Taking aim at the wino-higgsino plane with the LHC

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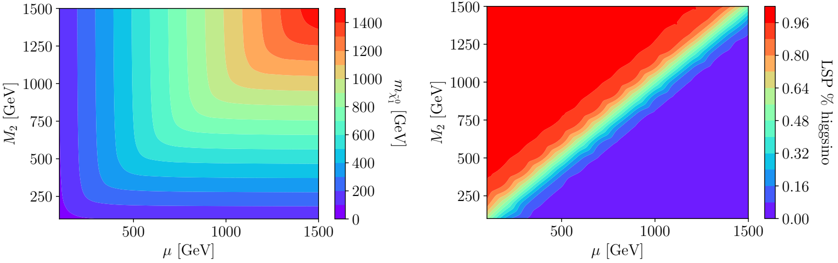
Studying MSSM with wino/higgsino LSP

- LHC bounds on weakly interacting sparticles $\ll$ color-charged states: lots of potential progress with Run 3
- Some recent progress in difficult parameter space with compressed electroweakinos
- Compressed spectra $(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0)$ are common in scenarios with light μ and/or M_2: higgsino and/or wino-like LSP
- Why study these, other than to cover allowed parameter space?
  - $|\mu| \sim 200\,\mathrm{GeV}$ motivated by naturalness
  - (Even if "unnatural", measuring μ would shed light on EWSB)
  - Wino LSP occurs naturally in AMSB scenarios
  - Wino/higgsino DM often underabundant (through freeze out) but alternate cosmologies/additional dark particles can work
- This work: limits + HL-LHC projections in the (μ, M_2) plane

Compressed EWinos: parameter space

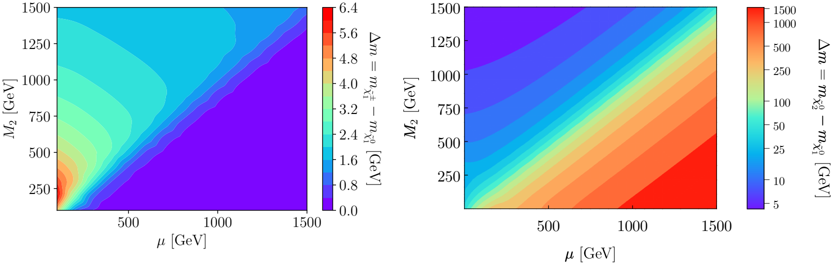
- LHC reach is highly sensitive to EWino mass splittings: even $\mathcal{O}(1)$ GeV splitting changes favor one analysis over others
- Spectra computed with SPheno v. 4.0.5 incl. NLO corrections (We take $\mu, M_2 \ll M_1$ throughout, and $\tan\beta = 10$)



- Current analyses probe $m_{\tilde{\chi}_1^0} \sim 200\,\text{GeV}$
- We also want to explore the "well mixed" region with $\mu \sim M_2$

COMPRESSED EWINOS: MASS SPLITTINGS

- Of particular significance are $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$

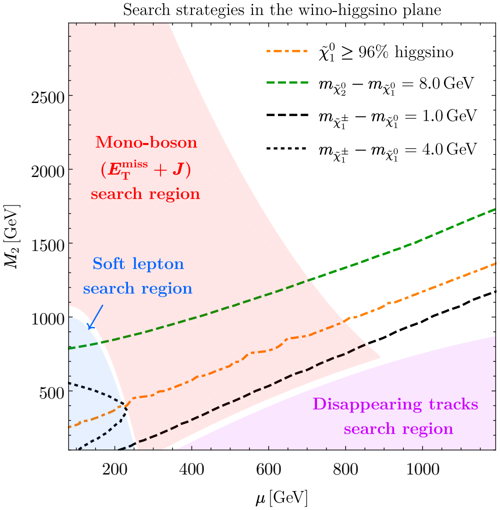


- Wino-like scenarios feature small splittings for $\{\tilde{\chi}_1^0, \tilde{\chi}_1^\pm\}$; higgsino-like scenarios have all three EWinos nearly degenerate
- $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim 7\,\text{GeV}$ for $\mathcal{O}(100)\,\text{GeV}$ well-mixed EWinos: this entire parameter space is "compressed", but not all compression is created equal

Compressed EWinos: search strategies

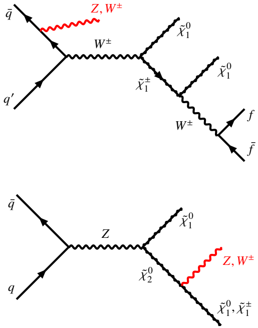
- Least compression, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \gtrsim 5\,\text{GeV}$
  - EWinos decay through off-shell W/Z and may produce leptons that are soft but observable
  - CMS-SUS-16-048 [1] ($35.9\,\text{fb}^{-1}$) looks for soft leptons from $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$
  - ATLAS-SUSY-2019-09 [2] ($139\,\text{fb}^{-1}$) looks for trilepton + E_T^miss
  - Also: hadronic diboson (ATLAS-SUSY-2018-41 [3]), monojet
- Extreme compression, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \lesssim 0.5\,\text{GeV}$
  - Leptons and jets too soft + $\tilde{\chi}_1^\pm$ lives long enough to deposit a track
  - CMS-EXO-19-010 [4] ($101\,\text{fb}^{-1}$) looks for "disappearing" tracks
- Moderate compression, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \in (1, 5)\,\text{GeV}$
  - Charginos decay promptly, but decay products are too soft... unless EWinos are produced in association with something visible
  - ATLAS-EXOT-2016-23 [5] ($36.1\,\text{fb}^{-1}$) seeks hadronic W/Z + E_T^miss
  - We upgrade this analysis to significantly increase its sensitivity

Compressed EWinos: search strategies



ATLAS-EXOT-2016-23: HADRONIC W/Z

- Typical events have missing energy with ≥ 2 jets or ≥ 1 large-radius jet (anti-k_t $R = 1.0$)
- Hadronic W/Z can come from ISR and/or EWino decays
- Search can be sensitive to both higgsino- and wino-like LSP if we include all light EW pairs $\{\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0\}$
- For $\mathcal{O}(100)$ GeV EWinos, $\sigma(pp \to \tilde{\chi}\tilde{\chi} + V) \sim (1\text{–}10)$ fb at NNLO + approx. NNLL
- Multiple non-overlapping SRs in two topologies (narrow vs. fat jet) classified by $N_{b\text{-jet}}$

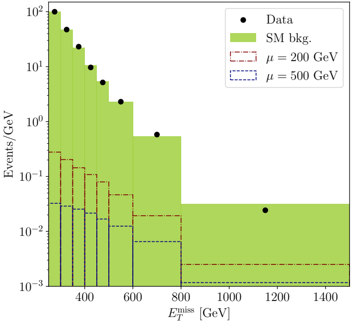


ATLAS-EXOT-016-23: HADRONIC W/Z

	Merged topology				Resolved topology	
$E_{\mathrm{T}}^{\mathrm{miss}}$	$> 250\,\mathrm{GeV}$				$> 150\,\mathrm{GeV}$	
Jets, leptons	$\geq 1J,\ 0\ell$				$\geq 2j,\ 0\ell$	
b-jets	no b-tagged jets outside of J				≤ 2 b-tagged small-R jets	
Multijet suppression	$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\ J \text{ or } jj) > 2\pi/3$ $\min_{i=1,2,3}\left[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}},\ j_i)\right] > \pi/9$ $\left\lvert\vec{p}_{\mathrm{T}}^{\ \mathrm{miss}}\right\rvert > 30\,\mathrm{GeV}$ or ≥ 2 b-jets $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\ \mathrm{miss}}) < \pi/2$					
Signal properties					$p_{\mathrm{T}}^{j_1} > 45\,\mathrm{GeV}$ $\sum_i p_{\mathrm{T}}^{j_i} > 120\ (150)\,\mathrm{GeV}$ for 2 (≥ 3) jets	
Signal region	0b-HP	0b-LP	1b-HP	1b-LP	0b-Res	1b-Res
J or jj	HP	LP	HP	LP	$\Delta R_{jj} < 1.4$ and $m_{jj} \in [65, 105]\,\mathrm{GeV}$	
b-jet	no b-jet	no b-jet	1 b-jet	1 b-jet	no b-jet	1 b-jet

Improving the mono-boson search

- Observation: ATLAS provides background yields binned by $E_{\mathrm{T}}^{\mathrm{miss}}$ though selection in each topology is flat



- EWino signal $E_{\mathrm{T}}^{\mathrm{miss}}$ diminishes slower than backgrounds $\Longrightarrow$ tighter $E_{\mathrm{T}}^{\mathrm{miss}}$ cuts can improve search sensitivity

(Vague) implementation details

- $N_{\text{event}} = 5 \times 10^4$ samples with $\delta m \leq 100\,\text{GeV}$ produced in MG5_aMC v. 2.7.2, showered with Pythia 8 v. 8.245
- Cross sections (cumulative) computed at NNLO + aNNLL with Resummino v. 3.1.2
- Detector simulation in Delphes 3, selections with ExRootAnalysis
- Merged (fat-jet) topology SR with 0 b-jets has best sensitivity
- Compute joint likelihood $\mathcal{L}$ and TS

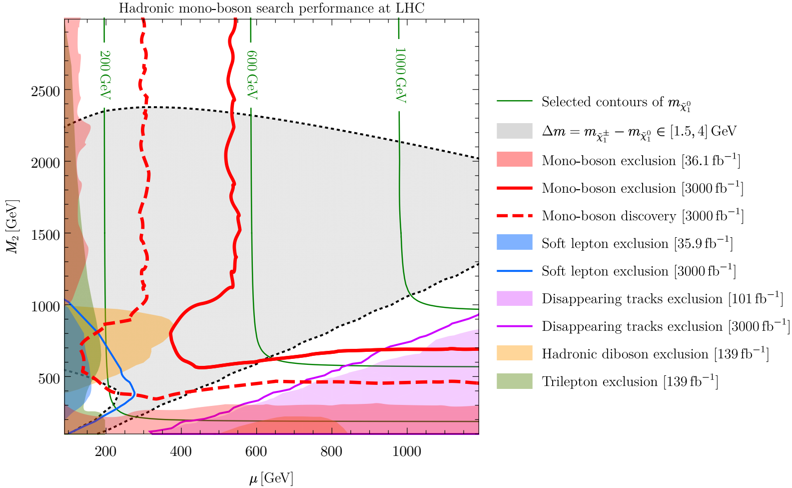
$$q_\mu^m = -2 \ln \frac{\mathcal{L}(m \mid \mu, \hat{\hat{b}})}{\mathcal{L}(m \mid \hat{\mu}, \hat{b})}$$

for each EWino hypothesis assuming Poisson data + Gaussian background, then 95% CL limit, discovery potential...

OTHER REINTERPRETATIONS

- CMS soft leptons (higgsino-like only): implemented in MADANALYSIS 5; very low efficiencies require $\mathcal{O}(10^5)$ event samples
- ATLAS diboson (mostly higgsino-like): results given in (μ, M_2); shamelessly stolen
- ATLAS trilepton (higgsino-like only): interpreted already for higgsino-like LSP; mapped from physical masses onto (μ, M_2)
- CMS disappearing tracks (wino-like only): implemented in MA5; extremely low efficiencies but good reach nonetheless
- Monojet: 1 ATLAS [6] + 1 CMS analysis [7] implemented in MA5; work ongoing at Paris but I can sketch results
    - CMS and ATLAS results are pretty different; CMS is stronger but imposes fairly weak limits

Results


Hadronic mono-boson search performance at LHC
200 GeV
600 GeV
1000 GeV
2500
2000
1500
1000
500
M_2 [GeV]
200
400
600
800
1000
μ [GeV]
Selected contours of $m_{\tilde{\chi}_1^0}$
$\Delta m = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \in [1.5, 4]$ GeV
Mono-boson exclusion [36.1 fb^{-1}]
Mono-boson exclusion [3000 fb^{-1}]
Mono-boson discovery [3000 fb^{-1}]
Soft lepton exclusion [35.9 fb^{-1}]
Soft lepton exclusion [3000 fb^{-1}]
Disappearing tracks exclusion [101 fb^{-1}]
Disappearing tracks exclusion [3000 fb^{-1}]
Hadronic diboson exclusion [139 fb^{-1}]
Trilepton exclusion [139 fb^{-1}]

Results

- Striking complementarity between searches: dependence on $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ is clear
- Wino-like LSP limits are better right now than higgsino-like: $\geq 500\,\mathrm{GeV}$ vs. $150\text{–}300\,\mathrm{GeV}$
- $36.1\,\mathrm{fb}^{-1}$ hadronic mono-boson search competitive today (after our $E_\mathrm{T}^\mathrm{miss}$ enhancement) with full Run 2 searches... shows good potential to (a) improve with statistics, (b) probe well-mixed region
- Limitation: searches recast in MA5 (and our own analysis) can be stats-rescaled to provide HL-LHC projections; not so for mapped/pasted limits
- HL-LHC can exclude most space with $\mu, M_2 \lesssim 500\,\mathrm{GeV}$... ruling out "natural" MSSM?

Outlook

- We have explored multiple constraints on higgsino- and/or wino-like LSP scenarios in the MSSM
- Results are presented in fundamental (μ, M_2) plane based on an array of recasts and a re-analyzed ATLAS hadronic mono-boson search
- Joint-likelihood analysis based on binned $E_{\mathrm{T}}^{\mathrm{miss}}$ yields provides tighter EWino constraints than simple recast; *viz.* earlier work on higgsinos and sneutrinos
- Currently examining what parameter space can accommodate $\sim 2\sigma$ excesses in ATLAS-SUSY-2018-16 [8]

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Thank you for your attention

I am happy to answer questions if we have time

Bibliography (1)

[1] A. M. Sirunyan *et al.* (CMS), Phys. Lett. B **782**, 440 (2018), arXiv:1801.01846 [hep-ex] .

[2] G. Aad *et al.* (ATLAS), Eur. Phys. J. C **81**, 1118 (2021), arXiv:2106.01676 [hep-ex] .

[3] G. Aad *et al.* (ATLAS), Phys. Rev. D **104**, 112010 (2021), arXiv:2108.07586 [hep-ex] .

[4] A. M. Sirunyan *et al.* (CMS), Phys. Lett. B **806**, 135502 (2020), arXiv:2004.05153 [hep-ex] .

[5] M. Aaboud *et al.* (ATLAS), J. High Energy Phys. **10**, 180, arXiv:1807.11471 [hep-ex] .

[6] G. Aad *et al.* (ATLAS), Phys. Rev. D **103**, 112006 (2021), arXiv:2102.10874 [hep-ex] .

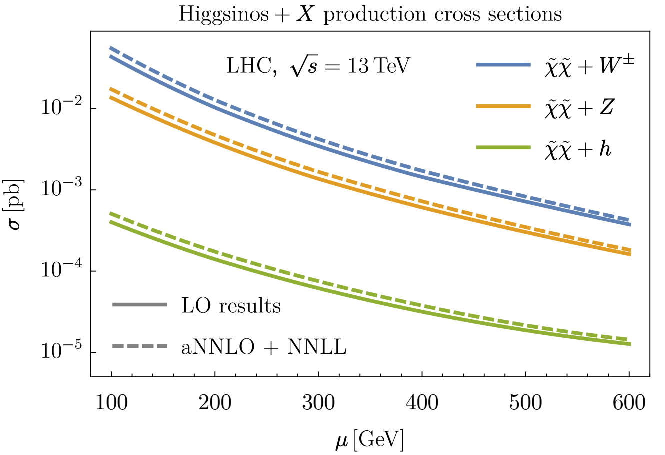
Bibliography (2)

[7] *Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at* $\sqrt{s} = 13$ TeV, Tech. Rep. (2021).

[8] G. Aad *et al.* (ATLAS), Phys. Rev. D **101**, 052005 (2020), arXiv:1911.12606 [hep-ex] .

Bonus material

Inclusive EWino + W/Z pair production



Statistics for our analysis

- Likelihood function:

$$\mathcal{L}(m \mid \mu, b) = \prod_{i=1}^{N_{\rm bin}} \frac{(\mu s_i + b_i)^{m_i}}{m_i!}\, \mathrm{e}^{-(\mu s_i + b_i)} \times \frac{1}{\sqrt{2\pi}\,\sigma_{b,i}} \exp\left\{ -\frac{1}{2} \frac{(b_i - \langle b_i \rangle)^2}{\sigma_{b,i}^2} \right\}$$

- Test statistic:

$$q_\mu^m = -2 \ln \frac{\mathcal{L}(m \mid \mu, \hat{\hat{b}})}{\mathcal{L}(m \mid \hat{\mu}, \hat{b})}, \quad \hat{\mu} \leq \mu$$

- Exclusion and discovery:

$$\mathrm{CL_s} = \frac{1 - \Phi([q_{\mu=1}^{m=n_{\rm obs}}]^{1/2})}{\Phi([q_{\mu=1}^{m=\langle b \rangle}]^{1/2} - [q_{\mu=1}^{m=n_{\rm obs}}]^{1/2})}, \quad Z = \begin{cases} [q_{\mu=1}^{m=\langle b \rangle}]^{1/2}, & \text{excl.} \\ [q_{\mu=0}^{m=s+\langle b \rangle}]^{1/2}, & \text{disc.} \end{cases}$$