

# Searches for supersymmetric particles with prompt decays with the ATLAS detector

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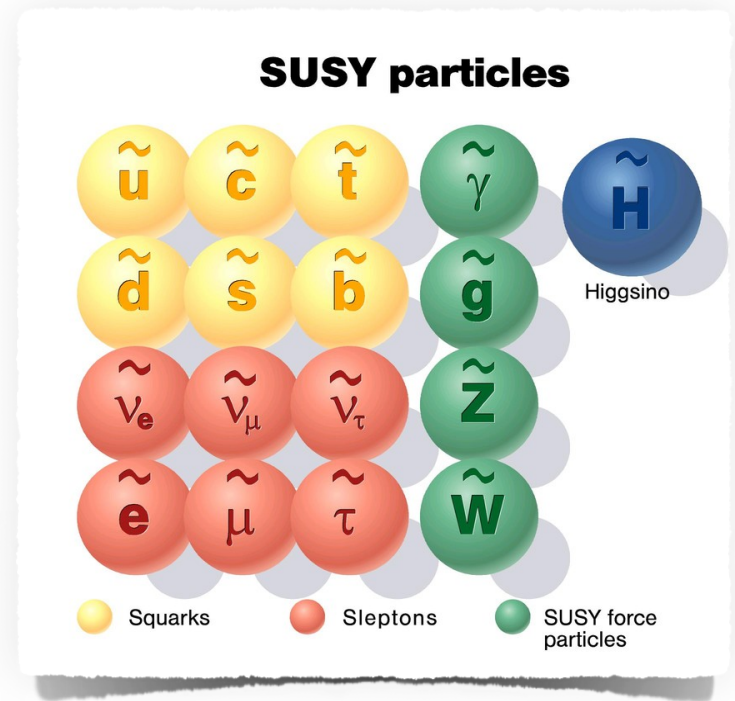
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on behalf of the ATLAS Collaboration

HEP 2023  
Valparaíso, Chile

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# SUSY

- ▶ **Supersymmetry (SUSY)** is one of the most elegant theories beyond the Standard Model
  - solves the **hierarchy problem**
  - achieves **grand unification**
  - provides **Dark Matter** candidate
- ▶ introduces supersymmetric partners
- ▶ No evidence for SUSY at LHC Run1 and Run2 so far
- ▶ Why is there no clue yet?
  - SUSY exists beyond the limit → Run 3 and beyond
  - We have, but missed it
- ▶ Exploiting the large amount of data
  - New techniques allow us to tackle challenging signatures
  - New scenarios and models



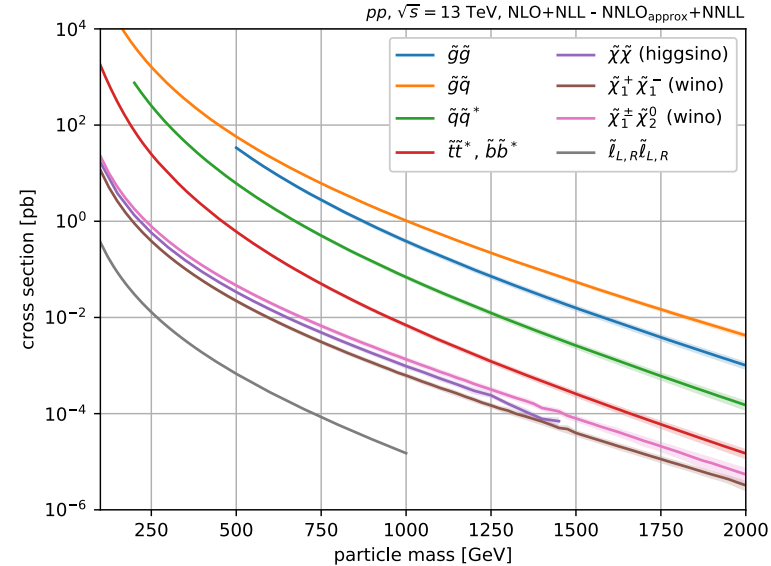
# SUSY Production at LHC

► **140 fb<sup>-1</sup> data** recorded at  $\sqrt{s}=13$  TeV in Run 2

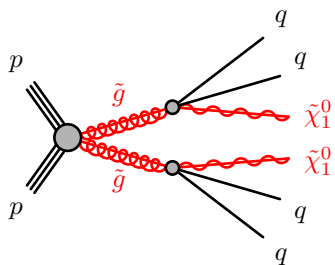
- 140 gluino (2 TeV) pairs
- 960 stop (1 TeV) pairs
- 6400  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  (500 GeV) wino pairs
- 1500  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  (500 GeV) higgsino pairs

► Stable Lightest Supersymmetric Particle (LSP)  
in R-parity conserved models

→ **large E<sub>T</sub><sup>miss</sup>** is the key signature

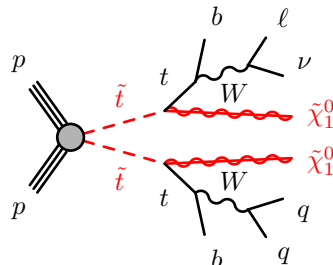


Gluino



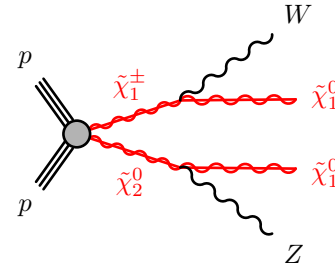
E<sub>T</sub><sup>miss</sup> + jets

Stop



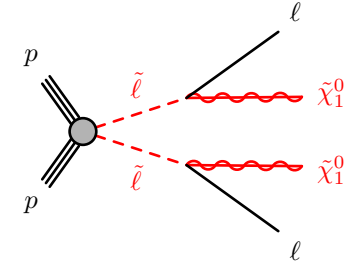
E<sub>T</sub><sup>miss</sup> + b-jets

Chargino, Neutralino



E<sub>T</sub><sup>miss</sup> + Bosons

Slepton



E<sub>T</sub><sup>miss</sup> + leptons

# SUSY Search Strategy

## ▶ Signal model building

- **Simplified model** — 100% branching ratio, decoupled other SUSY particles

## ▶ Event selection: $E_{\text{T}}^{\text{miss}}$ + something (jets, leptons, etc.) for R-parity conserving SUSY

- $E_{\text{T}}^{\text{miss}}$  trigger in many analyses

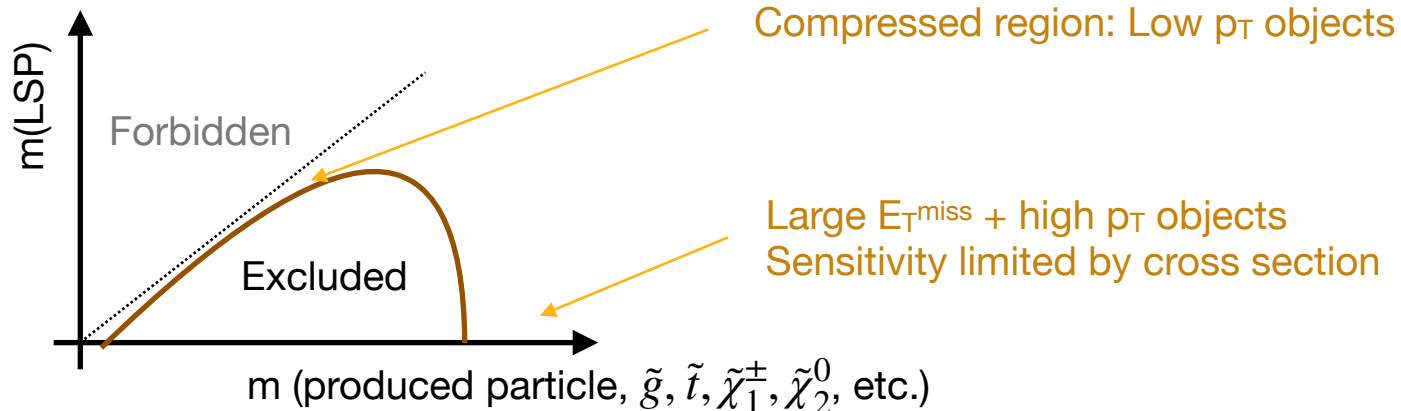
## ▶ Background estimation

- Normalize MC in control regions. Normalization checked in validation regions

## ▶ Uncertainty evaluation

- Experimental syst.: Jet energy scale/resolution, b-tagging, lepton ID, etc.
- Theoretical syst.: scale uncertainties, parton shower, etc.
- Statistical uncertainty is dominant in most SUSY analyses

## ▶ Discover SUSY! ... or exclude models



# New Techniques

## Dedicated object reconstruction for challenging signatures

► Low pt objects for compressed region

Soft muon and electron for compressed region

Fake lepton background

→ data-driven background estimation

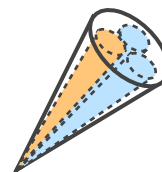
Soft b-tagging for compressed stop and sbottom

$p_T$  below jet reconstruction threshold (20 GeV)

Dedicated SV-based algorithm

► High pt objects for high mass region

Boosted top and boson tagging for large radius jet using jet substructure variables ([2108.07586](#))



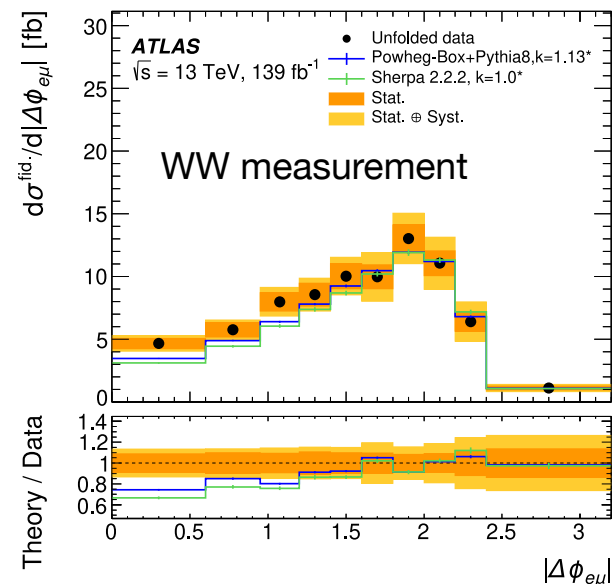
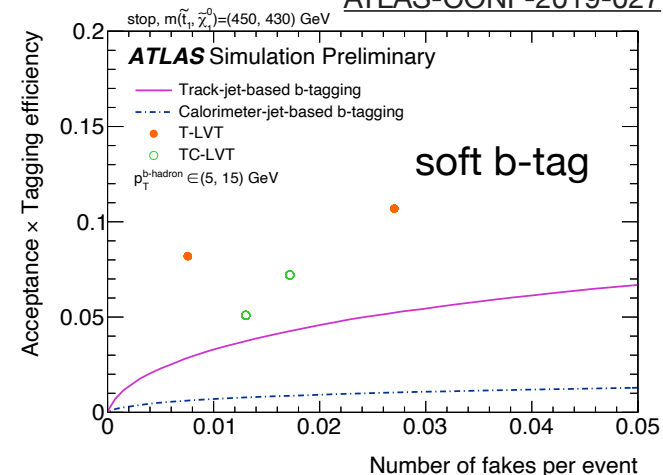
## Background measurement for SUSY searches

Measurement of WW production in decay topology

inspired by EW SUSY searches ([2206.15231](#))

→ improved background modeling in control regions

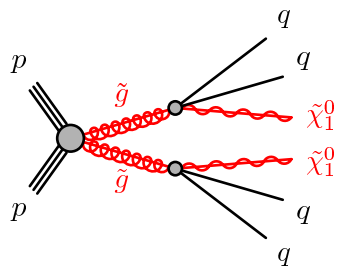
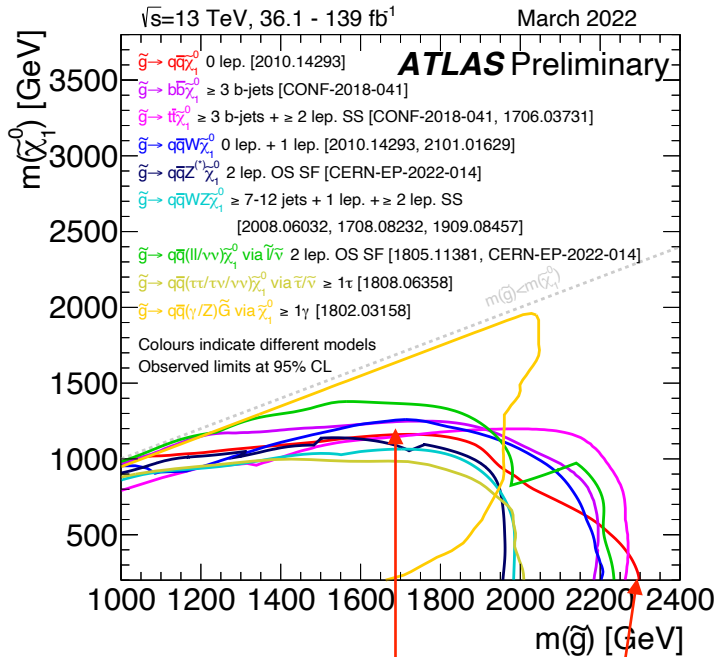
ATLAS-CONF-2019-027



# Gluino, Squark

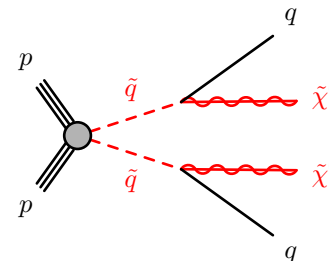
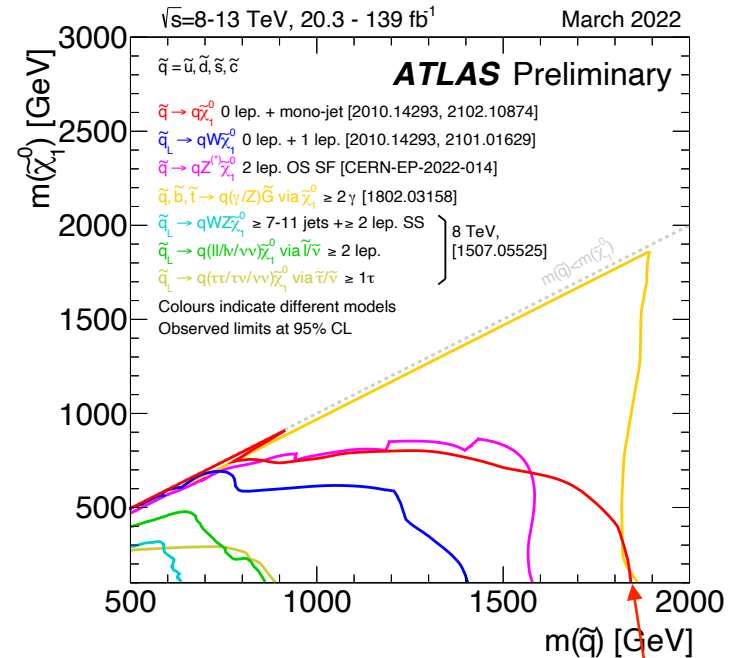
►  $E_T^{\text{miss}} + \text{jets}$  signatures

► Excluded up to around 2 TeV thanks to the large cross sections



LSP 1.2 TeV

gluino 2.3 TeV



squark 1.85 TeV

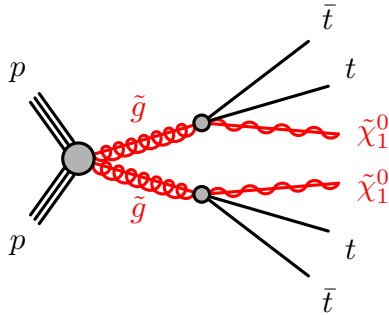
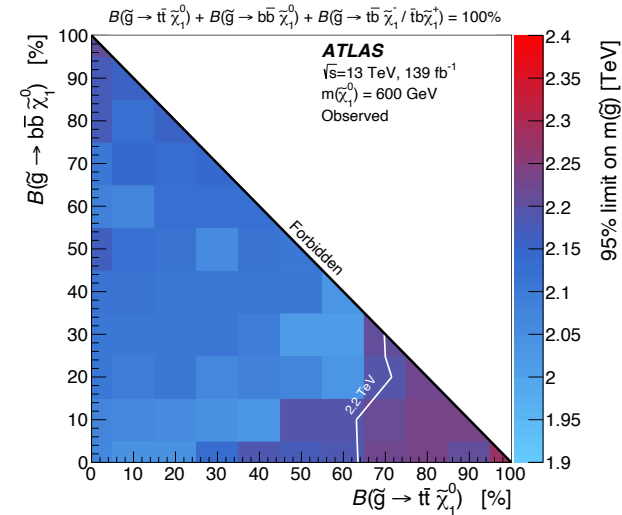
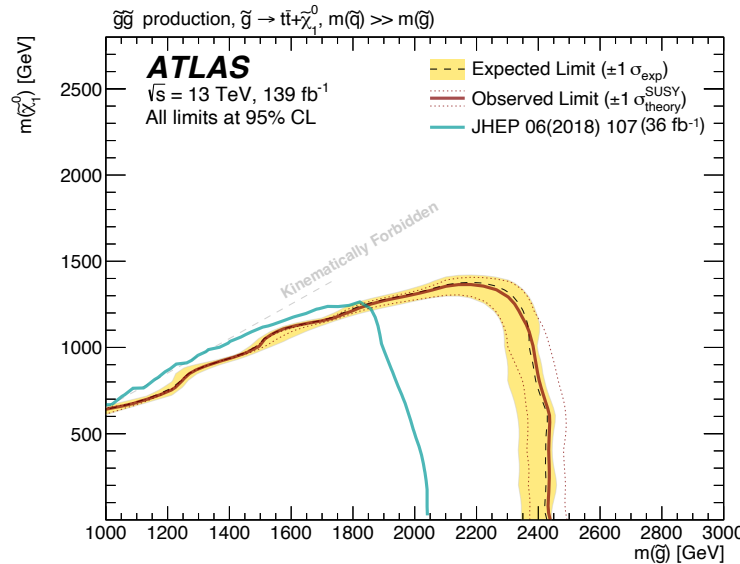
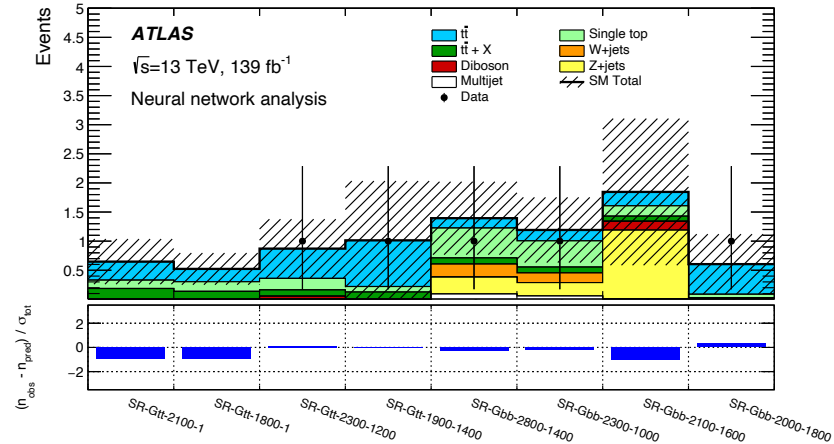
# Gluino $\rightarrow$ tt, bb, tb

New result

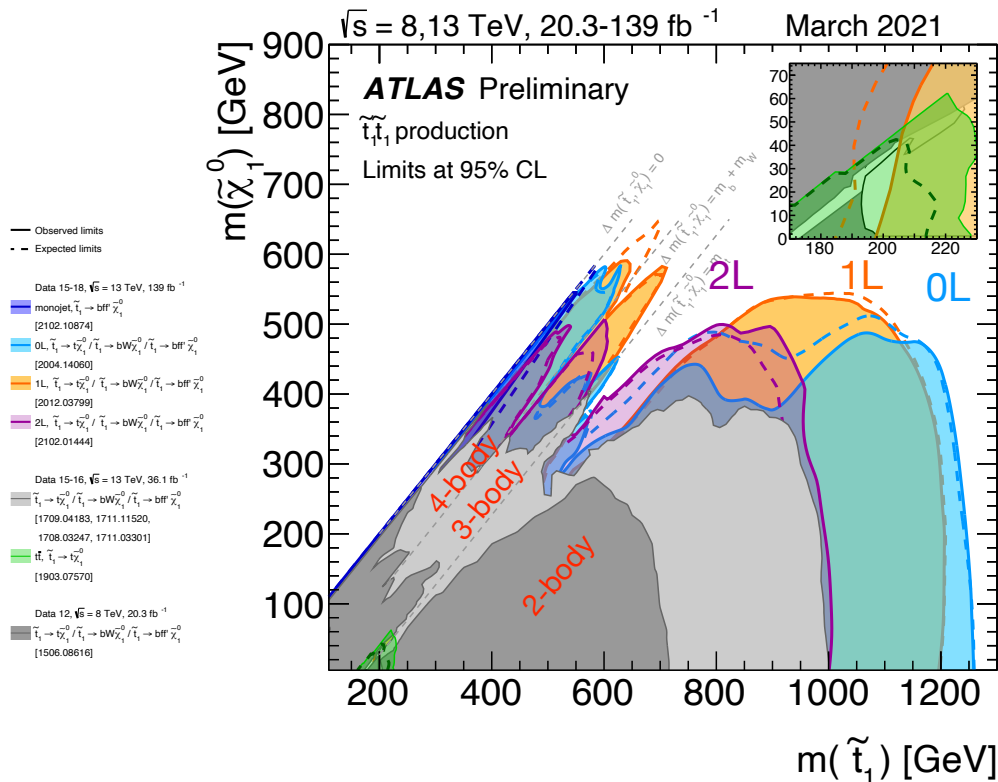
2211.08028

## Gluino decay via off-shell stop or sbottom

- ▶  $\geq 3$  b-jets + 0/1L +  $E_T^{\text{miss}}$
- ▶ Neural network in event selection
  - Input: 4 vectors of jets and leptons,  $E_T^{\text{miss}}$
  - $m(\tilde{g})$  and  $m(\tilde{\chi}_1^0)$  added as parameters
- ▶ Interpretation for 3 mixed decay modes
  - $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0, b\bar{b}\tilde{\chi}_1^0, \text{ or } t\bar{b}\tilde{\chi}_1^\pm$



# Stop Searches



- ▶ Stop  $\rightarrow t^{(*)} + \text{LSP}$
- ▶ Low  $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$  — compressed region
  - Soft b-tagging
- ▶ High  $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$ 
  - Boosted top reconstruction
- ▶ 0, 1, 2 lepton searches have compatible sensitivities
  - Combination will improve the limit

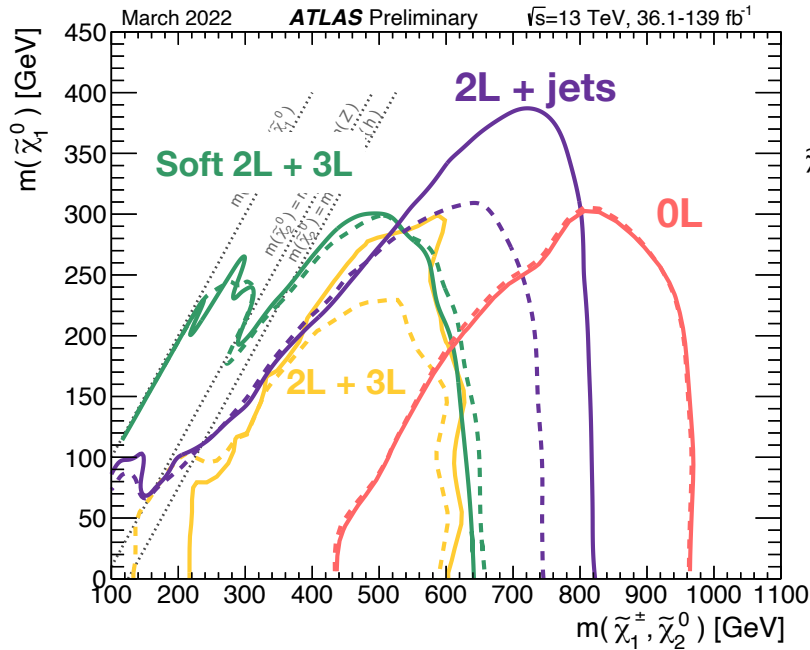
▶ Excluded up to 1.25 TeV for the simplest stop model

▶ However,  $m(\text{stop}) < 1 \text{ TeV}$  is still allowed in the compressed region and complicated scenarios (e.g. higgsino LSP,  $\tilde{t} \rightarrow t\tilde{\chi}_1^0 / b\tilde{\chi}_1^\pm$  mixed scenarios)

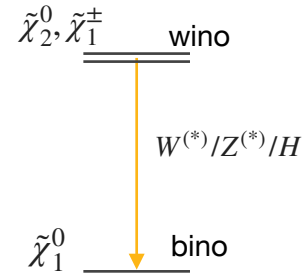
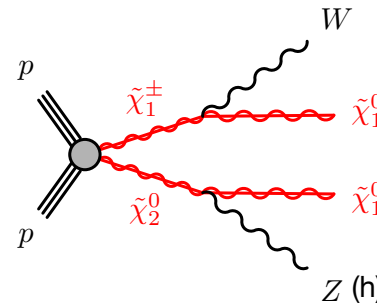


# Electroweak production

Chargino/Neutralino  $\rightarrow$  WZ + LSP



Wino production cross section for  $\tilde{\chi}_2^0, \tilde{\chi}_1^\pm$

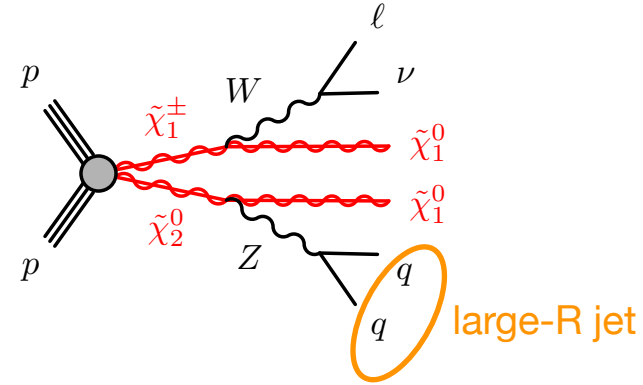


## New results for electroweak production

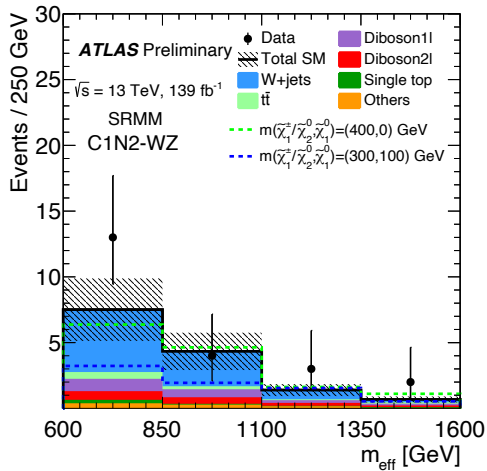
- ▶ 1 lepton + large-R jet for WZ and WW channels ([ATLAS-CONF-2022-059](#))
- ▶ 2 same-sign or 3 leptons for WZ and Wh, and RPV higgsino ([ATLAS-CONF-2022-057](#))
- ▶ 2 taus for electroweakino to stau decays ([ATLAS-CONF-2022-042](#))

# 1L + large-R jet

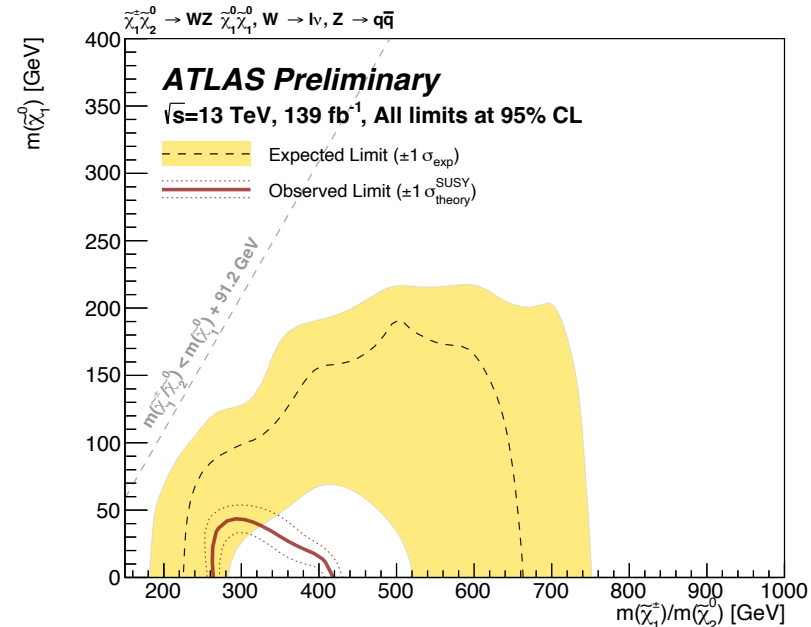
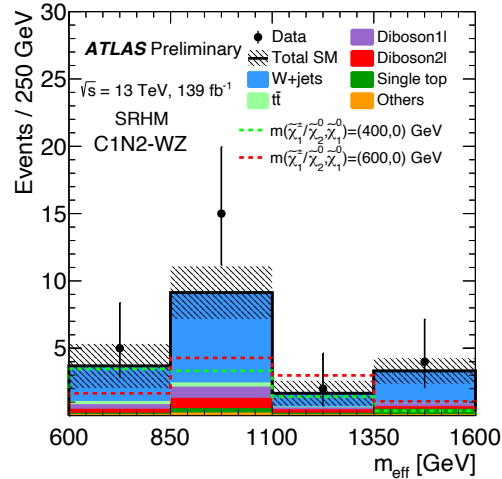
- ▶ Targeting WZ and WW channels
- ▶ For large  $\Delta m(\text{wino, bino})$
- ▶ W/Z boson tagging for large-R jet
- ▶ Large  $E_T^{\text{miss}}$  significance,  $m_T$ ,  $m_{\text{eff}}$
- ▶ Consistent with SM prediction ( $1.1\sigma$ ,  $1.5\sigma$ )



200 GeV <  $m_T$  < 300 GeV

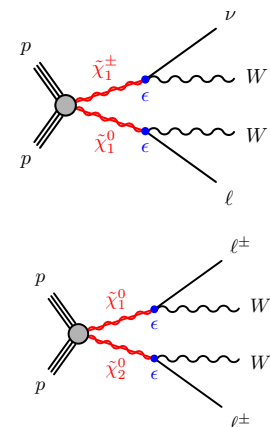
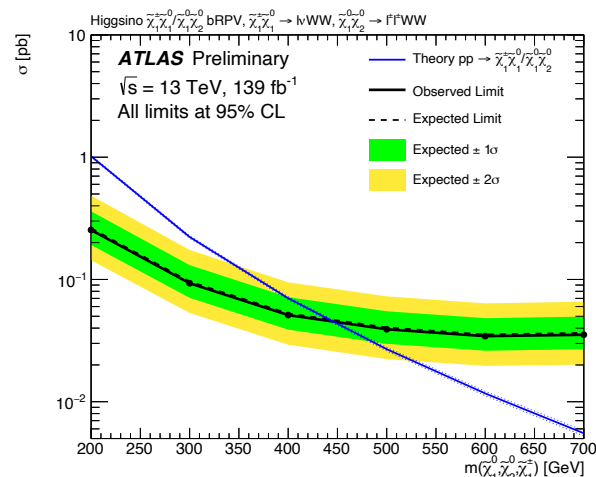
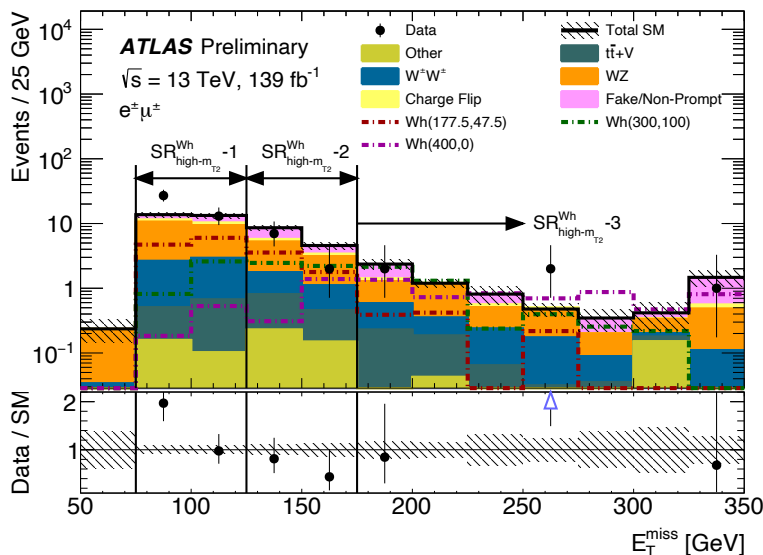
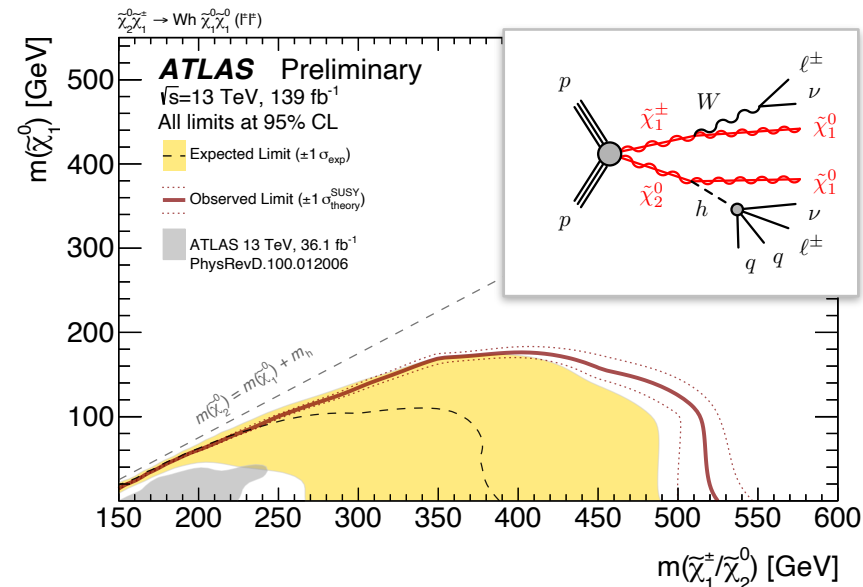


$m_T > 300$  GeV



# 2 same-sign or 3 leptons

- ▶ 2 same-sign or 3 leptons,  $\geq 1$  jets
- ▶ No significant excess observed
- ▶ wino-bino Wh channel
  - $m(\tilde{\chi}_1^\pm/\tilde{\chi}_2^0)$  excluded up to 520 GeV
- ▶ Higgsino-like electroweakino in RPV scenario
  - bilinear lepton-number violating term considered
  - higgsino excluded up to 440 GeV

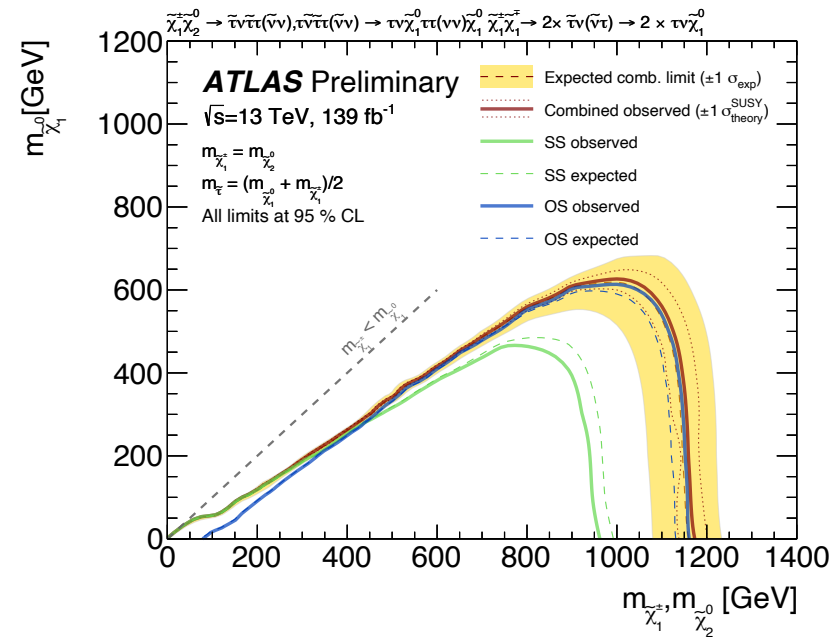
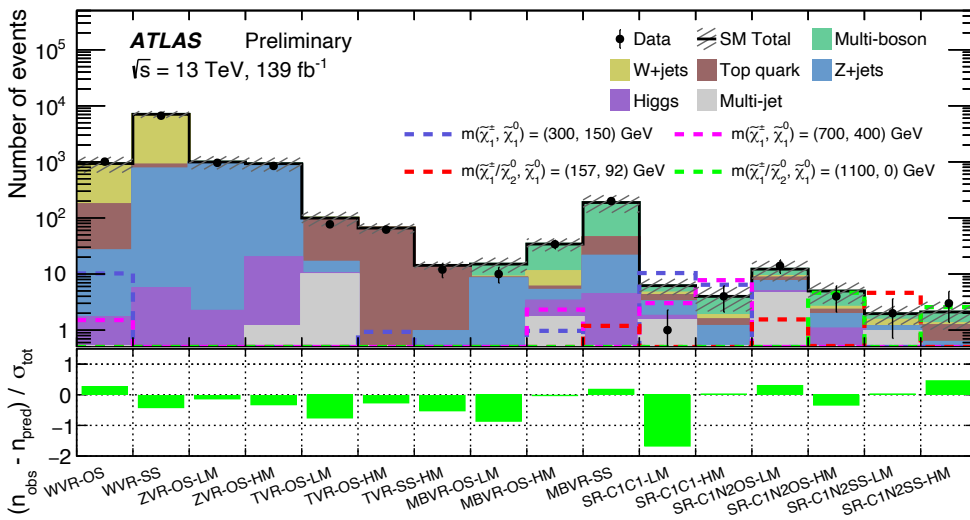
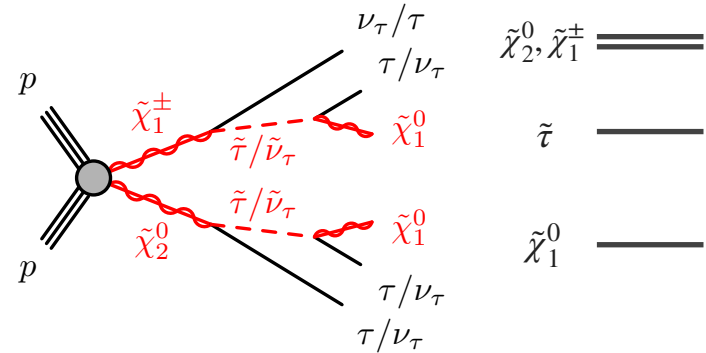


# 2 taus

► Chargino/Neutralino decaying into stau in light stau scenario

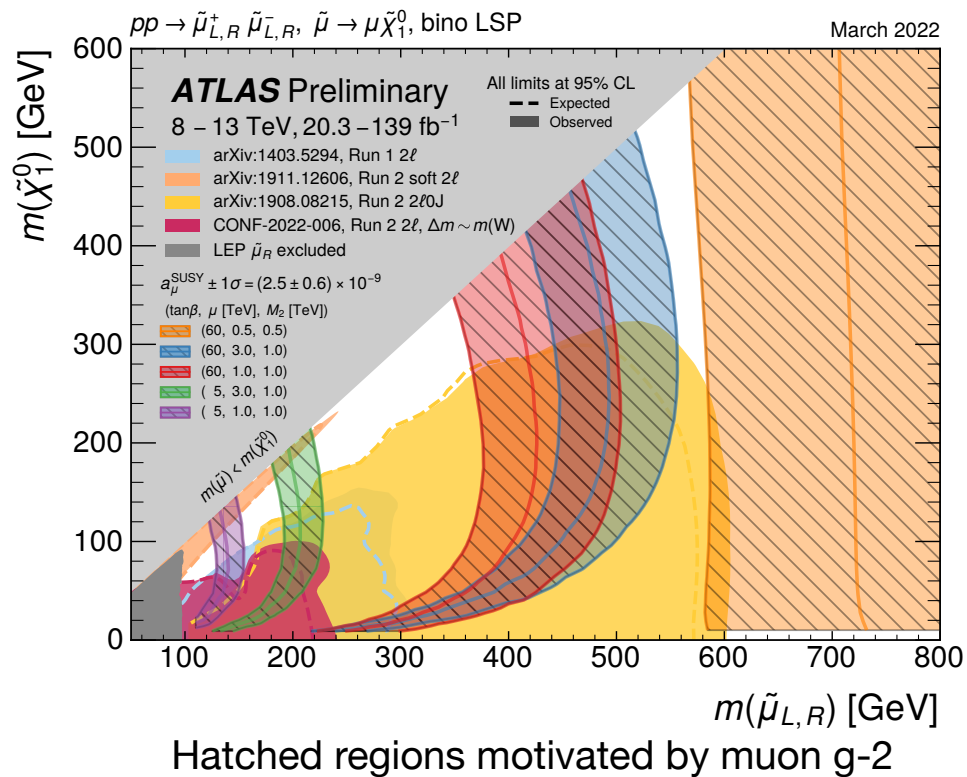
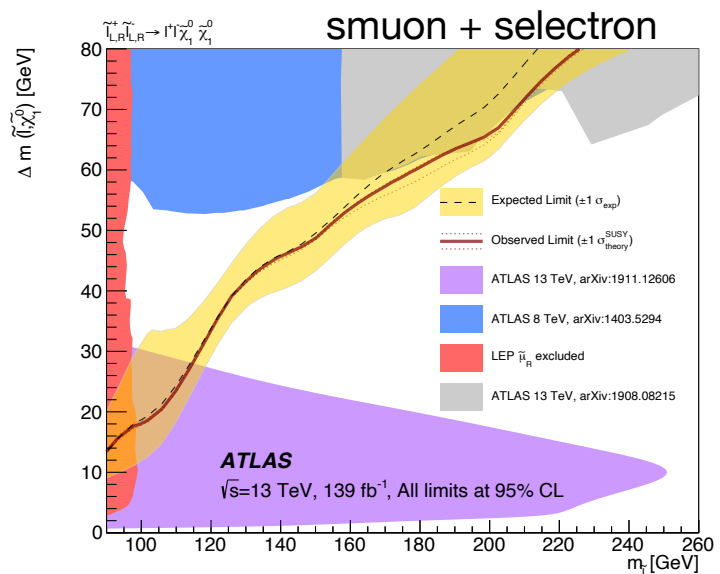
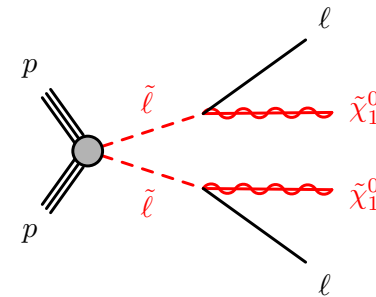
$$- m_{\tilde{\tau}} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2$$

- 2 hadronically decaying taus
- di-tau +  $E_T^{\text{miss}}$  trigger
- RNN-based hadronic tau ID
- High  $E_T^{\text{miss}}$ ,  $m_T$ ,  $m_{T2}$  required



# Slepton Searches

- ▶ Motivated by the **g-2 anomaly**
- ▶  $2L + E_T^{\text{miss}}$  searches
- ▶ Our slepton searches are exploring the preferred phase space
- ▶ New analysis targeting  $\Delta m \sim m_W$  (2209.13935)
- ▶ The gap region still needs to be searched using more data in Run3



# Conclusion

- ▶ Searches for various SUSY scenarios at Run-2
  - All ATLAS SUSY results are available [[here](#)]
  - No evidence found so far
- ▶ SUSY might be
  - a little bit heavier than the current limits.
  - not simple (e.g. low  $E_T^{\text{miss}}$ , SM-like signal)
  - uncovered models, e.g. mixed decay branching ratios
- ▶ Final Run2 analyses to tackle those challenging scenarios are ongoing
- ▶ We already have Run3 data!
- ▶ **Stay tuned for final Run2 and fresh Run3 results**

# Backup

# SUSY Summary

ATLAS SUSY Searches\* - 95% CL Lower Limits  
March 2022

ATLAS Preliminary  
 $\sqrt{s} = 13$  TeV

Model	Signature	$\int \mathcal{L} dt$ [fb <sup>-1</sup> ]	Mass limit	Reference						
Inclusive Searches	$q\bar{q}, \bar{q} \rightarrow q\bar{\chi}_1^0$	0 $e, \mu$ mono-jet	2-6 jets 1-3 jets	$E_{T}^{miss}$ $E_{T}^{miss}$	139 139	$\bar{q}$ [1x, 8x Degen.] $\bar{q}$ [8x Degen.]	1.0 0.9	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 5$ GeV	2010.14293 2102.10874	
	$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 $e, \mu$	2-6 jets	$E_{T}^{miss}$	139	$\bar{g}$ $\bar{g}$	2.3 1.15-1.95	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{\chi}_1^0) = 1000$ GeV	2010.14293 2010.14293	
	$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 $e, \mu$	2-6 jets		139	$\bar{g}$	2.2	$m(\tilde{\chi}_1^0) < 600$ GeV	2101.01629	
	$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$e, \mu$	2 jets	$E_{T}^{miss}$	139	$\bar{g}$	2.2	$m(\tilde{\chi}_1^0) < 700$ GeV	CERN-EP-2022-014	
	$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$	0 $e, \mu$	7-11 jets	$E_{T}^{miss}$	139	$\bar{g}$	1.97	$m(\tilde{\chi}_1^0) < 600$ GeV	2008.06032	
	$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}Z\tilde{\chi}_1^0$	SS $e, \mu$	6 jets		139	$\bar{g}$	1.15	$m(\tilde{g}) - m(\tilde{\chi}_1^0) = 200$ GeV	1909.08457	
	$\bar{g}\bar{g}, \bar{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 $e, \mu$ SS $e, \mu$	3 $b$ 6 jets	$E_{T}^{miss}$	79.8 139	$\bar{g}$ $\bar{g}$	2.25 1.25	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300$ GeV	ATLAS-CONF-2018-041 1909.08457	
	3 <sup>rd</sup> gen. squarks direct production	$\bar{b}_1\bar{b}_1$	0 $e, \mu$	2 $b$	$E_{T}^{miss}$	139	$\bar{b}_1$ $\bar{b}_1$	1.255 0.68	$m(\tilde{\chi}_1^0) < 400$ GeV 10 GeV $< \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527
$\bar{b}_1\bar{b}_1, \bar{b}_1 \rightarrow b\tilde{\nu}_2^0 \rightarrow b\tilde{h}_1^0$		0 $e, \mu$ 2 $\tau$	6 $b$ 2 $b$	$E_{T}^{miss}$ $E_{T}^{miss}$	139 139	$\bar{b}_1$ $\bar{b}_1$	0.23-1.35 0.13-0.85	$\Delta m(\tilde{\nu}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV $\Delta m(\tilde{\nu}_2^0, \tilde{\chi}_1^0) = 130$ GeV, $m(\tilde{\chi}_1^0) = 0$ GeV	1908.03122 2103.08189	
$\bar{t}_1\bar{t}_1, \bar{t}_1 \rightarrow t\tilde{\chi}_1^0$		0-1 $e, \mu$	$\geq 1$ jet	$E_{T}^{miss}$	139	$\bar{t}_1$	1.25	$m(\tilde{\chi}_1^0) = 1$ GeV	2004.14060, 2012.03799	
$\bar{t}_1\bar{t}_1, \bar{t}_1 \rightarrow Wb\tilde{\chi}_1^0$		1 $e, \mu$	3 jets/1 $b$	$E_{T}^{miss}$	139	$\bar{t}_1$	0.65	$m(\tilde{\chi}_1^0) = 500$ GeV	2012.03799	
$\bar{t}_1\bar{t}_1, \bar{t}_1 \rightarrow \tau b\nu, \tau_1 \rightarrow \tau\tilde{G}$		1-2 $\tau$	2 jets/1 $b$	$E_{T}^{miss}$	139	$\bar{t}_1$	1.4	$m(\tau_1) = 800$ GeV	2108.07665	
$\bar{t}_1\bar{t}_1, \bar{t}_1 \rightarrow c\bar{c}^0 / \bar{c}\bar{c}, \bar{c} \rightarrow c\tilde{\chi}_1^0$		0 $e, \mu$ 0 $e, \mu$	2 $c$ mono-jet	$E_{T}^{miss}$ $E_{T}^{miss}$	36.1 139	$\bar{t}_1$ $\bar{t}_1$	0.85 0.55	$m(\tilde{\chi}_1^0) = 0$ GeV $m(\tilde{t}_1, \bar{c}) - m(\tilde{\chi}_1^0) = 5$ GeV	1805.01649 2102.10874	
$\bar{t}_1\bar{t}_1, \bar{t}_1 \rightarrow c\bar{c}_2^0, \bar{c}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$		1-2 $e, \mu$	1-4 $b$	$E_{T}^{miss}$	139	$\bar{t}_1$	0.067-1.18	$m(\tilde{\chi}_1^0) = 500$ GeV	2006.05880	
$\bar{t}_2\bar{t}_2, \bar{t}_2 \rightarrow \bar{t}_1 + Z$		3 $e, \mu$	1 $b$	$E_{T}^{miss}$	139	$\bar{t}_2$	0.86	$m(\tilde{\chi}_1^0) = 360$ GeV, $m(\tilde{t}_1) - m(\tilde{\chi}_1^0) = 40$ GeV	2006.05880	
EW direct		$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via $WZ$	Multiple $\ell$ /jets $e, \mu$	$\geq 1$ jet	$E_{T}^{miss}$ $E_{T}^{miss}$	139 139	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ $\tilde{\chi}_1^+ \tilde{\chi}_2^0$	0.96 0.205	$m(\tilde{\chi}_1^0) = 0$ , wino-bino $m(\tilde{\chi}_1^+) - m(\tilde{\chi}_1^0) = 5$ GeV, wino-bino	2106.01676, 2108.07586 1911.12606
		$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via $WW$	2 $e, \mu$		$E_{T}^{miss}$	139	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	0.42	$m(\tilde{\chi}_1^0) = 0$ , wino-bino	1908.08215
	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via $Wb$	Multiple $\ell$ /jets		$E_{T}^{miss}$	139	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$	1.06	$m(\tilde{\chi}_1^0) = 70$ GeV, wino-bino	2004.10894, 2108.07586	
	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$ via $\tilde{\ell}_L/\tilde{\nu}$	2 $e, \mu$		$E_{T}^{miss}$	139	$\tilde{\chi}_1^+$	1.0	$m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_1^+) + m(\tilde{\chi}_1^0))$	1908.08215	
	$\tilde{\tau}_1, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 $\tau$		$E_{T}^{miss}$	139	$\tilde{\tau}$ [ $\tilde{\tau}_L, \tilde{\tau}_{R,L}$ ]	0.16-0.3 0.12-0.39	$m(\tilde{\chi}_1^0) = 0$	1911.06660	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$ $e, \mu$	0 jets $\geq 1$ jet	$E_{T}^{miss}$ $E_{T}^{miss}$	139 139	$\tilde{\ell}$ $\tilde{\ell}$	0.7 0.256	$m(\tilde{\chi}_1^0) = 0$ $m(\tilde{\ell}) - m(\tilde{\chi}_1^0) = 10$ GeV	1908.08215 1911.12606	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 $e, \mu$ 4 $e, \mu$ 0 $e, \mu$	$\geq 3$ $b$ 0 jets $\geq 2$ large jets	$E_{T}^{miss}$ $E_{T}^{miss}$ $E_{T}^{miss}$	36.1 139 139	$\tilde{H}$ $\tilde{H}$ $\tilde{H}$	0.13-0.23 0.55 0.45-0.93	$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G}) = 1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G}) = 1$	1806.04030 2103.11684 2108.07586	
	Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^0$ prod., long-lived $\tilde{\chi}_1^+$	Disapp. trk	1 jet	$E_{T}^{miss}$	139	$\tilde{\chi}_1^+$ $\tilde{\chi}_1^+$	0.21 0.66	Pure Wino Pure higgsino	2201.02472 2201.02472
		Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_{T}^{miss}$	139	$\tilde{g}$	2.05		CERN-EP-2022-029
		Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	pixel dE/dx		$E_{T}^{miss}$	139	$\tilde{g}$ [ $\tau(\tilde{g}) = 10$ ns]	2.2	$m(\tilde{\chi}_1^0) = 100$ GeV	CERN-EP-2022-029
$\tilde{\ell}\tilde{\ell}, \tilde{\ell} \rightarrow \ell\tilde{G}$		Displ. lep		$E_{T}^{miss}$	139	$\tilde{\ell}, \tilde{\mu}$ $\tilde{\tau}$	0.7 0.34 0.36	$\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\ell}) = 0.1$ ns $\tau(\tilde{\ell}) = 10$ ns	2011.07812 2011.07812 CERN-EP-2022-029	
RPV	$\tilde{\chi}_1^+ \tilde{\chi}_1^0 / \tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow Z\ell - \ell\ell\ell$	3 $e, \mu$		$E_{T}^{miss}$	139	$\tilde{\chi}_1^+ \tilde{\chi}_1^0$ [ $BR(Z\tau) = 1, BR(Z\ell) = 1$ ]	0.625 1.05	Pure Wino	2011.10543	
	$\tilde{\chi}_1^+ \tilde{\chi}_1^0 / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 $e, \mu$	0 jets	$E_{T}^{miss}$	139	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ [ $A_{033} \neq 0, A_{124} \neq 0$ ]	0.95 1.55	$m(\tilde{\chi}_1^0) = 200$ GeV	2103.11684 1804.03568	
	$\bar{g}\bar{g}, \bar{g} \rightarrow q\bar{q}\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow q\bar{q}q$	4-5 large jets			36.1	$\bar{g}$ [ $m(\tilde{\chi}_1^0) = 200$ GeV, 1100 GeV]	1.3 1.9	Large $\tilde{\chi}_{1,2}^0$	ATLAS-CONF-2018-003	
	$\bar{u}, \bar{t} \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow tbs$	Multiple			36.1	$\bar{t}$ [ $A_{123} = 2e-4, 1e-2$ ]	0.55 1.05	$m(\tilde{\chi}_1^0) = 200$ GeV, bino-like		
	$\bar{u}, \bar{t} \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow bbs$	$\geq 4b$			139	$\bar{t}$	0.95	$m(\tilde{\chi}_1^0) = 500$ GeV		
	$\bar{t}_1\bar{t}_1, \bar{t}_1 \rightarrow bs$	2 jets + 2 $b$			36.7	$\bar{t}_1$ [ $q\bar{q}, b\bar{s}$ ]	0.42 0.61			
	$\bar{t}_1\bar{t}_1, \bar{t}_1 \rightarrow q\ell$	2 $e, \mu$ 1 $\mu$	2 $b$ DV		36.1 136	$\bar{t}_1$ $\bar{t}_1$	1.0 1.6	$BR(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta = 1$	2010.01015 1710.07171 1710.05544 2003.11956	
$\tilde{\chi}_1^0 / \tilde{\chi}_2^0 / \tilde{\chi}_1^+, \tilde{\chi}_1^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 $e, \mu$	$\geq 6$ jets		139	$\tilde{\chi}_1^0$ $\tilde{\chi}_1^+$	0.2-0.32	Pure higgsino	2106.09609		

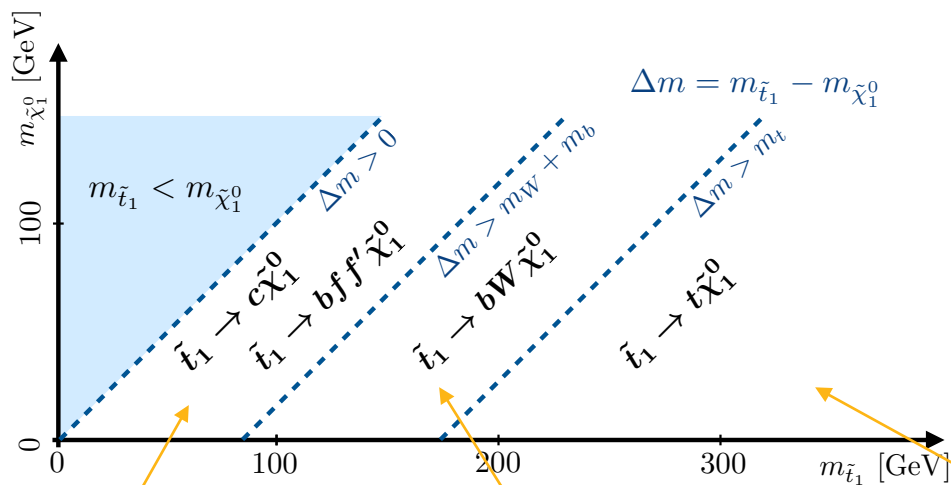
\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

10<sup>-1</sup> 1 Mass scale [TeV]

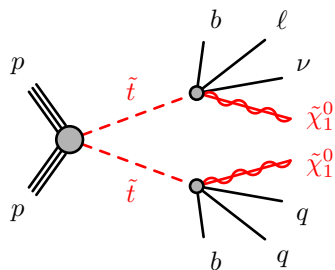


# Stop Searches

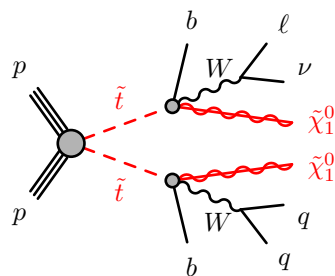
- ▶ Light stop favored by **naturalness**
- ▶ Decay modes depend on  $\Delta m(\text{stop}, \text{LSP})$
- ▶ stop simplified model : stop  $\rightarrow t^* + \text{LSP}$ 
  - stop  $\rightarrow b\tilde{\chi}_1^\pm$  is not considered in this model



4-body (off-shell W)



3-body (off-shell top)



2-body (on-shell top)

