± 1.2	3.5 ± 1.3	3.9 ± 1.3	11.0 ± 2.0	17.8 ± 2.7	8.3 ± 1.4	10.1 ± 1.5	19.6 ± 2.3
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		
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		
SR–E low ee	Observed			7	11	16	16	10	*9*
	Fitted SM events			5.3 ± 1.5	8.6 ± 1.8	16.7 ± 2.5	15.5 ± 2.6	12.9 ± 2.1	18.8 ± 2.2
SR–E low $\mu\mu$	Observed	*9*	7	7	12	17	18	16	**44**
	Fitted SM events	15.4 ± 2.4	8.0 ± 1.7	6.5 ± 1.6	11.3 ± 1.9	15.6 ± 2.3	16.7 ± 2.3	15.3 ± 2.0	35.9 ± 3.3

NEUTRALINO DECAYS TO LEPTONS

- Full differential decay rate, $\tilde{\chi}_2^0 \to Z^* + \tilde{\chi}_1^0$:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}m_{\ell\ell}} = C m_{\ell\ell} \frac{\{m_{\ell\ell}^4 - m_{\ell\ell}^2[(\Delta m)^2 + M^2] + (M\Delta m)^2\}^{1/2}}{(m_{\ell\ell}^2 - M_Z^2)^2} \times \{-2m_{\ell\ell}^4 + m_{\ell\ell}^2[2M^2 - (\Delta m)^2] + (M\Delta m)^2\}$$

$M, \Delta m = m_{\tilde{\chi}_2^0} \pm m_{\tilde{\chi}_1^0}$: $2M^2 - (\Delta m)^2$ sensitive to signed $\tilde{\chi}^0$ masses

- "Flat" decay rate used by PYTHIA 8:

$$\frac{\mathrm{d}\Gamma^{\mathrm{flat}}}{\mathrm{d}m_{\ell\ell}} = C^{\mathrm{flat}}\, m_{\ell\ell}\, \{m_{\ell\ell}^4 - m_{\ell\ell}^2[(\Delta m)^2 + M^2] + (M\Delta m)^2\}^{1/2}$$

Flat vs. accurate $m_{\ell\ell}$