Searches for Squarks and Gluinos with ATLAS

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Outline

Introduction - ATLAS and SUSY

- Status of ATLAS and SUSY in 2018
- Motivation for squark and gluino searches at ATLAS

Squark and gluino searches at ATLAS

- The anatomy of a typical SUSY search
- Some recent searches and results
  - Long-lived particles
  - Leptonic final states

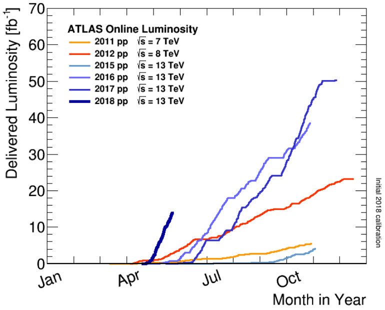
Summary and Outlook

- Current limits and potential sensitivity at the end of Run 2 and beyond

Introduction - ATLAS and SUSY

The LHC and ATLAS - where are we now?

- SUSY searches are a key part of the ATLAS physics program
- Huge variety of ATLAS searches with 2015+2016 and $\sqrt{s} = 13$ TeV data completed
- SPOILER ALERT no sign of SUSY, yet ;)
- Analysis ongoing for 2017 data
- 2018 data taking under way with higher than ever instantaneous luminosity



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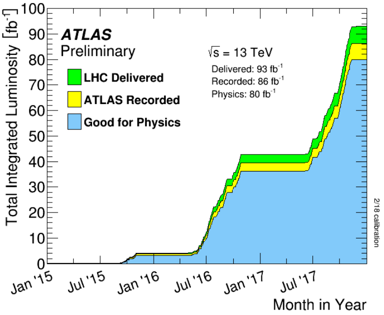

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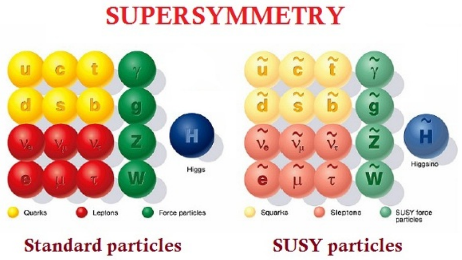
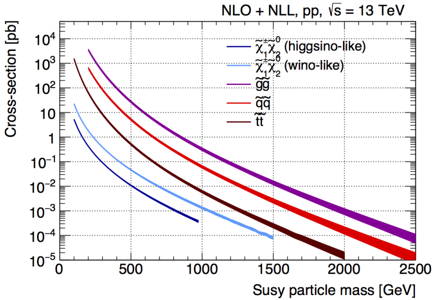
Squarks and Gluinos



Why SUSY?

- Cancel quadratic divergences to Higgs mass calculation
- Unification of gauge interactions
- LSP - excellent candidate for dark matter



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Why squarks and gluinos?

- Natural SUSY spectrum without fine tuning requires light stop and gluino masses
- Should be accessible to the LHC
- Squarks and gluinos → higher cross sections

SUSY Models

Gauge eigenstates		Spin	Mass eigenstates	
bino, wino, higgsinos	$\tilde{B}, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0$	$\frac{1}{2}$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	neutralinos
wino, higgsinos	$\tilde{W}^+, \tilde{H}_u^+$	$\frac{1}{2}$	$\tilde{\chi}_1^+, \tilde{\chi}_2^+$	charginos
	$\tilde{W}^-, \tilde{H}_d^-$	$\frac{1}{2}$	$\tilde{\chi}_1^-, \tilde{\chi}_2^-$	
gluinos	$\tilde{g}$	$\frac{1}{2}$	no mixing	
selectron, smuon, stau	$\tilde{e}_{L,R}, \tilde{\mu}_{L,R}, \tilde{\tau}_{L,R}$	0	$\tilde{e}_{L,R}, \tilde{\mu}_{L,R}, \tilde{\tau}_1, \tilde{\tau}_2$	sleptons
sneutrinos	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	0	$\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$	sleptons or sneutrinos
sup, scharm, stop	$\tilde{u}_{L,R}, \tilde{c}_{L,R}, \tilde{t}_{L,R}$	0	$\tilde{u}_{L,R}, \tilde{c}_{L,R}, \tilde{t}_1, \tilde{t}_2$	squarks
sdown, sstrange, sbottom	$\tilde{d}_{L,R}, \tilde{s}_{L,R}, \tilde{b}_{L,R}$	0	$\tilde{d}_{L,R}, \tilde{s}_{L,R}, \tilde{b}_1, \tilde{b}_2$	

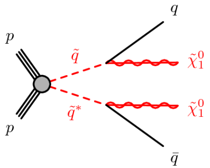
arXiv:1609.01686v1 [hep-ex]

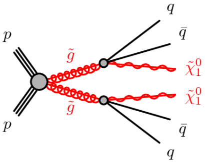
Rich phenomenology

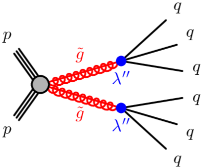
- MSSM has > 100 parameters $\rightarrow$ cannot scan all of parameter space
- Simplified models - sparticle masses not involved in signature of interest set to high values

Typical signal topologies

- R-parity conserving (RPC)
  - Pair produced
  - Decaying to LSP
  - Large E_T^{miss}
- R-parity violating (RPV)
  - Decay to SM
  - Lifetime depends on λ coupling





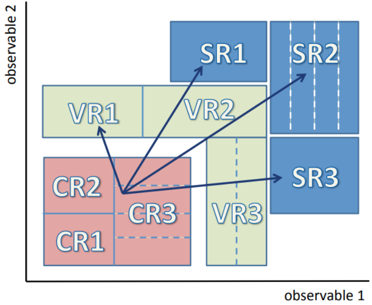


Squark and gluino searches at ATLAS

Typical search strategy

Design kinematic selections for background rejection and estimation

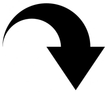
- Signal regions rich in signal events
- Control regions rich in specific background process
- Validation regions lie somewhere between SRs and CRs



arXiv:1410.1280v1 [hep-ex] 6 Oct 2014

Background estimation

- Reducible backgrounds - determine from data
- Irreducible backgrounds
  - Dominant - normalise in CR
  - Subdominant - MC estimation



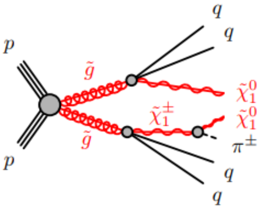
Simultaneous fit

- Combined fit of all regions including experimental and theoretical uncertainties

Long-lived searches

SUSY scenario with $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$

- Almost pure wino $\rightarrow$ nearly mass degenerate
- $\tilde{\chi}_1^{\pm}$ long-lived $\mathcal{O}$(ns)
- Soft π^+ $\rightarrow$ *disappearing track*
- Run 2 improvement - reconstruct shorter *tracklets*



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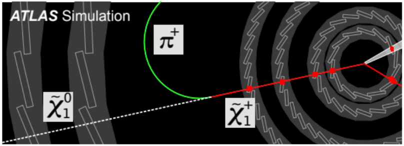

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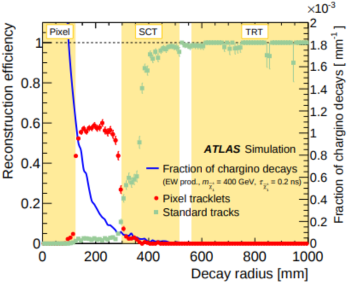

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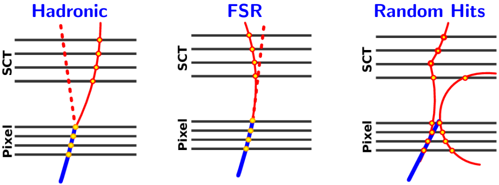
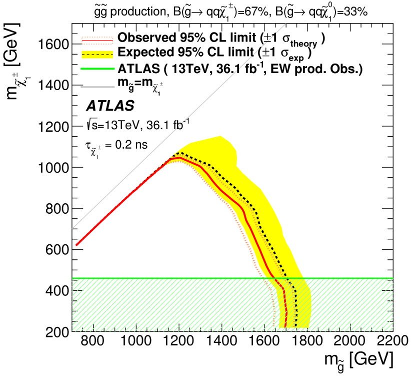
Backgrounds



Exclusion limits

- Limits depend on the lifetime of the chargino
- Disappearing track analysis sensitive when the chargino decays in the inner detector



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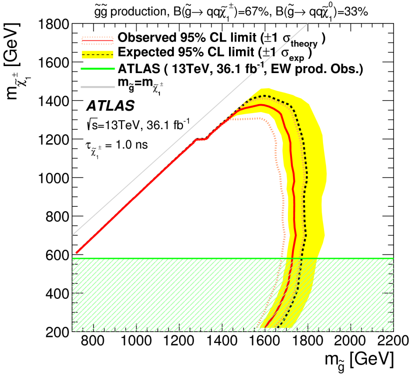

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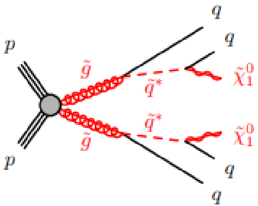
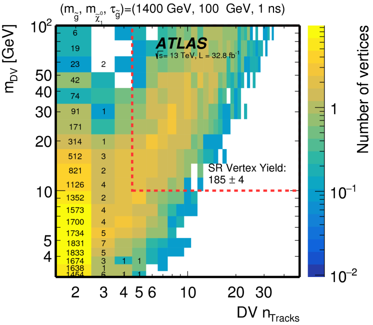
Split SUSY models

- Large squark masses → gluino long-lived
- Hadronise into R-hadron leading to displaced vertex (DV)
- Reconstruct displaced vertex using large radius tracking
- Hadronic interactions in material rich detector regions - map-based veto





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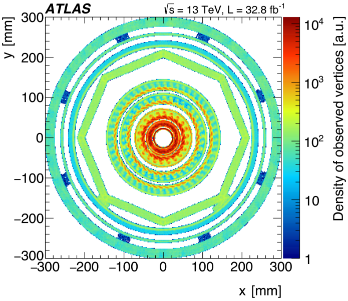

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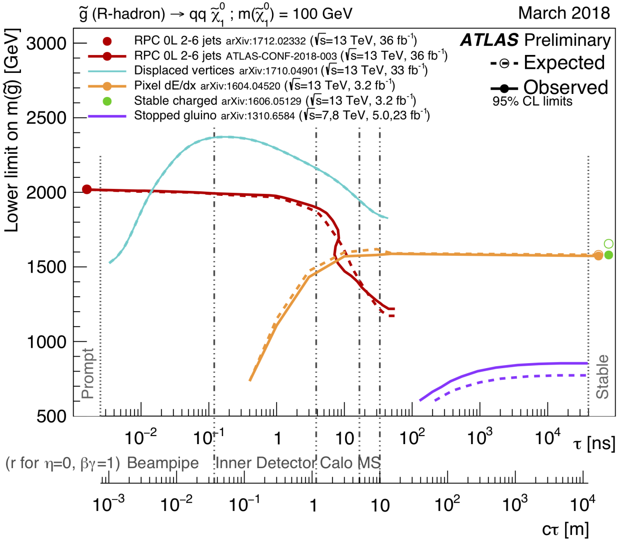

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Gluino mass limit vs. lifetime

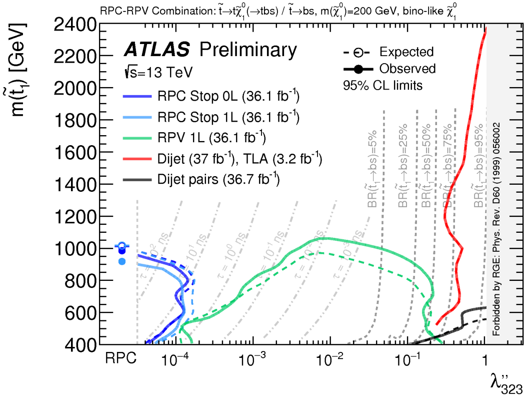
- Reinterpretation of existing ATLAS analyses in the context of R-hadrons from split SUSY
- RPC 0L + jets - strong limits until decay of R-hadron reaches calorimeters
- Displaced vertex - most powerful analysis for intermediate lifetimes
- Pixel dE/dx - sensitivity when R-hadron track can be reconstructed before decay

RPV reinterpretation

Reinterpret existing ATLAS searches in the context of RPV SUSY

- SUSY model - light gluinos and LSP
- Non-zero λ''_{323}, all other RPV couplings set to zero

$$\mathcal{W}_{RPV} = \frac{\lambda_{ijk}}{2} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j \bar{D}_k + \kappa_i L_i H_u$$



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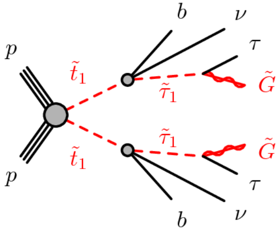
Leptonic final states

Gauge-mediated SUSY breaking

- $\tilde{G}$ is the LSP
- Ditau final state - semileptonic and fully hadronic SRs
- lep-had region - single lepton trigger
- had-had region - $E_{\mathrm{T}}^{\mathrm{miss}}$trigger
- Dominant background - misidentified taus
    - lep-had - Fake factor
    - had-had - Control Region



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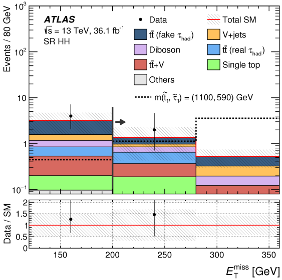

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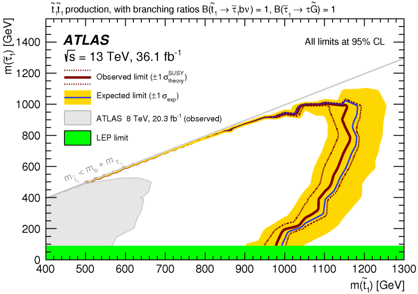

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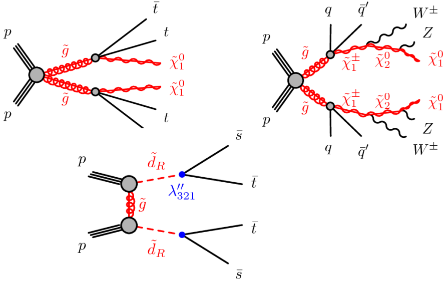
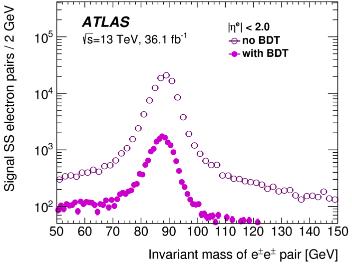
Same sign / three leptons present in many SUSY scenarios

- Low SM background
- Reducible background: charge-flip electrons - reject with BDT
- Extract charge-flip probability from $Z \to ee$ electrons





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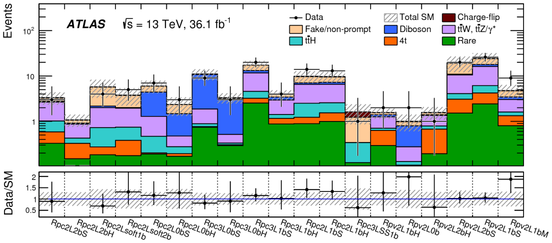

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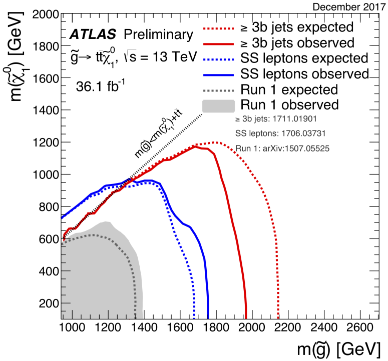
Exclusion limits

- Improved sensitivity for compressed scenarios



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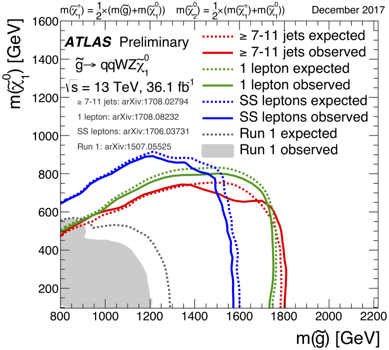

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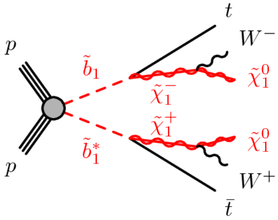
Exclusion limits

- Sensitivity to direct sbottom pair production via $\tilde{\chi}_1^{\pm}$



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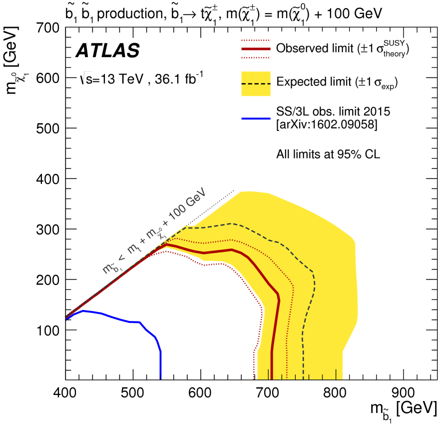

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ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

$\sqrt{s}$ = 7, 8 TeV | $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 1.57 TeV	$m(\tilde{\chi}^0_1)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ 710 GeV	$m(\tilde{q})$-$m(\tilde{\chi}^0_1)$<5 GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.02 TeV	$m(\tilde{\chi}^0_1)$<200 GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.01 TeV	$m(\tilde{\chi}^0_1)$<200 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}^0_1)$+$m(\tilde{g})$)
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$ 1.7 TeV	$m(\tilde{\chi}^0_1)$<300 GeV,
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.87 TeV	$m(\tilde{\chi}^0_1)$=0 GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8 TeV	$m(\tilde{\chi}^0_1)$ <400 GeV
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV	
	GGM (bino NLSP)	2 γ	-	Yes	36.1	$\tilde{g}$ 2.15 TeV	$c\tau$(NLSP)<0.1 mm
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde{g}$ 2.05 TeV	$m(\tilde{\chi}^0_1)$=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})$>1.8 × 10^{-4} eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	36.1	$\tilde{g}$ 1.92 TeV	$m(\tilde{\chi}^0_1)$<600 GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 1.97 TeV	$m(\tilde{\chi}^0_1)$<200 GeV
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	36.1	$\tilde{b}_1$ 950 GeV	$m(\tilde{\chi}^0_1)$<420 GeV
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e, μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$ 275-700 GeV	$m(\tilde{\chi}^0_1)$<200 GeV, $m(\tilde{\chi}^\pm_1)$= $m(\tilde{\chi}^0_1)$+100 GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^\pm_1$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 117-170 GeV, 200-720 GeV	$m(\tilde{\chi}^\pm_1)$ = 2$m(\tilde{\chi}^0_1)$, $m(\tilde{\chi}^0_1)$=55 GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 90-198 GeV, 0.195-1.0 TeV	$m(\tilde{\chi}^0_1)$=1 GeV
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet	Yes	36.1	$\tilde{t}_1$ 90-430 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}^0_1)$=5 GeV
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-600 GeV	$m(\tilde{\chi}^0_1)$>150 GeV
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$ 290-790 GeV	$m(\tilde{\chi}^0_1)$=0 GeV
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 320-880 GeV	$m(\tilde{\chi}^0_1)$=0 GeV
Long-lived particles	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV	$m(\tilde{\chi}^0_1)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 1.58 TeV	
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.57 TeV	$m(\tilde{\chi}^0_1)$=100 GeV, τ>10 ns
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	displ. vtx	-	Yes	32.8	$\tilde{g}$ 2.37 TeV	$\tau(\tilde{g})$=0.17 ns, $m(\tilde{\chi}^0_1)$ = 100 GeV
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$ 537 GeV	10<tanβ<50
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 440 GeV	1<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model
	$\tilde{g}\tilde{g}, \tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}^0_1$ 1.0 TeV	7 <$c\tau(\tilde{\chi}^0_1)$< 740 mm, $m(\tilde{g})$=1.3 TeV
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.45 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}^\pm_1$ 1.14 TeV	$m(\tilde{\chi}^0_1)$>400GeV, $\lambda_{12k}\neq 0$ (k = 1, 2)
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 450 GeV	$m(\tilde{\chi}^0_1)$>0.2×$m(\tilde{\chi}^\pm_1)$, $\lambda_{133}\neq 0$
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ 1.875 TeV	$m(\tilde{\chi}^0_1)$=1075 GeV
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 2.1 TeV	$m(\tilde{\chi}^0_1)$= 1 TeV, $\lambda_{112}\neq 0$
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 1.65 TeV	$m(\tilde{t}_1)$= 1 TeV, $\lambda_{323}\neq 0$
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ 100-470 GeV, 480-610 GeV	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$ 510 GeV	$m(\tilde{\chi}^0_1)$<200 GeV

10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_Summary/ATLAS_SUSY_Summary.png

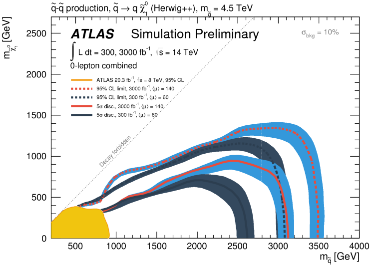
Conclusions

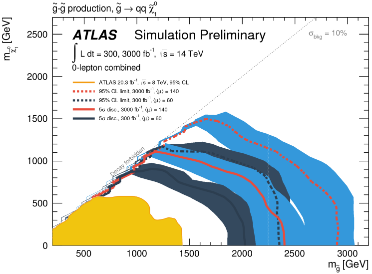
Rich and varied program of searches for squarks and gluinos at ATLAS

- No sign of SUSY yet in 2015 + 2016 data
- Stop limits approaching the 1 TeV level
- Gluino limits approaching the 2 TeV level
- SUSY is running out of places to hide...

R&D under way for 2017 + 2018 data

- By the end of the year the total integrated luminosity will be > 100 fb^{-1}
- High luminosity LHC - much much more!
- Watch this space...





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2014-010/