

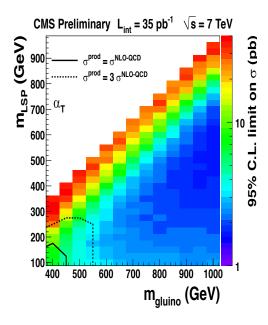
SUSY Searches at the LHC

Keith Ulmer University of Colorado Boulder

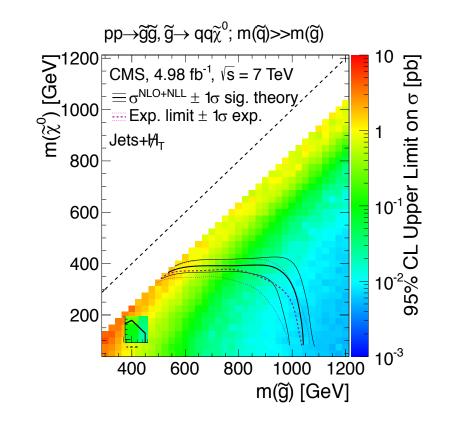
Aspen Winter Conference March 25, 2019



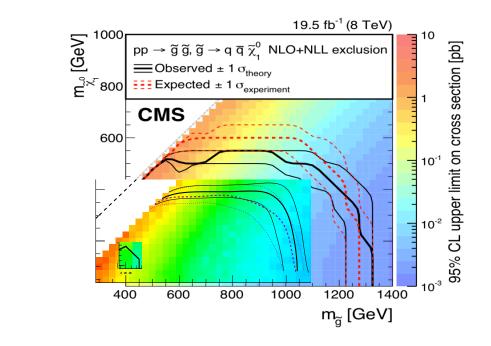




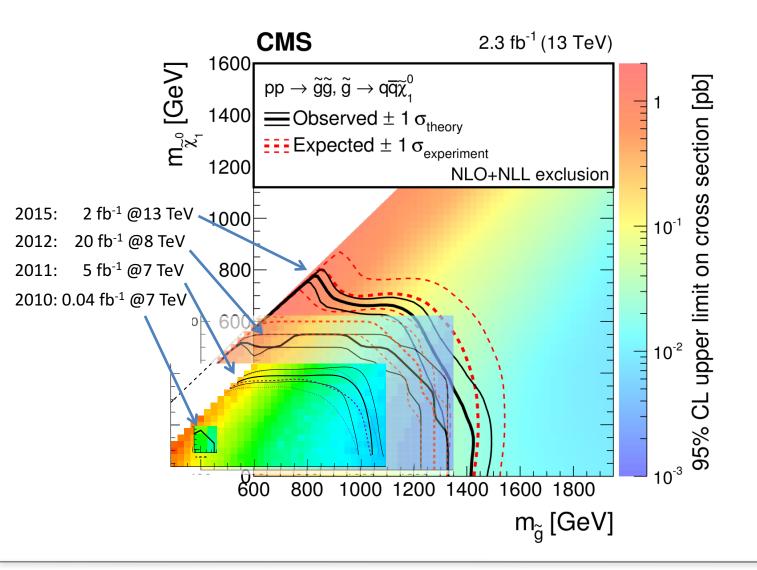
2010:

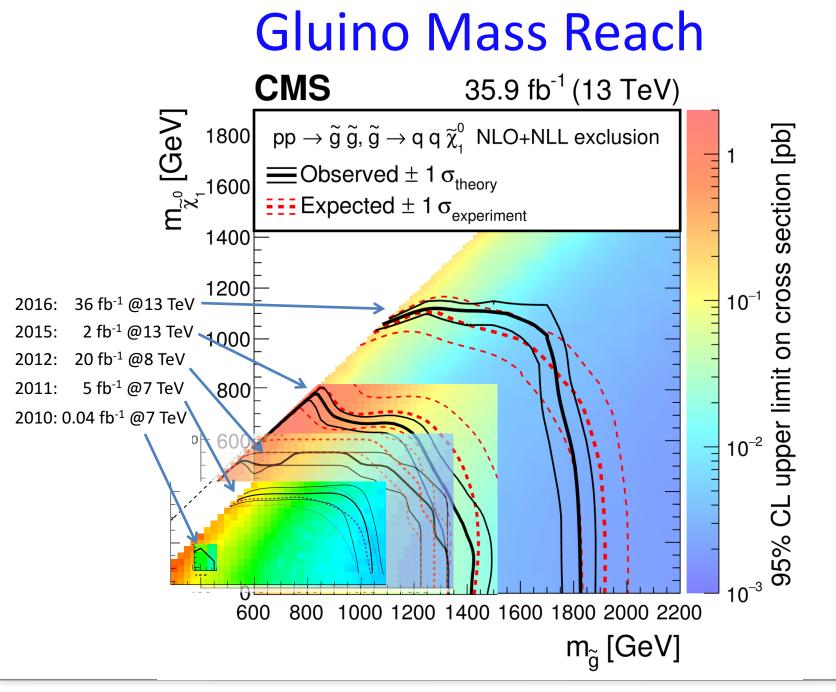


2011:



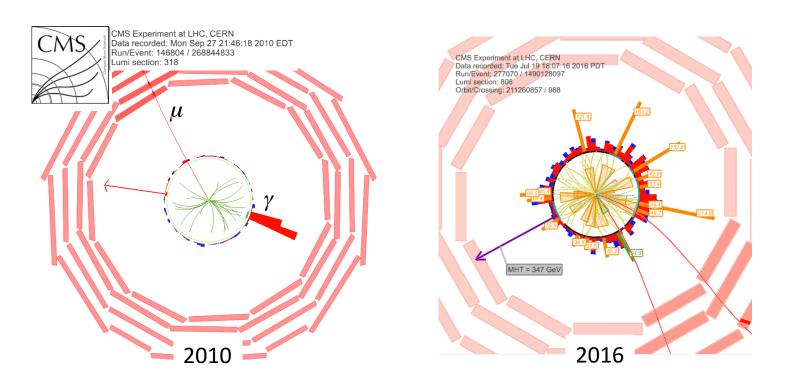
2012:



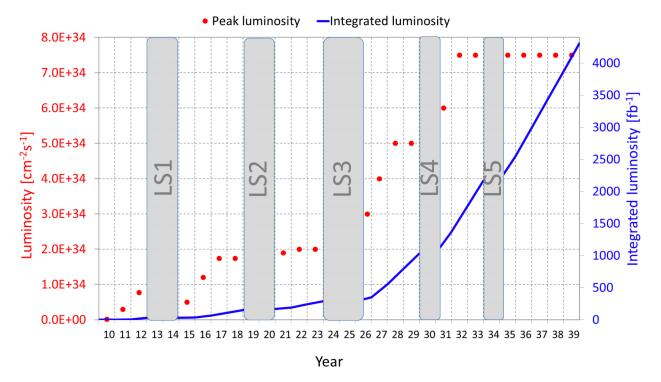


SUSY at the LHC

- Despite lack of observation, have made huge of progress in SUSY searches
 - Generally very inclusive searches with broad reach
 - Sophisticated analysis techniques, robust background predictions, comprehensive interpretation techniques, searching further in kinematic tails, ...



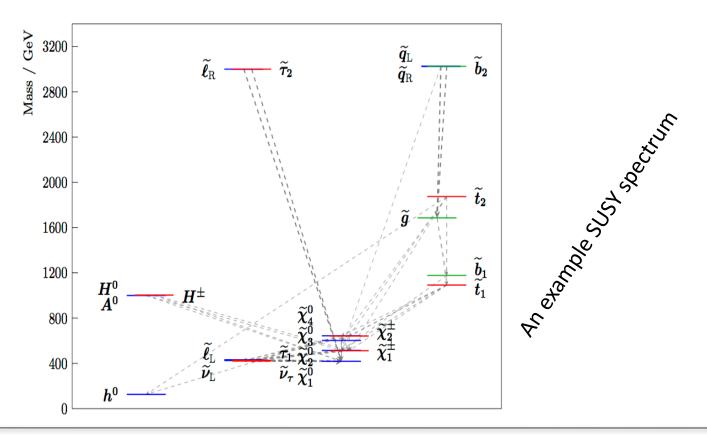
Some paths forward



- The era of large jumps in energy or luminosity is over (for awhile!)
- This talk: My view of ways to push beyond the inclusive, high p_T SUSY searches
 - Digging deeper under background
 - Targeting more specific signatures
 - New experimental techniques
 - More comprehensive searches

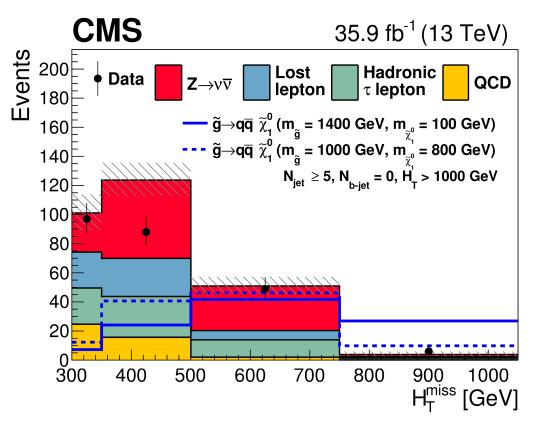
Digging Under Background

- SUSY can give a remarkably wide range of potential signatures
 - Essentially anything from the SM + missing energy
 - CMS and ATLAS have recent and ongoing searches in just about every combination imaginable
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults



Digging Under Background

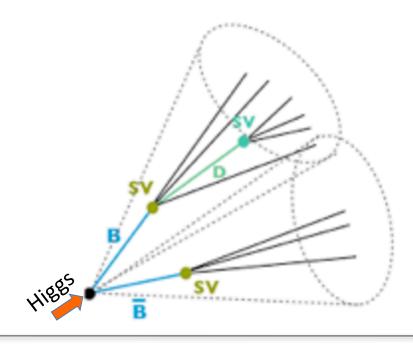
• Traditional approach is to look in extreme tails of kinematic distributions

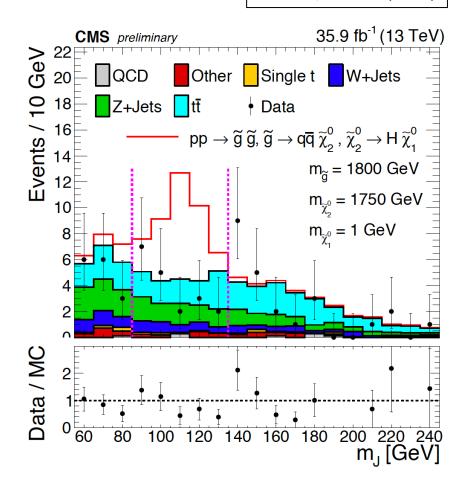


- But signals could be hiding in the bulk with lower rates
- Another option is to use new unique signatures to beat down backgrounds in these cases
- Will give two examples from canonical multi-jet signals

Boosted Object Tagging

- High p_T H→bb decay with small opening angle
- Use large angle jets to capture full Higgs decay
- Identify Higgs tags by presence of two displaced subjets
- Jet mass shows clear peaking structure

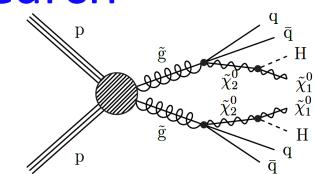


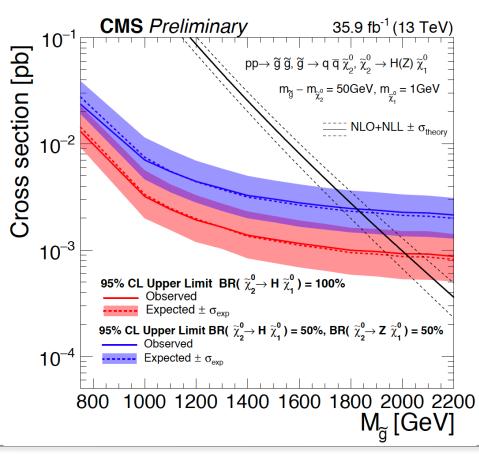


CMS-SUS-17-006 PRL 120, 241801 (2018)

Boosted Higgs Search

- Select events with 1 or 2 Higgs tags and large missing energy
 - ◆ 2 AK8 jets with p_T > 300 GeV
 - ♦ MET > 300 GeV
- Backgrounds predicted from mass and bb-tag sidebands in data
- Interpret in gluino decay model with mass splittings that give high p_T Higgs bosons

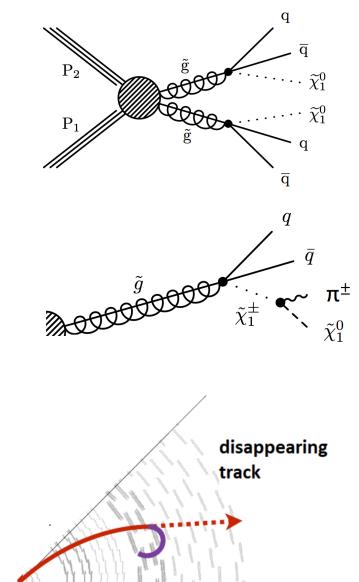




Disappearing tracks

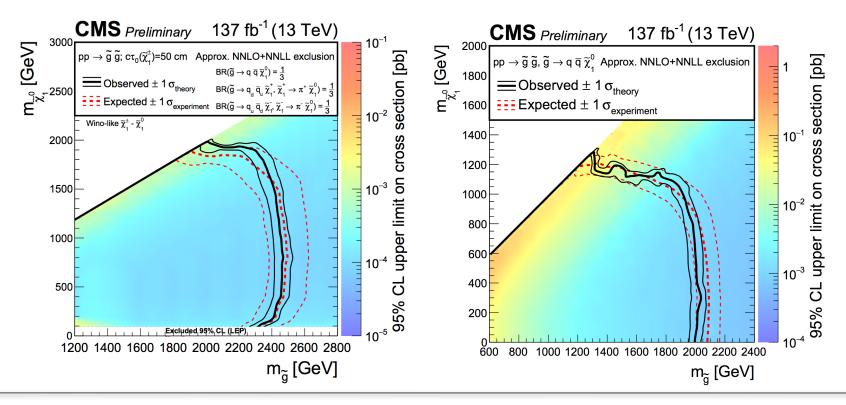
CMS-SUS-19-005

- Typical SUSY decay ends with LSP
- Consider instead if a chi1+ sits just above the chi0
 - As is typical with Wino or Higgsinolike LSPs
- Small mass splitting between chi1+ and chi0 order(100 MeV)
 - Can result in long-lived chi1+ with limited phase space for decay
 - Decays through a pi+ which is too soft to detect and a chi0
- Can select for "disappearing tracks"
 - Well reconstructed track in the inner layers of the tracker
 - Require at least two outer tracker layers missing hits
 - Categorize by length of observed track to catch a range of lifetimes



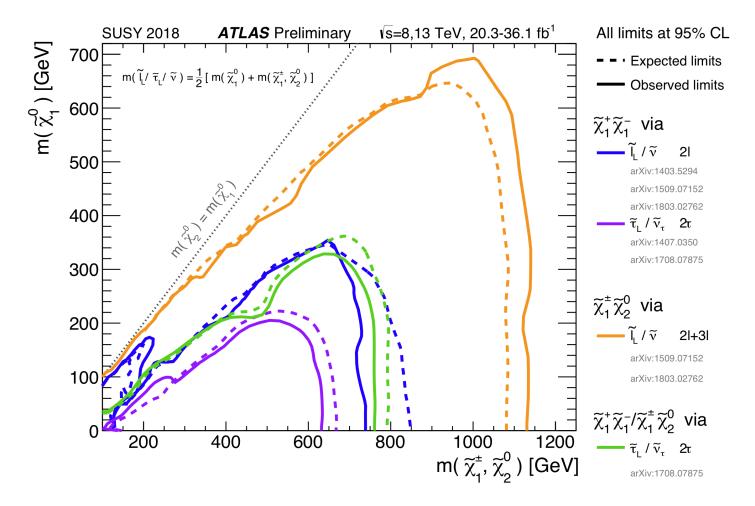
Disappearing tracks

- Search binned in jet multiplicity, HT, and disappearing track pT
- No significant excess observed in any search bin
- Limits extended by ~400 GeV compared to case without long-lived chargino



Aspen 2019 - K. Ulmer

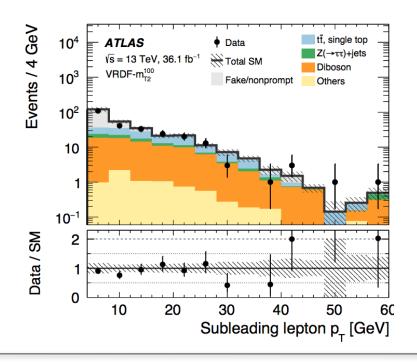
Targeting Corners

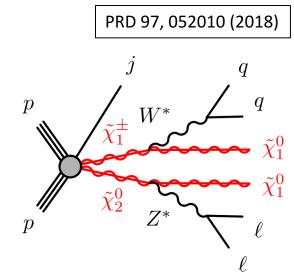


- Broad inclusive searches can leave gaps in sensitivity in challenging regions
 - Dedicated searches extend and complete the coverage

Higgsinos with low p_T leptons

- Target compressed scenarios through low p_T leptons from far offshell W* and Z* decays
- Stretching detector capabilities to reconstruct electrons (muons) down to 4 (4.5) GeV





$$\widetilde{\chi}_{2}^{0} \xrightarrow{\ell} \ell^{\ell} \qquad \ell^{\ell}$$

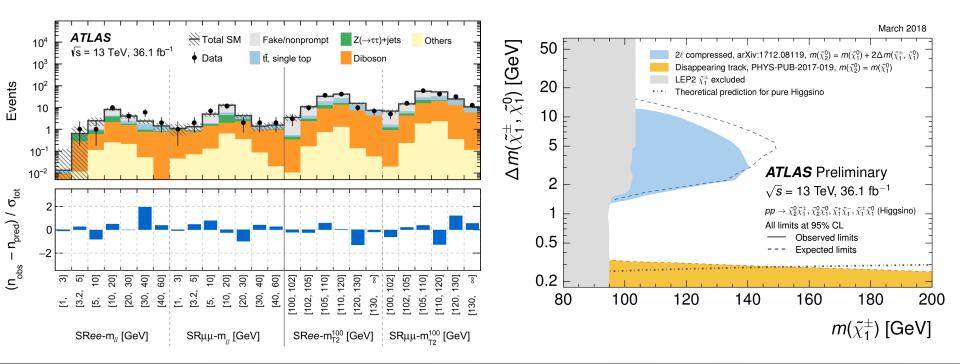
$$Z^{*} \rightarrow \ell^{+}\ell^{-}$$

$$m(\widetilde{\chi}_{1}^{\pm}) = \frac{1}{2}[m(\widetilde{\chi}_{1}^{0}) + m(\widetilde{\chi}_{2}^{0})]$$

$$Higgsino mass spectrum$$

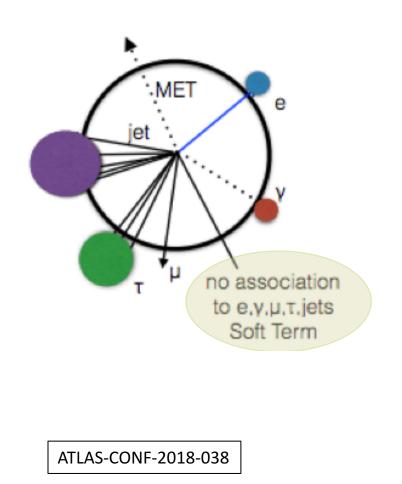
Higgsinos with low p_T leptons

- Difficult search with backgrounds from many different sources and detailed detector response to understand
- No excess observed
- Interpret results in EW-ino mass vs mass splitting

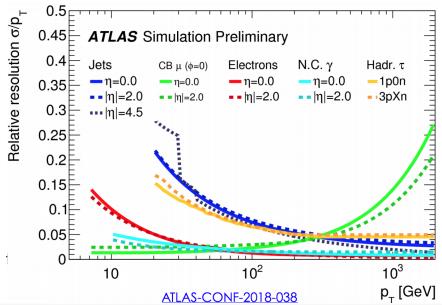


New experimental techniques

 Missing Energy is the hallmark signature for SUSY and other dark matter searches



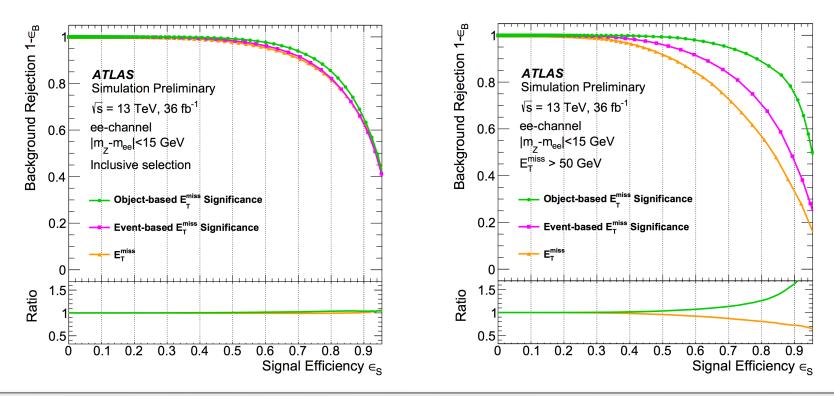
- Normally computed as the vector sum of observed energy deposits in the detector
- But not all energy deposits are measured with equal resolution
- Can exploit this with "MET significance"



MET significance

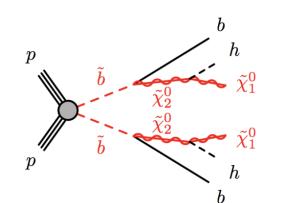
• Compute as $S = \frac{\left|E_{T}^{miss}\right|}{\sqrt{\sigma_{L}^{2}\left(1 - \rho_{LT}^{2}\right)}}$

 Evaluate performance in simulated Z→ee events as background and ZZ→(ee)(neutrinos) as signal

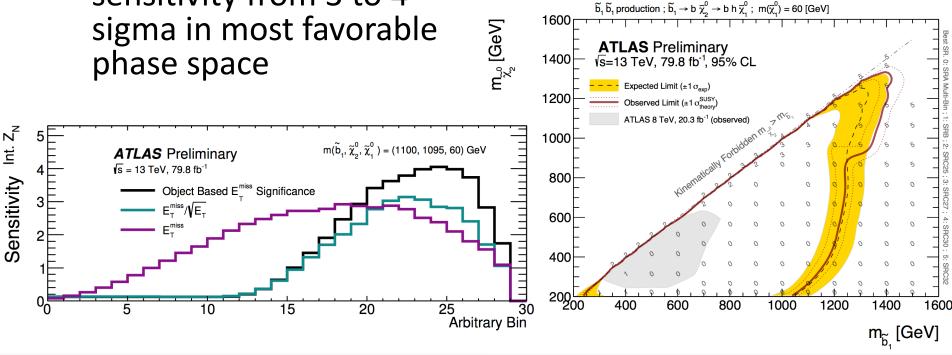


sbottom decays through Higgs

- Search in multi-b plus missing energy final state (up to 6 b's!)
- Exploits MET significance as main search variable
- Can boost expected sensitivity from 3 to 4 sigma in most favorable phase space



ATLAS-CONF-2018-040



More comprehensive results

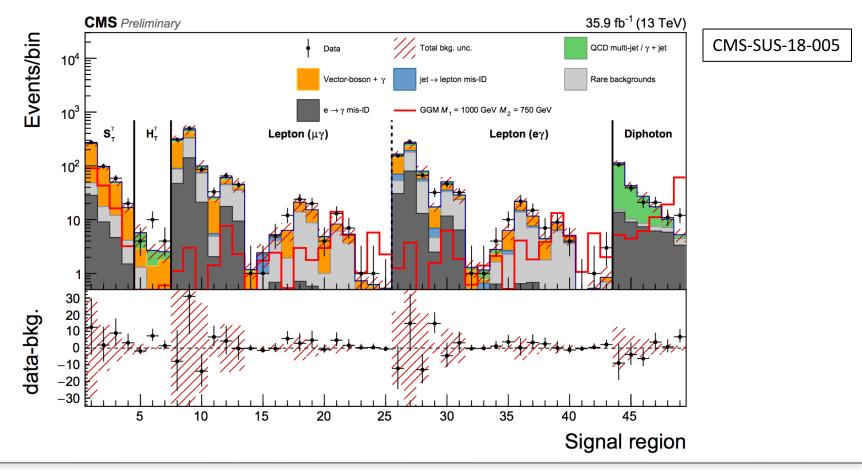
simplified models, c.f. refs. for the assumptions made.

ATLAS SUSY Sea July 2018 Model	e, μ, τ, γ					ss limit		$\sqrt{s} = 7, 8$	TeV $\sqrt{s} = 13 \text{ TeV}$	ATLAS Prelimina $\sqrt{s} = 7, 8, 13$ Te Reference
$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	 <i>q</i> [2×, 8× Degen.] <i>q</i> [1×, 8× Degen.] 	0.43	0.9 0.71	1.55	$m(\tilde{\chi}_1^0) < 100 \text{ GeV}$ $m(\tilde{q}) \cdot m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	1712.02332 1711.03301
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$	0	2-6 jets	Yes	36.1	ğ ğ		Forbidden	2.0 0.95-1.6	$m(\tilde{\chi}_{1}^{0}) < 200 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0}) = 900 \text{ GeV}$	1712.02332 1712.02332
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell \ell)\tilde{\chi}_{1}^{0}$	3 e, μ ee, μμ	4 jets 2 jets	- Yes	36.1 36.1	ğ ğ			1.85 1.2	m($ ilde{t}_1^0$)<800 GeV m($ ilde{g}$)-m($ ilde{t}_1^0$)=50 GeV	1706.03731 1805.11381
$\begin{array}{cccc} & & & & \\ & & & & \\ & & & & \\ & & & & $	0 3 e,µ	7-11 jets 4 jets	Yes -	36.1 36.1	ĩc ĩc		0.98	1.8	m($\tilde{\chi}_1^0$) <400 GeV m($\tilde{\chi}$)-m($\tilde{\chi}_1^0$)=200 GeV	1708.02794 1706.03731
$\widetilde{g}_{\widetilde{g}, \widetilde{g} \to t\overline{t}} \widetilde{\chi}_1^0$	0-1 e,μ 3 e,μ	3 b 4 jets	Yes	36.1 36.1	25, 150			2.0 1.25	m($\tilde{\chi}_{1}^{0}$)<200 GeV m(\tilde{g})-m($\tilde{\chi}_{1}^{0}$)=300 GeV	1711.01901 1706.03731
$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$		Multiple Multiple Multiple		36.1 36.1 36.1	$egin{array}{ccc} & & & & & & & & & & & & & & & & & &$	Forbidden Forbidden	0.9 0.58-0.82 0.7	m(${ ilde t}_1^0)$	$\begin{array}{c} m(\tilde{x}_{1}^{0}){=}300~\text{GeV},~BR(\delta\tilde{x}_{1}^{0}){=}1\\ m(\tilde{x}_{1}^{0}){=}300~\text{GeV},~BR(\delta\tilde{x}_{1}^{0}){=}BR(i\tilde{x}_{1}^{\pm}){=}0.5\\ {=}200~\text{GeV},~m(\tilde{x}_{1}^{\pm}){=}300~\text{GeV},~BR(i\tilde{x}_{1}^{\pm}){=}1 \end{array}$	1708.09266, 1711.03301 1708.09266 1706.03731
$\tilde{b}_1 \tilde{b}_1, \tilde{t}_1 \tilde{t}_1, M_2 = 2 \times M_1$ $\tilde{b}_1 \tilde{b}_1, \tilde{t}_1 \tilde{t}_1, M_2 = 0$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$		Multiple Multiple		36.1 36.1	τ̃ ₁ τ̃ ₁ Forbidden		0.7		$m(\tilde{\chi}_{1}^{0})=60 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}$	1709.04183, 1711.11520, 1708.03247 1709.04183, 1711.11520, 1708.03247
$\begin{array}{c} \begin{array}{c} \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ $	0-2 <i>e</i> , <i>µ</i>	0-2 jets/1-2 Multiple Multiple	b Yes	36.1 36.1 36.1	τ̃ ₁ τ̃ ₁ τ̃ ₁ Forbidden		1.0 0.4-0.9 0.6-0.8	$m(\tilde{\chi}_1^0)$	$m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$ = 150 GeV, $m(\tilde{\chi}_{1}^{\pm})\cdot m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$, $\tilde{\iota}_{1} \approx \tilde{\iota}_{L}$ = 300 GeV, $m(\tilde{\chi}_{1}^{\pm})\cdot m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$, $\tilde{\iota}_{1} \approx \tilde{\iota}_{L}$	1506.08616, 1709.04183, 1711.11520 1709.04183, 1711.11520 1709.04183, 1711.11520
$\vec{\tilde{t}}_{1} \vec{\tilde{t}}_{1}, \text{ Well-Tempered LSP} \\ \vec{\tilde{t}}_{1} \vec{\tilde{t}}_{1}, \vec{\tilde{t}}_{1} \rightarrow c \vec{\tilde{t}}_{1}^{0} / \tilde{c} \vec{c}, \ \vec{c} \rightarrow c \vec{\tilde{t}}_{1}^{0}$	0	Multiple 2c	Yes	36.1 36.1		0.46	0.48-0.84		=150 GeV, $m(\tilde{\chi}_1^{\pm}) \cdot m(\tilde{\chi}_1^0) = 5$ GeV, $\tilde{t}_1 \approx \tilde{t}_L$ $m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \tilde{c}) \cdot m(\tilde{\chi}_1^0) = 50$ GeV	1709.04183, 1711.11520 1805.01649 1805.01649
$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	0 1-2 e,μ	mono-jet 4 b	Yes Yes	36.1 36.1	τ ₁ τ ₂	0.43	0.32-0.88		$m(\tilde{t}_1, \tilde{c}) \cdot m(\tilde{\chi}_1^0) = 5 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 0 \text{ GeV}, m(\tilde{t}_1) \cdot m(\tilde{\chi}_1^0) = 180 \text{ GeV}$	1711.03301 1706.03986
$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via WZ	2-3 e, μ ee, μμ		Yes Yes	36.1 36.1			0.6		$m(\tilde{\chi}_{1}^{0})=0$ $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=10 \text{ GeV}$	1403.5294, 1806.02293 1712.08119
$ \begin{array}{c} \tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} \text{ via } Wh \\ \tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{1}/\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_{2}^{0} \rightarrow \tilde{\tau}\tau(\nu\tilde{\nu}) \\ \tilde{\chi}_{1}^{0}\tilde{\chi}_{1}^{-}/\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_{2}^{0} \rightarrow \tilde{\tau}\tau(\nu\tilde{\nu}) \end{array} $	<i>ℓℓ/ℓγγ/ℓbb</i> 2 τ	-	Yes Yes	20.3 36.1	$\begin{array}{cccc} \tilde{x}_{1}^{+}/\tilde{x}_{2}^{0} & 0.26 \\ \tilde{x}_{1}^{+}/\tilde{x}_{2}^{0} & \tilde{x}_{1}^{+}/\tilde{x}_{2}^{0} \\ \tilde{x}_{1}^{+}/\tilde{x}_{2}^{0} & 0.22 \end{array}$		0.76	m(X ⁺)-m(X	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^0)=0$, $m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^0))$ $n^0)=100$ GeV, $m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^+)+m(\tilde{\chi}_1^0))$	1501.07110 1708.07875 1708.07875
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e,μ 2 e,μ	0 ≥ 1	Yes Yes	36.1 36.1	<i>ℓ</i> <i>ℓ</i>	0.5			$m(\tilde{\xi}_1^0)=0$ $m(\tilde{\ell})\cdot m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1803.02762 1712.08119
$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 4 <i>e</i> , µ	$\geq 3b$ 0	Yes Yes	36.1 36.1	<i>Й</i> 0.13-0.23 <i>Й</i> 0.3		0.29-0.88		$BR(\tilde{\chi}^0_1 \rightarrow h\tilde{G})=1$ $BR(\tilde{\chi}^0_1 \rightarrow Z\tilde{G})=1$	1806.04030 1804.03602
Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$ \tilde{\chi}_{1}^{\pm} \\ \tilde{\chi}_{1}^{\pm} $ 0.15	0.46			Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow gq\tilde{\chi}_1^0$ GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$, long-lived $\tilde{\chi}_1^0$	SMP 2γ	- Multiple	- Yes	3.2 32.8 20.3	\tilde{g} \tilde{g} [$\tau(\tilde{g}) = 100 \text{ ns}, 0.2 \text{ ns}$] τ^{0}	0.44		1.6 1.6	2.4 $m(\tilde{\chi}_1^0)=100 \text{ GeV}$ $1 < r(\tilde{\chi}_1^0) < 3 \text{ ns. SPS8 model}$	1606.05129 1710.04901, 1604.04520 1409.5542
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow eev/e\mu v/\mu\mu v$	displ. ee/eµ/µ	иμ -	-	20.3	ğ	0.44		1.3	$1 < \tau(\tilde{x}_1) < 3$ ns, SPS6 model 6 $< c\tau(\tilde{x}_1^0) < 1000$ mm, m(\tilde{x}_1^0)=1 TeV	1504.05162
LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$ $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{2}^{0} \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	eμ,eτ,μτ 4 e,μ	-	- Yes	3.2 36.1	\tilde{v}_{τ} $\bar{\chi}_{1}^{\pm}/\bar{\chi}_{2}^{0} [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$		0.82	1.9	$\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$ $m(\tilde{\chi}^0_1)=100 \text{ GeV}$	1607.08079 1804.03602
$\tilde{g}\tilde{g}, \tilde{g} \to qq\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \to qqq$ $\tilde{g}\tilde{g}, \tilde{g} \to ths / \tilde{g} \to t\bar{t}\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \to ths$	0 4	-5 large- <i>R</i> j Multiple	ets -	36.1 36.1	$\tilde{g} = [m(\tilde{\chi}_1^0)=200 \text{ GeV}, 1100 \text{ GeV}] \\ \tilde{g} = [\lambda''_{112}=2e-4, 2e-5]$		1.0		Large λ_{112}'' m($\tilde{\chi}_1^0$)=200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$ $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	0 2 e, µ	Multiple Multiple 2 jets + 2 i 2 b	b - -	36.1 36.1 36.7 36.1	$\tilde{g} = [\lambda'_{323}=1, 10-2]$ $\tilde{g} = [\lambda'_{323}=2e-4, 1e-2]$ $\tilde{t}_1 = [qq, bs]$ \tilde{t}_1	0.55 0.42 0	i 1.0		$m(\tilde{\chi}_1^0)=200 \text{ GeV, bino-like}$ $m(\tilde{\chi}_1^0)=200 \text{ GeV, bino-like}$ $BR(\tilde{t}_1 \rightarrow be/b\mu)>20\%$	ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 1710.07171 1710.05544
$r_1r_1, r_1 \rightarrow ss$ $r_1r_1, r_1 \rightarrow b\ell$ Duly a selection of the available n	2 e,µ	2 b	-	36.1	<i>t</i> ₁ [<i>qq</i> , <i>bs</i>] <i>ī</i> ₁ 0 ⁻¹	0.42 (0.4-1.45	$BR(\tilde{i}_1 {\rightarrow} be/b\mu) {>} 20\%$	

Would like to turn wide collection of individual searches into more comprehensive statement about progress and viable parameter space

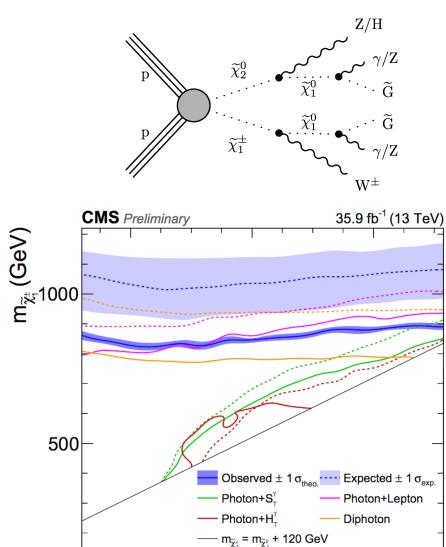
GMSB photon combination

- New effort combines results from variety of searches with photons
- Aim to understand global reach for searches sensitive to similar models



GMSB photon combination

- Consider gauge mediated full SUSY model
 - Decouple squarks and gluinos
 - Include full range of NLSP composition, which drives the NLSP branching ratios
- Complementarity between di-photon and photon + lepton searches
- Also small consistent excess between them...



400

200

600

 $m_{\widetilde{\chi}^0_{\circ}}$ (GeV)

Conclusions

- Lots of progress in LHC SUSY searches
- But still no signs of new physics
- The low hanging fruit has been picked
- Further progress requires new approaches, techniques, and final states
- But there are still lots of fruitful new ideas coming out of LHC SUSY searches
- And more to come with the full Run 2 dataset