

Searches for strong production of supersymmetric particles with the ATLAS detector

Yi-Lin Yang
On the behalf of ATLAS collaboration

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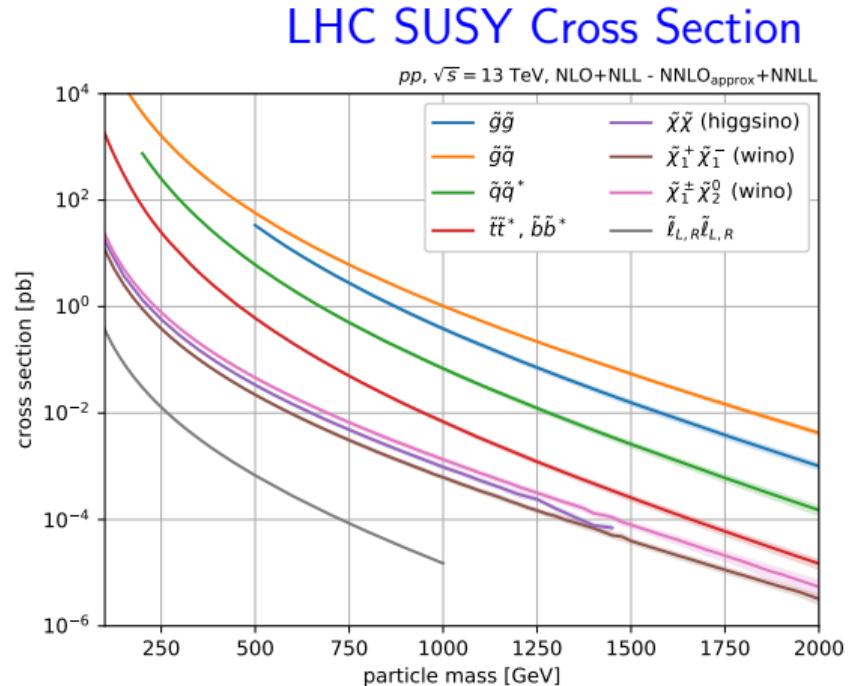


SMU[®]



Introduction

- 13 TeV pp collisions at LHC provide possibility of the search for strong production of supersymmetry particles.
 - ▶ Based on the prediction for cross section.
- For each decay mode, models of both R-parity conservation and violation are considered.
 - ▶ **R-parity conservation (RPC)** : High E_T^{miss} from LSP.
 - ▶ **R-parity violation (RPV)**: High multiplicities of final state, low E_T^{miss} .

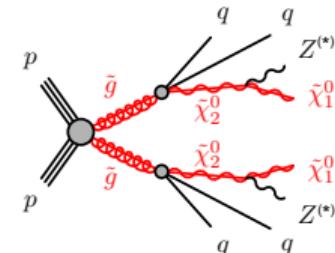


All results with full dataset of 139 fb^{-1} collected by ATLAS.

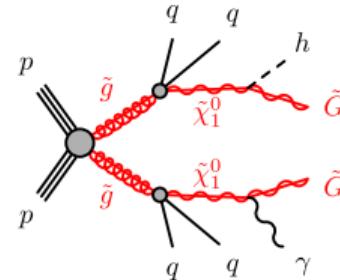
Final states searched in ATLAS

- Various final states are searched in ATLAS for pair production of gluino, squark, stop and sbottom.
- Five publications are selected for this talk.

■ Two opposite-sign leptons, jets and E_T^{miss} ([arXiv: 2204.13072](#))
⇒ aiming for \tilde{g} and 1st/2nd squark with R-parity conservation.

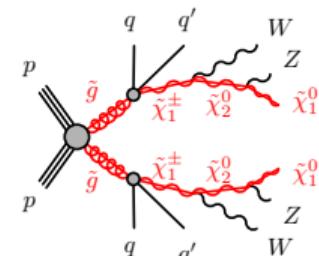


■ Photons, jets and E_T^{miss} ([arXiv:2206.06012](#))
⇒ aiming for \tilde{g} with RPC and
Gauge-Mediated Supersymmetry Breaking (GMSB).



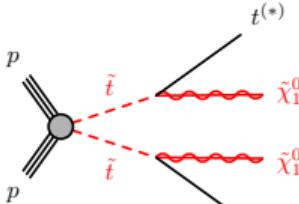
Final states searched in ATLAS

- Two/three same-sign leptons and jets (JHEP 06 (2020) 046)
⇒ aiming for \tilde{t} and \tilde{b} with RPC and \tilde{g} with both RPC and RPV.



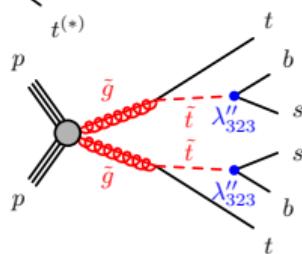
- All-hadronic $t\bar{t}$ and E_T^{miss} (Eur. Phys. J. C 80 (2020) 737)

⇒ aiming for \tilde{t} with RPC.



- Leptons and many jets (Eur. Phys. J. C 81 (2021) 1023)

⇒ aiming for \tilde{g} and \tilde{t} with RPV.



Other relative talks:

- Philipp Mogg's talk for DM on June 27.
- Devanshu Kiran Panchal's talk for long-lived particles on June 27.
- Leonardo Rossi's talk for long-lived particles on July 1.

Special variables for SUSY search

- M_{T2} algorithm:

- ▶ Consider pair production of S . $S_{1/2} \rightarrow P_{1/2}^{Vis} + X_{1/2}^{Invis.}$

$$M_{T2} = \min_{\vec{x}_{T,1} + \vec{x}_{T,2} = \vec{p}_T^{\text{miss}}} \{ \max[M_T(\vec{p}_{T,1}^{\text{Vis}}, \vec{x}_{T,1}), M_T(\vec{p}_{T,2}^{\text{Vis}}, \vec{x}_{T,2})] \}$$

$$m_T^2 (\vec{p}_{T,1/2}, \vec{p}_T^{\text{miss}}) = 2 \times (p_{T,1/2} \times E_T^{\text{miss}} - \vec{p}_{T,1/2} \cdot \vec{p}_T^{\text{miss}})$$

- ▶ M_{T2} can be considered as the transverse mass of S .

- Object-based E_T^{miss} significance (\mathcal{S}):

- ▶ Quantification of the consistency of true zero E_T^{miss} .

high value indicates a real source of E_T^{miss}

$$\mathcal{S}^2 = \frac{|E_T^{\text{miss}}|^2}{\sigma_L^2(1 - \rho_{LT}^2)}$$

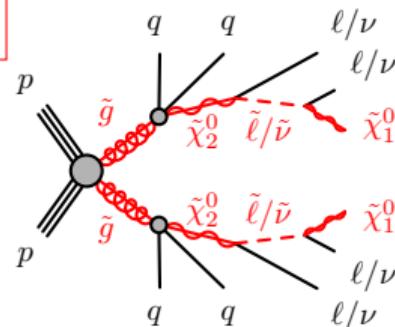
σ_L : total longitudinal resolution relative to the direction of \vec{p}_T^{miss} .

σ_{LT}^2 : correlation factor between total longitudinal and transverse relative resolution.

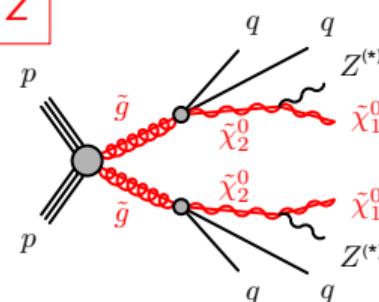
Two opposite-sign leptons

Ref: arXiv: 2204.13072

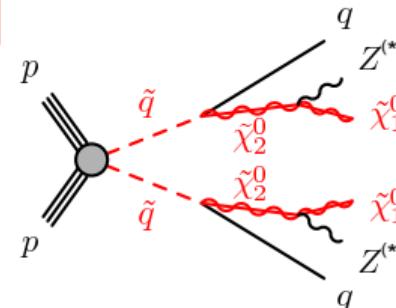
$\tilde{g} - \tilde{\ell}$



$\tilde{g} - Z$



$\tilde{q} - Z$

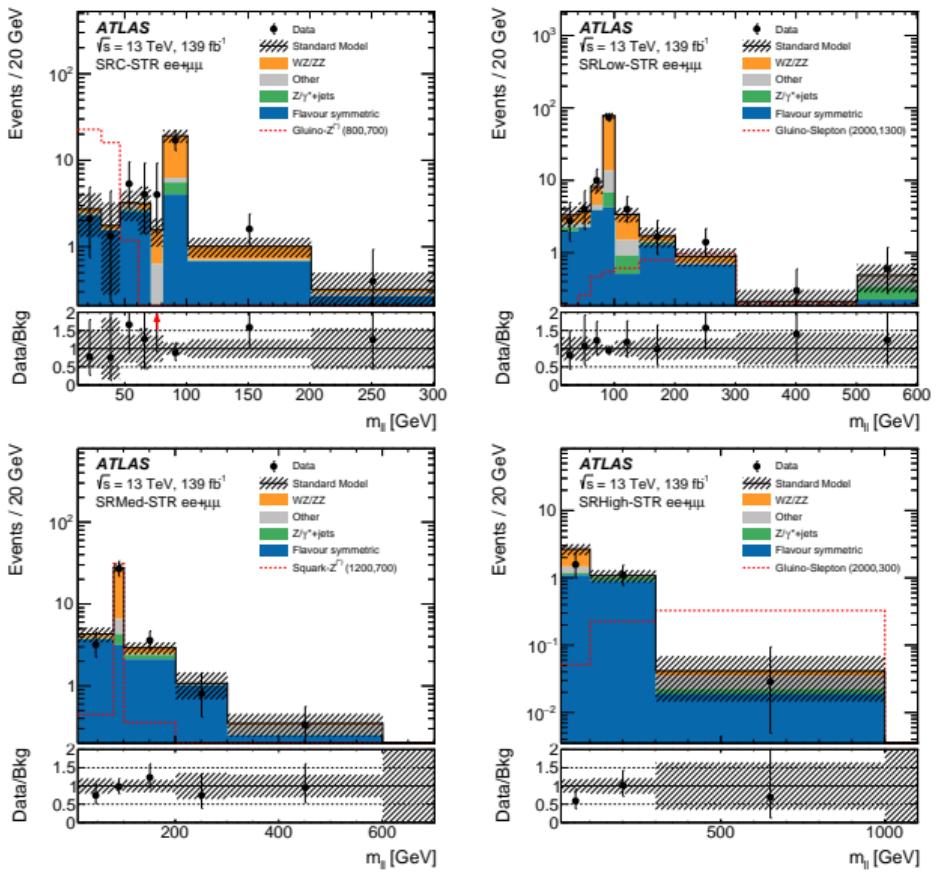


- Gluinos or squarks decay to light quarks and $\tilde{\chi}_2^0$, and the decay of $\tilde{\chi}_2^0$ produces two opposite-sign leptons and $\tilde{\chi}_1^0$.
- The mass of $\tilde{\chi}_2^0$ is assumed as $m_{\tilde{\chi}_2^0} = \frac{m_{\tilde{g}/\tilde{q}} + m_{\tilde{\chi}_1^0}}{2}$
- To cover most of mass difference range between gluino/squarks and $\tilde{\chi}_1^0$, four signal regions, SRC-STR (compressed region), SRLow-STR (low $\Delta(m_{\tilde{g}/\tilde{q}}, m_{\tilde{\chi}_1^0})$), SRMed-STR (medium $\Delta(m_{\tilde{g}/\tilde{q}}, m_{\tilde{\chi}_1^0})$) and SRHigh-STR (high $\Delta(m_{\tilde{g}/\tilde{q}}, m_{\tilde{\chi}_1^0})$), are defined.

Two opposite-sign leptons

- Common selections:
 - ▶ Same-flavour leptons
 - ▶ $n_{\text{jets}} \geq 2$
 - ▶ $\Delta\phi(j_{1,2}, \vec{p}_{\text{T}}^{\text{miss}}) > 0.4$
 - ▶ $m_{\ell\ell} > 12 \text{ GeV}$
 - ▶ $S(E_{\text{T}}^{\text{miss}}) > 10$ (only SRC)
 - ▶ Signal regions are optimized by using H_{T} , $m_{\text{T}2}$, and $p_{\text{T}}^{\ell\ell}$.
- Lower bound of $m_{\ell\ell}$ removes the background of low mass resonance.
- $S(E_{\text{T}}^{\text{miss}})$ and $m_{\text{T}2}$ is used for the reduction of $t\bar{t}$ background.

Ref: arXiv: 2204.13072

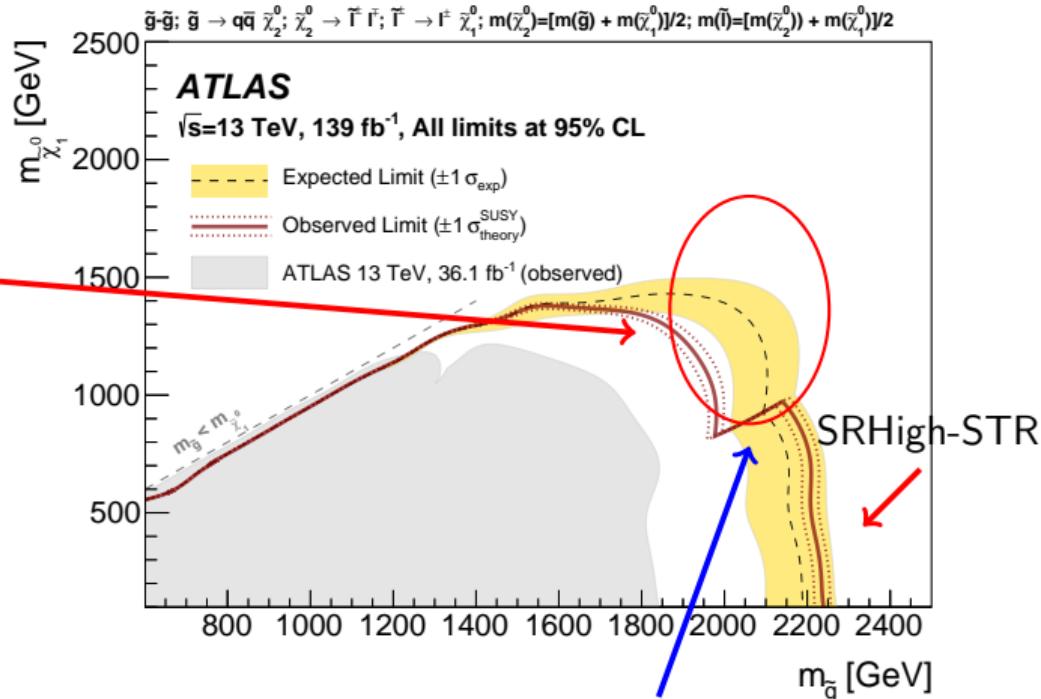
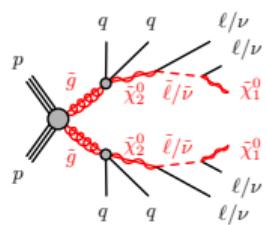


Two opposite-sign leptons: Results

Ref: arXiv: 2204.13072

- Shape fits to binned $m_{\ell\ell}$ in each signal region are combined into limits.
- Small excess in SRLow-STR causes weaker observed exclusion limits.

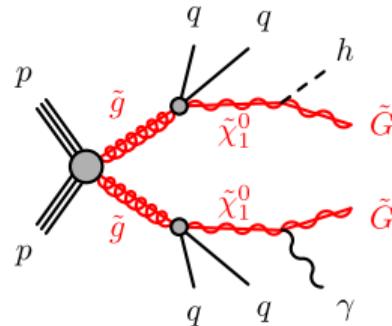
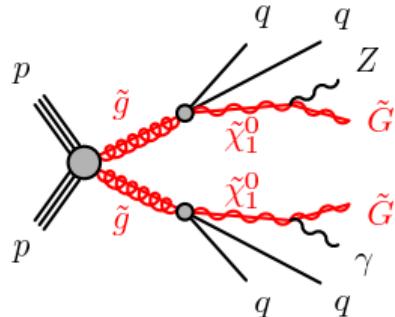
Scenarios	Limits
$\tilde{g} - \tilde{\ell}$	2.25 TeV
$\tilde{g} - Z$	1.95 TeV
$\tilde{q} - Z$	1.55 TeV



* A kink is due to switching between signal regions based on expected sensitivity.

Photons, jets and E_T^{miss}

Ref: arXiv:2206.06012



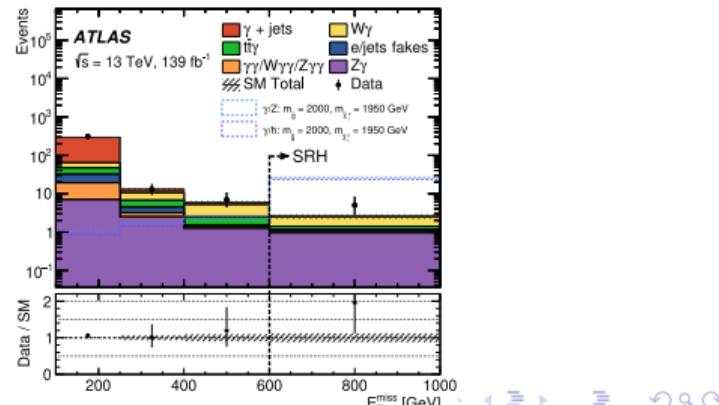
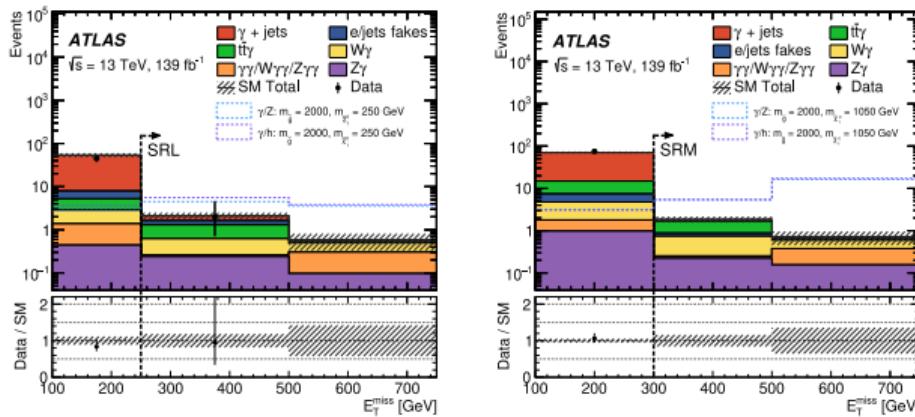
- With General Gauge Mediation (GGM) model, gravitinos with very light mass ($m_{\tilde{G}} = 10^{-9}$ GeV) are the lightest supersymmetry particles contributing to E_T^{miss} .
- Gluinos decay to gravitinos via $\tilde{\chi}_1^0$ with final states including γ/Z or γ/h .
- Three signal regions are designed for different $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$.
 - SRL (low $m_{\tilde{\chi}_1^0}$), SRM, SRH (high $m_{\tilde{\chi}_1^0}$, compressed).

Photons, jets and E_T^{miss}

Ref: arXiv:2206.06012

	SRL	SRM	SRH
N_{photons}	≥ 1	≥ 1	≥ 1
$p_T^{\text{leading-}\gamma}$	> 145 GeV	> 300 GeV	> 400 GeV
N_{leptons}	0	0	0
N_{jets}	≥ 5	≥ 5	≥ 3
$\Delta\phi(\text{jet}, E_T^{miss})$	> 0.4	> 0.4	> 0.4
$\Delta\phi(\gamma, E_T^{miss})$	> 0.4	> 0.4	> 0.4
E_T^{miss}	> 250 GeV	> 300 GeV	> 600 GeV
H_T	> 2000 GeV	> 1600 GeV	> 1600 GeV
R_T^4	< 0.90	< 0.90	-

- Zero lepton reduces leptonic decay of $V\gamma$.
- SRL has high jet activity due to high mass difference.
- High $m_{\tilde{\chi}_1^0}$ contributes to high E_T^{miss} .
- Main background: $t\bar{t}\gamma$, $W\gamma/Z\gamma$ (SRH)

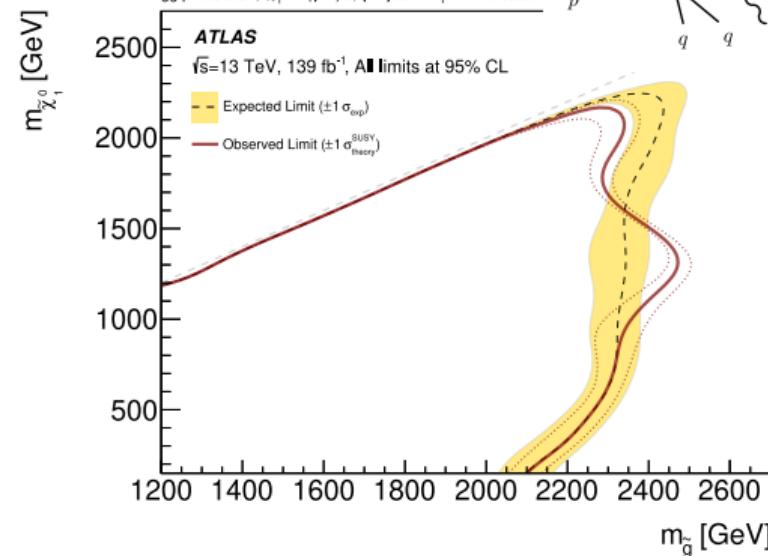
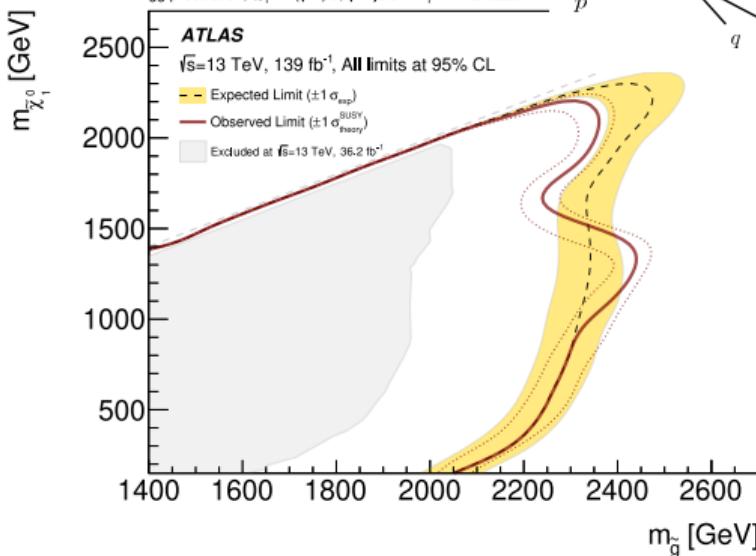
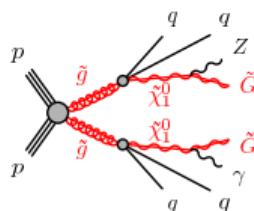


Photons, jets and E_T^{miss} : Results

Ref: arXiv:2206.06012

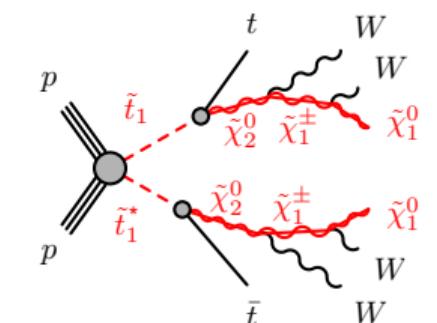
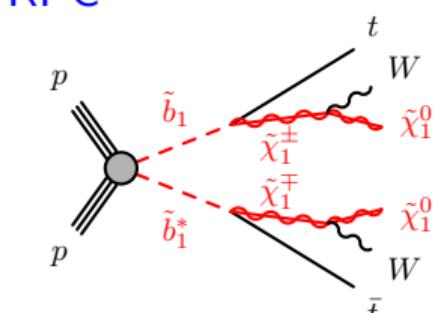
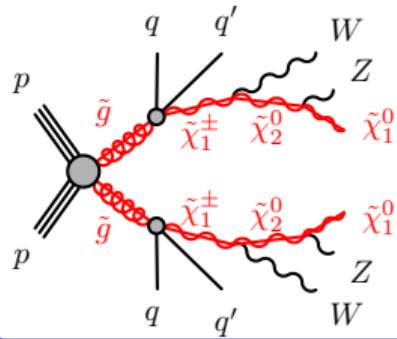
- No significant excess is found.

Scenarios	Limits
$\tilde{g} \rightarrow qq(\gamma/Z)\tilde{G}$	2.2 TeV
$\tilde{g} \rightarrow qq(\gamma/h)\tilde{G}$	2.2 TeV

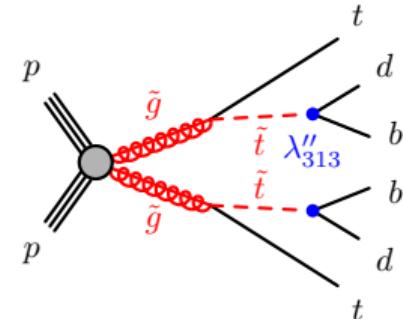


Two/three same-sign leptons

RPC



RPV



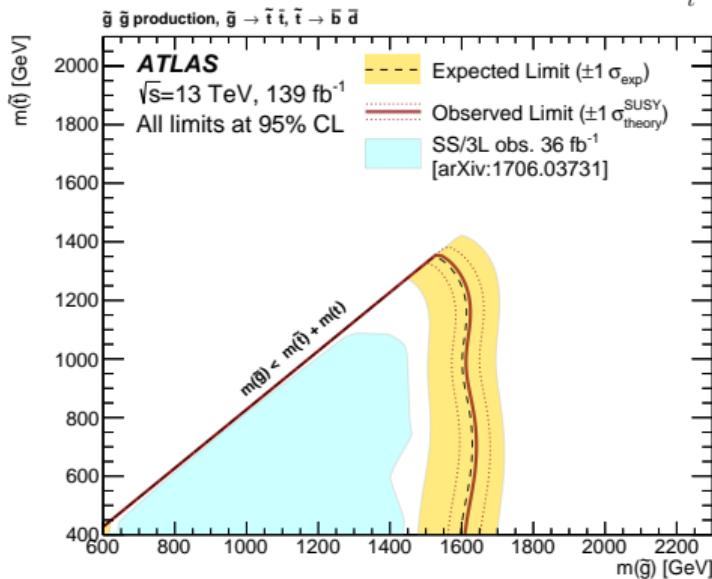
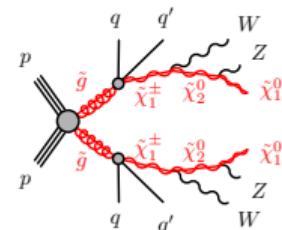
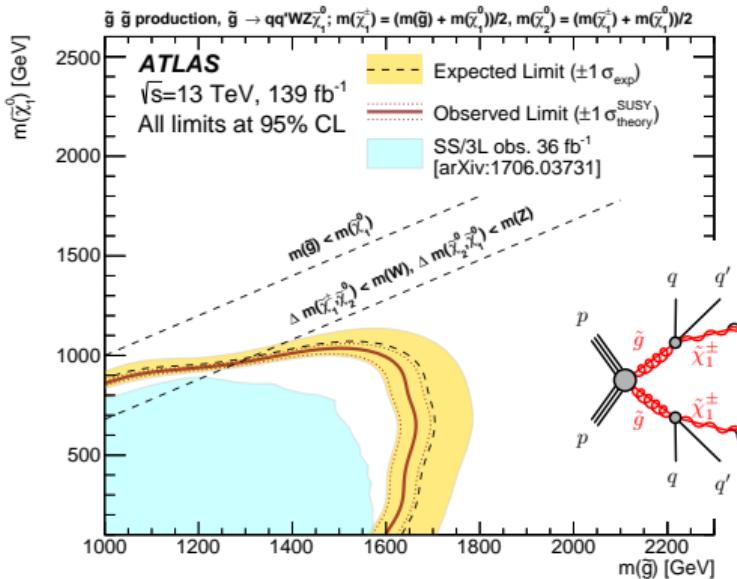
- Various strong productions (\tilde{g} , \tilde{t} , \tilde{b}) are considered in this paper.
- For the R-parity conservation (RPC), two same-sign leptons can be produced in a single decay chain, and one additional same-sign lepton is produced for \tilde{t} production.
- For \tilde{g} with the R-parity violation (RPV), two same-sign top quarks produce same-sign leptons.

Two/three same-sign leptons: Results

Ref: JHEP 06 (2020) 046

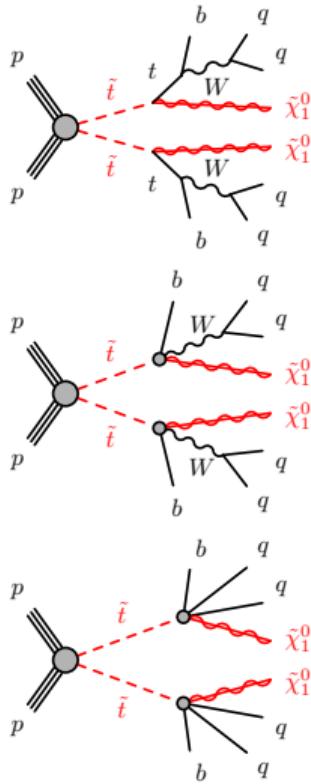
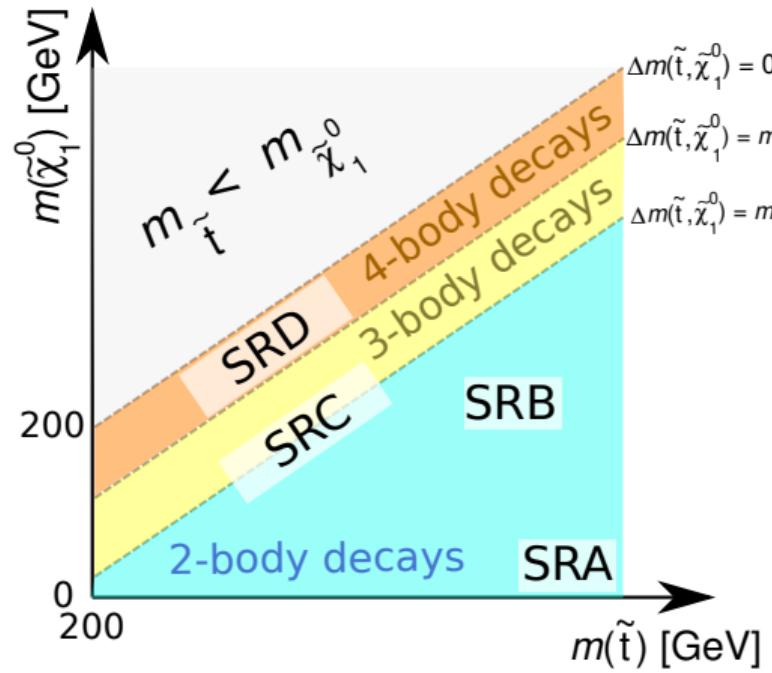
Scenarios	Limits
$\tilde{g} \rightarrow qq' WZ\tilde{\chi}_1^0$	1.6 TeV
$\tilde{g} \rightarrow \bar{t}d\bar{b}$	1.6 TeV
$\tilde{t}_1 \rightarrow tWW\tilde{\chi}_1^0$	750 GeV
$\tilde{b} \rightarrow tW\tilde{\chi}_1^0$	750 GeV

- No significant excess is found.



All-hadronic $t\bar{t}$ and E_T^{miss}

Ref: Eur. Phys. J. C 80 (2020) 737

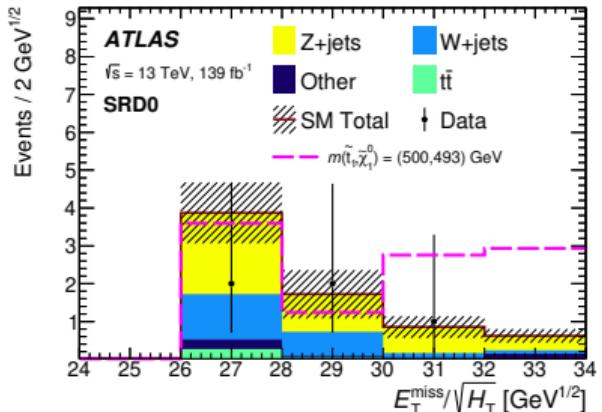
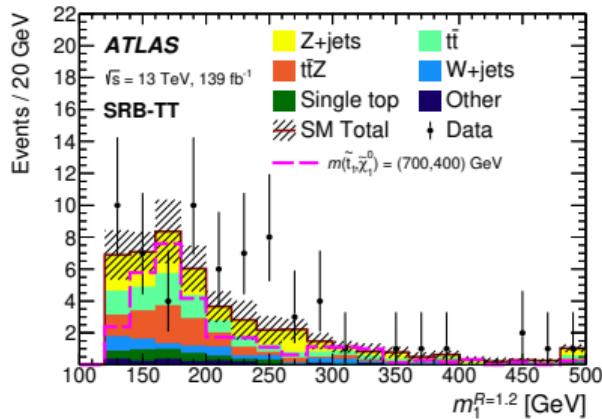


- **SRA**: two body
Highly boosted top quark
- **SRB**: two body
top quark with medium p_T
- **SRC**: two/three body
Compressed region, soft top quark
- **SRD**: four body
soft b quark

All-hadronic $t\bar{t}$ and E_T^{miss}

Ref: Eur. Phys. J. C 80 (2020) 737

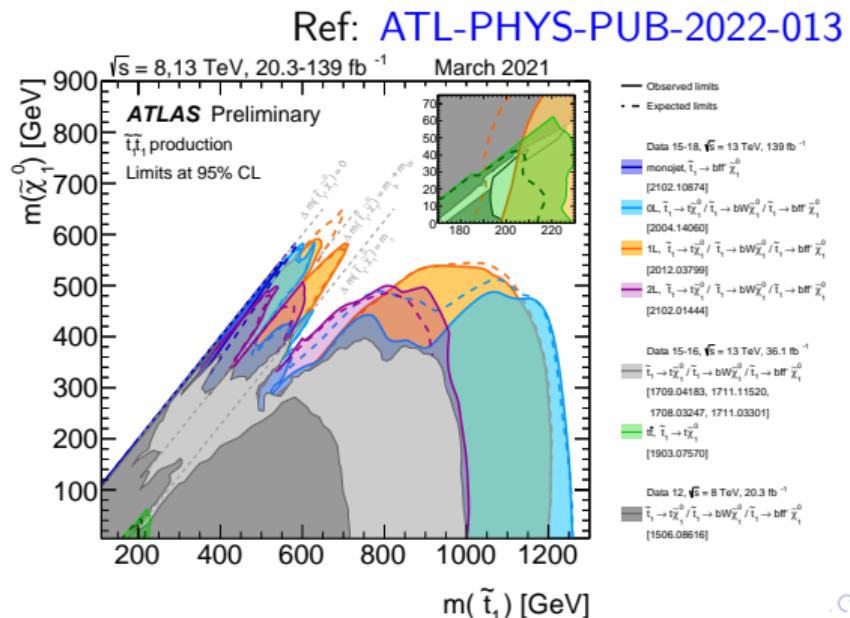
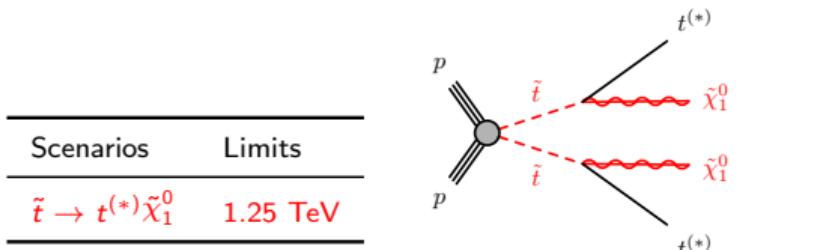
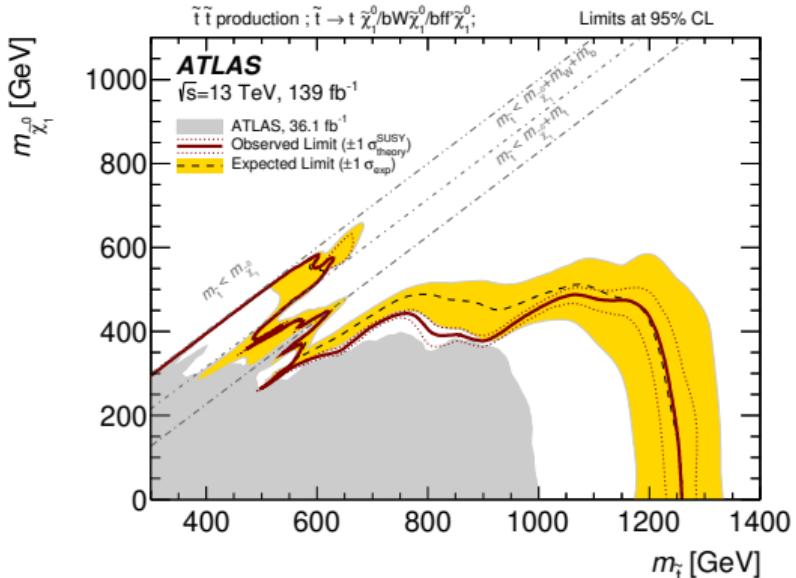
- SRA, SRB: use reclustering jets with large radius to tag boosted top quarks. M_{T2} used for a boundary of SRA and SRB, and object-based E_T^{miss} significance (\mathcal{S}) reduces $t\bar{t}$ background.
- SRC: use R-jigsaw method to identify a ISR hemisphere and a sparticle hemisphere.
- SRD: use soft b-tagging from track jets (down to pT of 5 GeV) and angular separation between jets and E_T^{miss} .
- Major background:
 - ▶ $Z(\rightarrow \nu\nu) + \text{jets}$, $t\bar{t}Z$ (SRA), $t\bar{t}$ (SRB and SRC), $W + \text{jets}$ (SRD).



All-hadronic $t\bar{t}$ and E_T^{miss} : Results

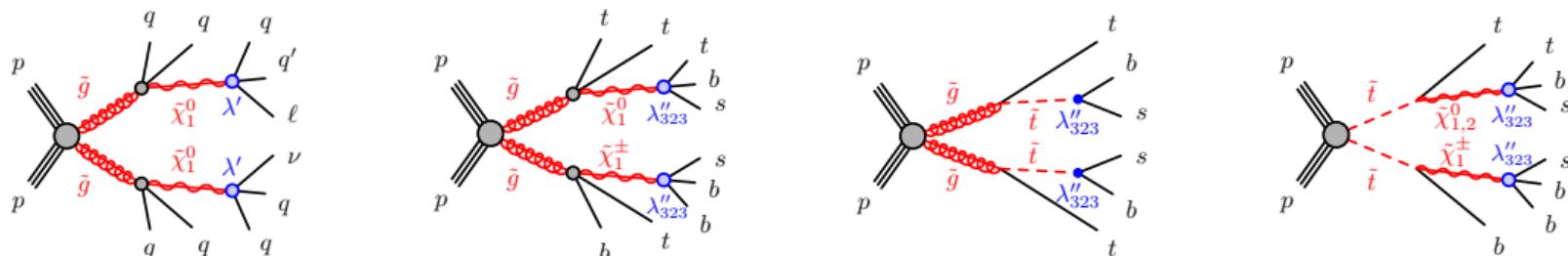
Ref: Eur. Phys. J. C 80 (2020) 737

- No significant excess is found.
- Reinterpret the LQ model (this paper) and DM+ $t\bar{t}$ in low E_T^{miss} region (ATLAS-CONF-2022-007).



Leptons and many jets

Ref: Eur. Phys. J. C 81 (2021) 1023



- Assume 100% branching ratio of $\tilde{\chi}_{1,2}^0 \rightarrow tbs$ and $\tilde{\chi}_1^\pm \rightarrow tbs$.

LSP type	stop		gluino		
	$t\tilde{\chi}_{1,2}^0$	$b\tilde{\chi}_1^\pm$	$tt\tilde{\chi}_{1,2}^0$	$bb\tilde{\chi}_{1,2}^0$	$tb\tilde{\chi}_1^\pm$
Bino	100%	0%	100%	0%	0%
Wino	33%	67%	17%	17%	66%
Higgsino	50%	50%	50%	0%	50%

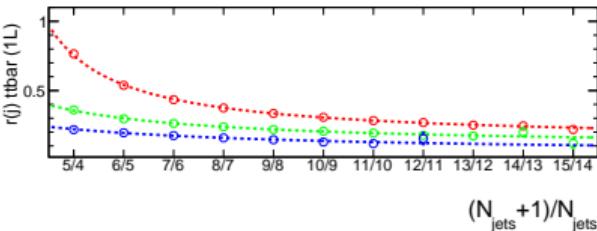
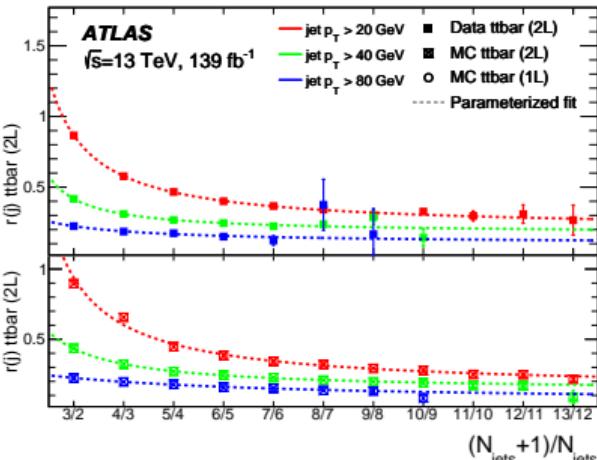
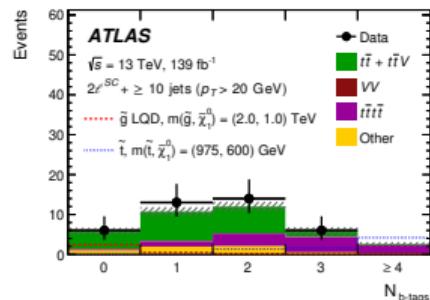
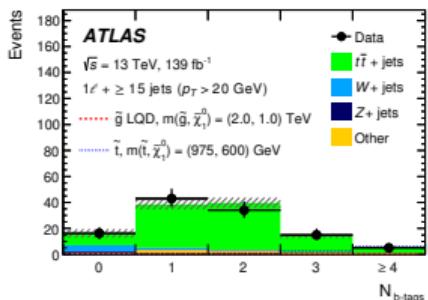
Leptons and many jets

Ref: Eur. Phys. J. C 81 (2021) 1023

Lepton category	Jet multiplicity	Analysis regions
1 ℓ category	4...7 jets	0b ℓ^- , 0b ℓ^+ , 0b $m_{\ell\ell}$, 1b, 2b, 3b, $\geq 4b$
	$8 \dots \geq N_{\text{last}}^l$ jets	0b, 1b, 2b, 3b, $\geq 4b$
2 ℓ^{SC} category	$4 \dots \geq N_{\text{last}}^{l^+ l^-}$ jets	0b 3 ℓ , 0b, 1b, 2b, 3b, $\geq 4b$

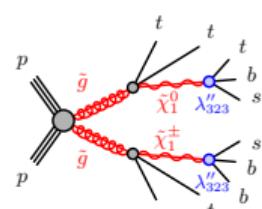
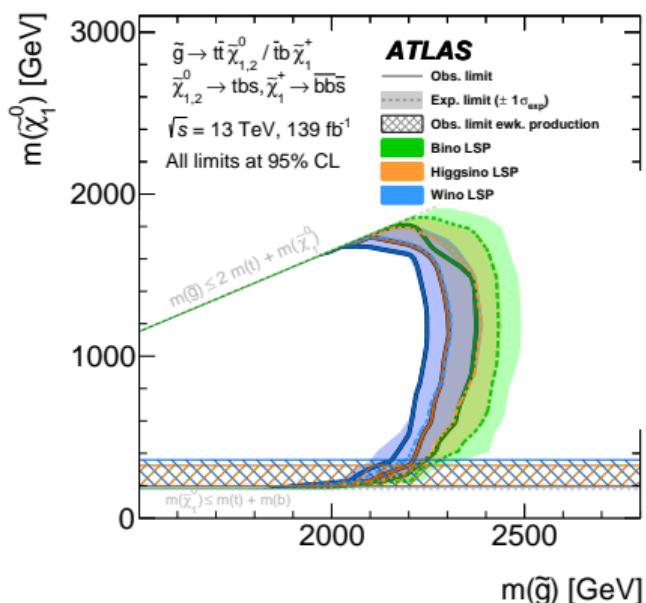
- Background prediction:

- ▶ Use data to extrapolate jet multiplicities to reduce modelling uncertainties.
- ▶ jet multiplicity: parametrization of $n_{\text{jet}+1}/n_{\text{jet}}$.
- ▶ b -jet multiplicity: parametrization of $n_{b\text{-jet}}/n_{\text{jet}}$.



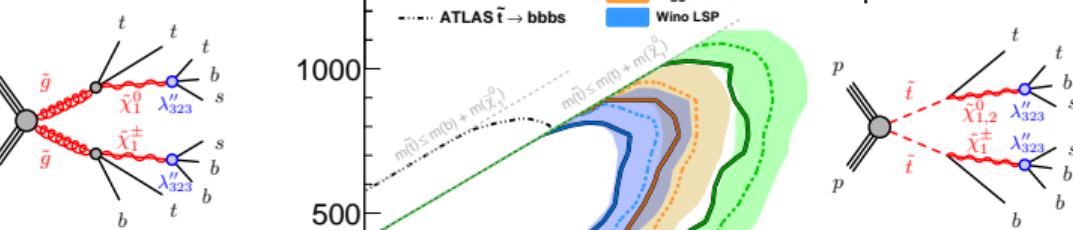
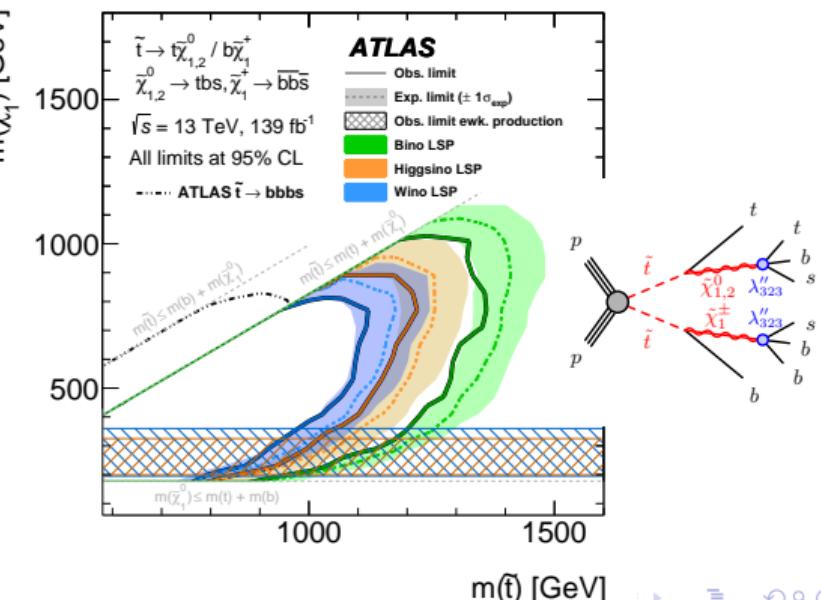
Leptons and many jets: Results

- No significant excess is found.



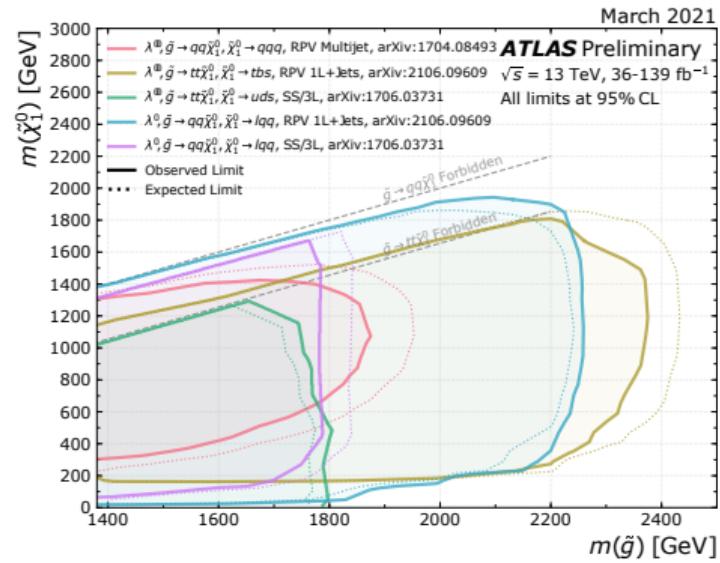
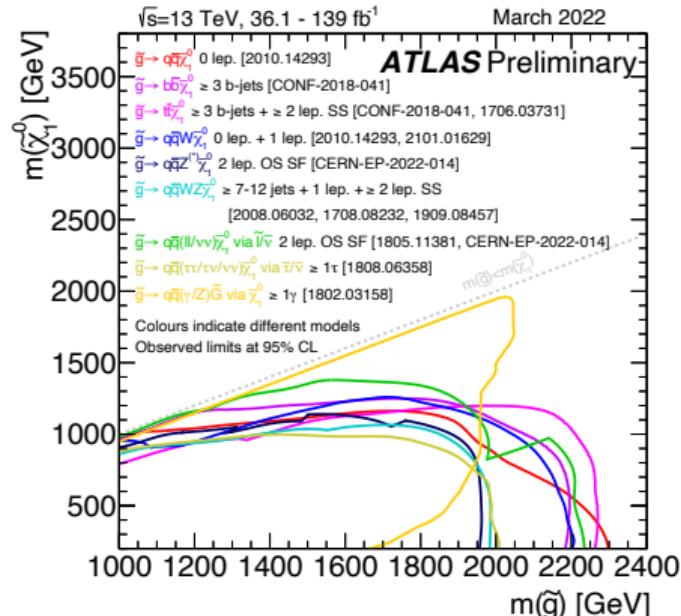
Ref: Eur. Phys. J. C 81 (2021) 1023

Scenarios	Limits
$\tilde{g} \rightarrow q\bar{q}(\ell/\nu)$	2.2 TeV
$\tilde{g} \rightarrow \tilde{t}\bar{b}\bar{s}$	1.8 TeV
$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_{1,2}^0 / \tilde{b}\tilde{b}\tilde{\chi}_1^+$	2.4 TeV
$\tilde{t} \rightarrow t\tilde{\chi}_{1,2}^0 / b\tilde{\chi}_1^+$	1.3 TeV



Summary

- No significant excess is found in all scenarios for this talk.
- A broad SUSY program in ATLAS targets both RPC and RPV models, which is employing advance objects and sophisticated analysis techniques.
- More results with Run2 and the start of Run3 are coming.



Summary Table

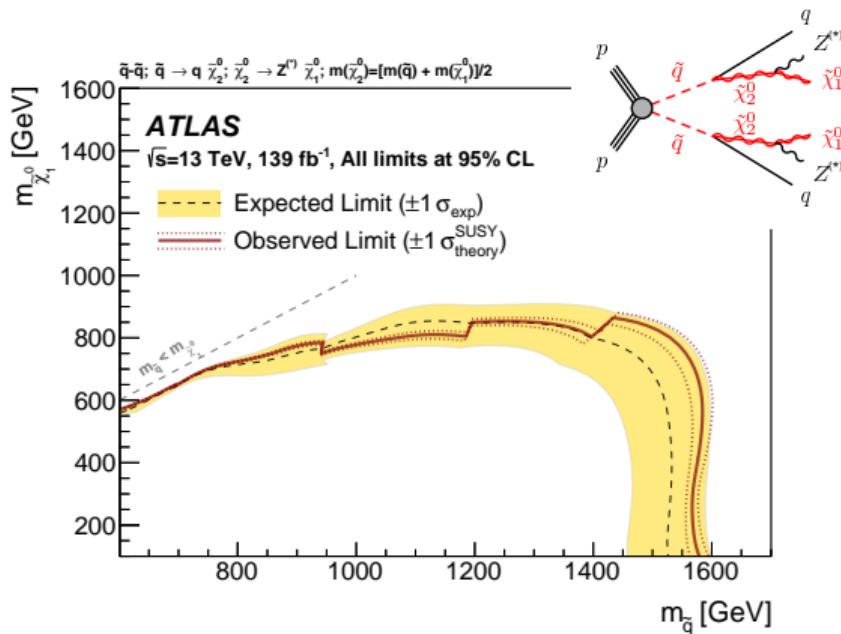
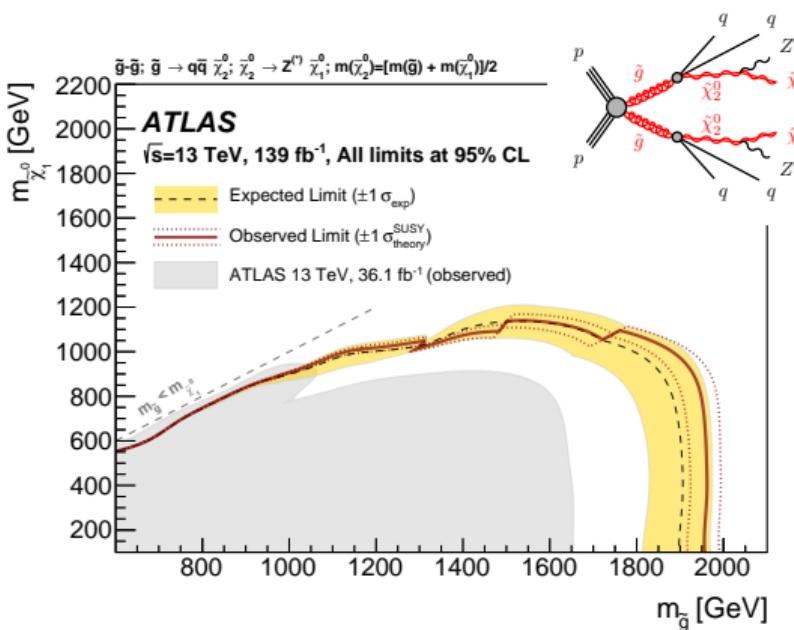
R-parity	Scenarios	OS lep	Photons	SS lep	All-had $t\bar{t}$	lep&jets
RPC	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0; \tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp; \tilde{\ell}^\pm \rightarrow \ell^\pm \tilde{\chi}_1^0$	2.25 TeV				
	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0; \tilde{\chi}_2^0 \rightarrow Z^*\tilde{\chi}_1^0$	1.95 TeV				
	$\tilde{g} \rightarrow qq'WZ\tilde{\chi}_1^0$				1.6 TeV	
	$\tilde{g} \rightarrow qq\tilde{\chi}_1^0; \tilde{\chi}_1^0 \rightarrow (\gamma/Z)\tilde{G}$			2.2 TeV		
	$\tilde{g} \rightarrow qq\tilde{\chi}_1^0; \tilde{\chi}_1^0 \rightarrow (\gamma/h)\tilde{G}$			2.2 TeV		
\tilde{q}	$\tilde{q} \rightarrow q\tilde{\chi}_2^0; \tilde{\chi}_2^0 \rightarrow Z^*\tilde{\chi}_1^0$	1.55 TeV				
\tilde{t}	$\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0; \tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^\pm; \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0$			750 GeV		
	$\tilde{t}_1 \rightarrow t^*\tilde{\chi}_1^0$				1.25 TeV	
\tilde{b}	$\tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm; \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0$			750 GeV		
RPV	$\tilde{g} \rightarrow \bar{t}\tilde{t}; \tilde{t} \rightarrow \bar{d}\bar{b}$			1.6 TeV		
	$\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0; \tilde{\chi}_1^0 \rightarrow q\bar{q}(\ell/\nu)$				2.2 TeV	
	$\tilde{g} \rightarrow \bar{t}\tilde{t}; \tilde{t} \rightarrow b\bar{s}$				1.8 TeV	
	$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_{1,2}^0/\bar{t}b\tilde{\chi}_1^+; \tilde{\chi}_{1,2}^0 \rightarrow tbs; \tilde{\chi}_1^+ \rightarrow \bar{b}\bar{b}\bar{s}$				2.4 TeV	
\tilde{t}	$\tilde{t} \rightarrow t\tilde{\chi}_{1,2}^0/b\tilde{\chi}_1^+; \tilde{\chi}_{1,2}^0 \rightarrow tbs; \tilde{\chi}_1^+ \rightarrow \bar{b}\bar{b}\bar{s}$				1.3 TeV	

Back up

Two opposite-sign leptons: Results

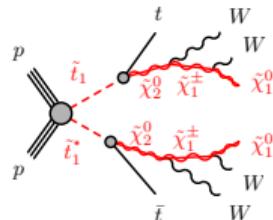
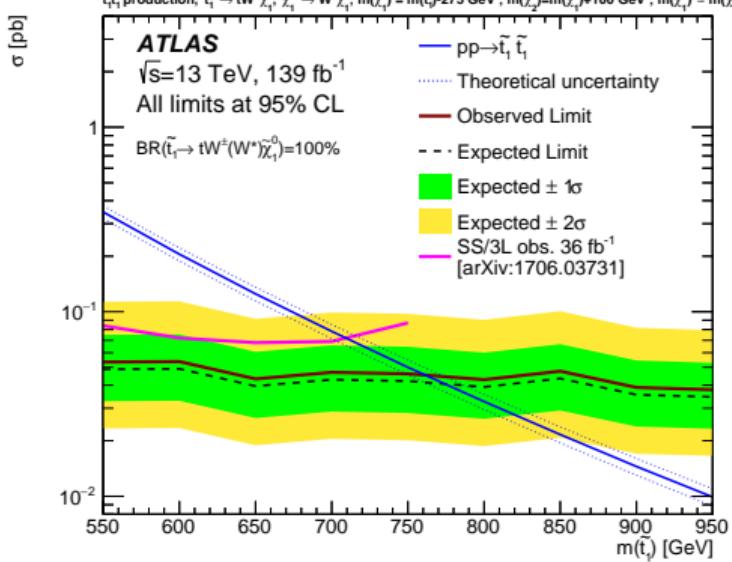
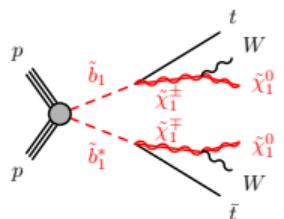
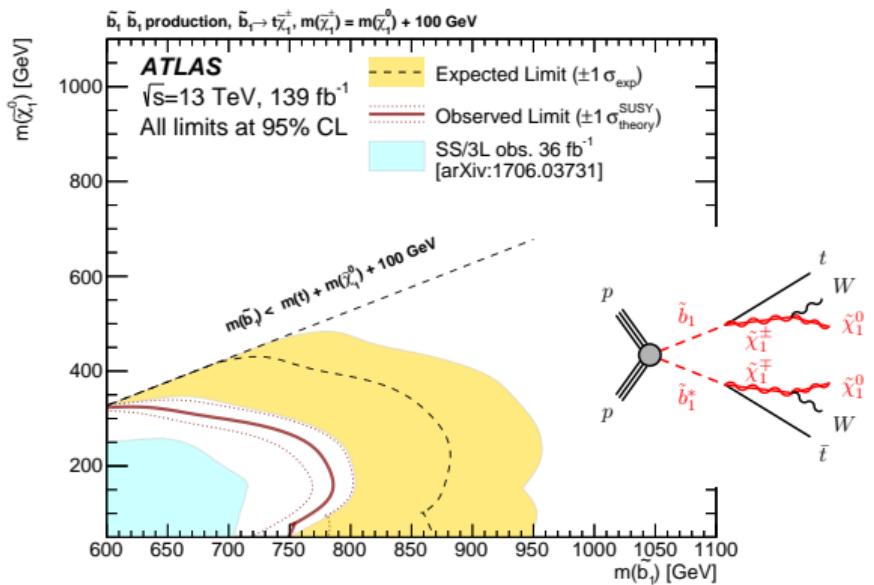
Ref: arXiv: 2204.13072

- $m_{\tilde{g}}$ is excluded up to **1.95 TeV** for $\tilde{g} - Z$ model and **1.55 TeV** for $\tilde{q} - Z$ model.



Two same-sign leptons: Results

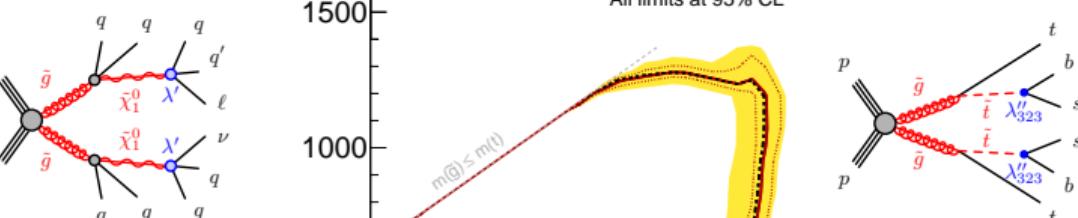
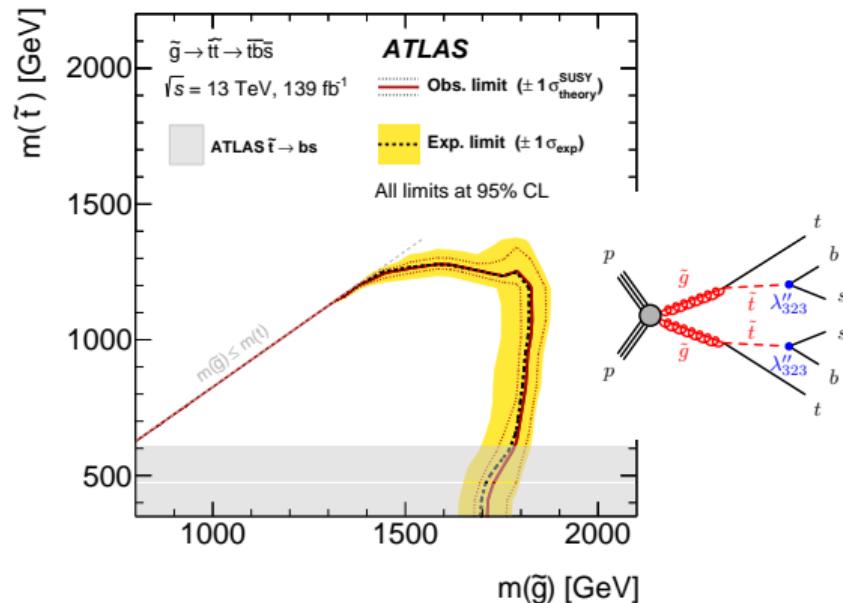
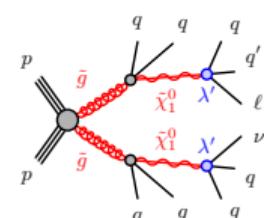
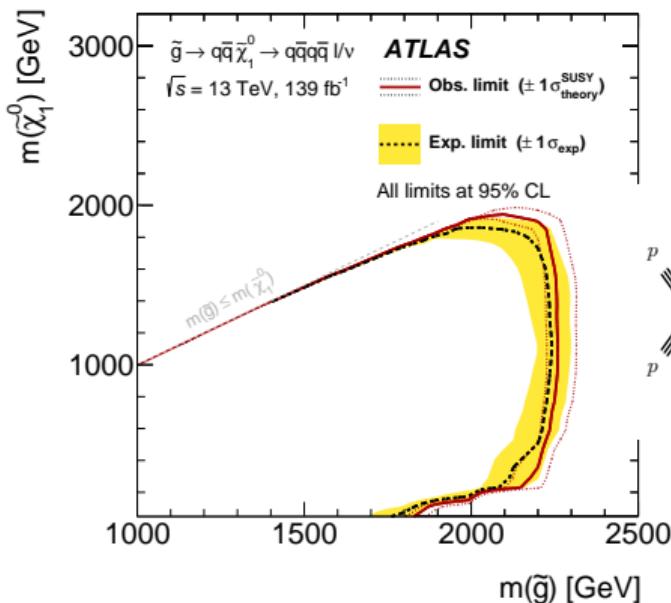
- No significant excess is found.
- The exclusion of $m_{\tilde{b}}$ and $m_{\tilde{t}}$ is reaching up to 750 GeV.



Leptons and many jets: Results

Ref: Eur. Phys. J. C 81 (2021) 1023

- No significant excess is found.
- $m_{\tilde{g}}$ is excluded up to **2.2 TeV** for $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ and **1.8** for $\tilde{g} \rightarrow t\tilde{t}$.



Two opposite-sign leptons:

- Table of model-independent limits.

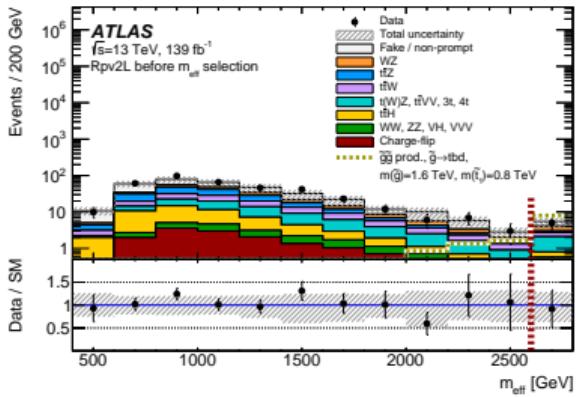
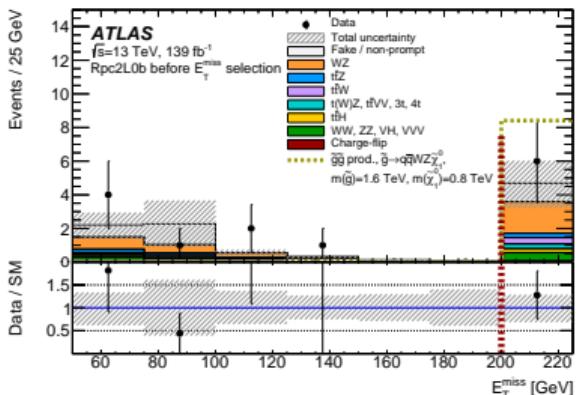
Signal Region	Total Bkg.	Data	$\langle A\epsilon\sigma \rangle_{\text{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}	CL _b	$p(s = 0) (Z)$
SRC-STR							
12–31	2.6 ± 1.3	2	0.03	4.7	$5.7^{+2.1}_{-1.5}$	0.33	0.50 (0.0)
12–61	6.3 ± 1.9	7	0.06	8.4	$8.3^{+3.1}_{-2.3}$	0.51	0.50 (0.0)
31–81	6.8 ± 2.8	9	0.08	11.0	$8.0^{+3.2}_{-1.7}$	0.83	0.18 (0.9)
81–	25.4 ± 3.5	27	0.12	16.4	$15.3^{+5.0}_{-4.6}$	0.61	0.34 (0.4)
SRLow-STR							
12–81	16.8 ± 2.6	18	0.09	12.6	$11.6^{+4.5}_{-3.6}$	0.61	0.39 (0.3)
101–201	12.0 ± 2.3	13	0.08	11.2	$9.6^{+3.8}_{-2.5}$	0.67	0.30 (0.5)
101–301	16.5 ± 2.6	20	0.11	15.4	$11.4^{+4.1}_{-3.6}$	0.84	0.17 (1.0)
301–	4.6 ± 1.4	6	0.07	9.5	$6.6^{+2.8}_{-1.8}$	0.85	0.09 (1.3)
SRMed-STR							
12–101	42 ± 5	38	0.10	13.6	$18.8^{+7.2}_{-5.0}$	0.15	0.50 (0.0)
101–	26 ± 4	27	0.12	16.7	$15.8^{+6.2}_{-4.2}$	0.56	0.41 (0.2)
SRHigh-STR							
12–301	22.7 ± 3.2	18	0.06	8.9	$13.0^{+5.8}_{-3.0}$	0.11	0.50 (0.0)
301–	1.5 ± 1.0	1	0.03	3.7	$4.4^{+1.8}_{-1.0}$	0.32	0.50 (0.0)
On-Z							
SRZLow-STR	33 ± 4	35	0.15	20.5	$17.0^{+5.4}_{-4.5}$	0.76	0.25 (0.7)
SRZMed-STR	15.2 ± 2.4	15	0.08	10.7	$10.3^{+4.4}_{-2.8}$	0.53	0.50 (0.0)
SRZHigh-STR	4.5 ± 1.2	3	0.04	5.0	$6.4^{+2.5}_{-1.9}$	0.24	0.50 (0.0)

Two same-sign leptons

Ref: JHEP 06 (2020) 046

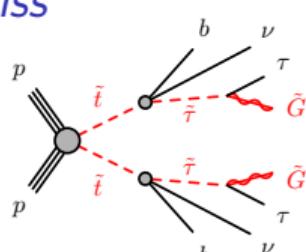
	Rpc2L0b	Rpc2L1b	Rpc2L2b	Rpc3LSS1b	Rpv2L
Target	$\tilde{g}\tilde{g}$	$\tilde{b}\tilde{b}$	$\tilde{t}\tilde{t}$	$\tilde{g}\tilde{g}$	
n_ℓ	≥ 2	≥ 2	≥ 2	≥ 3	≥ 2
n_{b-jet}	0	≥ 1	≥ 2	≥ 1	≥ 0
n_{jet}	≥ 6	≥ 6	≥ 6	-	≥ 6
E_T^{miss} [GeV]	> 200	-	> 300	-	-
m_{eff} [GeV]	> 1000	-	> 1400	-	> 2600
E_T^{miss}/m_{eff}	> 0.2	> 0.25	> 0.14	> 0.14	-

- A veto on n_{b-jet} in Rpc2L0b largely reduces $t\bar{t}$ background.
 - Additional veto on $81 \text{ GeV} < m_{e^\pm e^\pm} < 101 \text{ GeV}$ reduces $Z \rightarrow e^+ e^-$ background.
 - E_T^{miss} , m_{eff} , E_T^{miss}/m_{eff} are used for optimization.
- * $m_{eff} = H_T + E_T^{miss}$ (leptons is included in E_T^{miss})

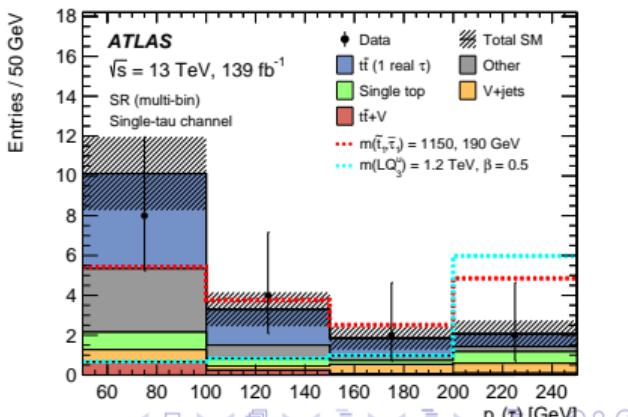
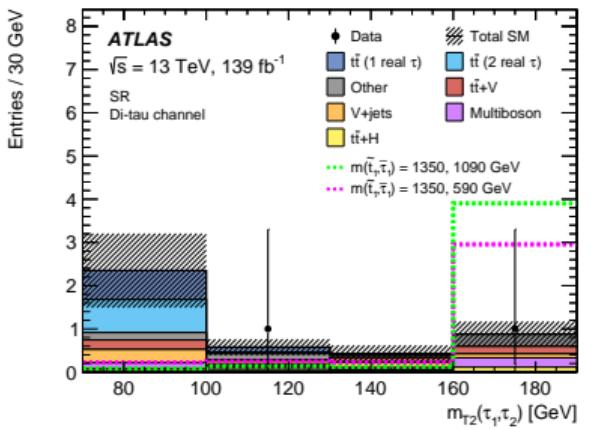


Tau leptons, b -jets and E_T^{miss}

- Tau leptons decay hadronically so there are zero electrons and muons.
- A hadronic tau lepton is reconstructed from $R = 0.4$ jets tagged by a neural network algorithm.
- Common selection: $E_T^{miss} > 280$ GeV, $n_{jet} \geq 2$.
- Two signal regions:
 - ▶ Di-tau channel: $n_{b-jet} \geq 1$, Opposite-sign tau leptons, $m_{T2}(\tau_1, \tau_2) > 70$ GeV.
 - ▶ Single-tau channel: $n_{b-jet} \geq 2$, $s_T > 600$ GeV, $\sum m_T(b_{1,2}) > 700$ GeV, $m_T(\tau) > 150$ GeV, $p_T(\tau)$ binned.
- Major background:
 - ▶ $t\bar{t}$ and single top (Single-tau channel).



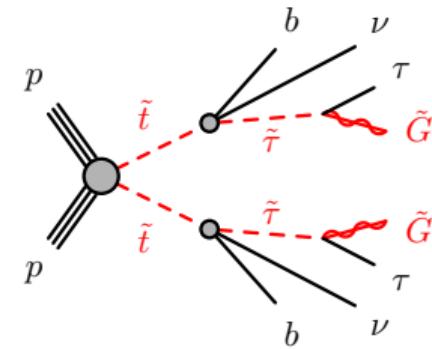
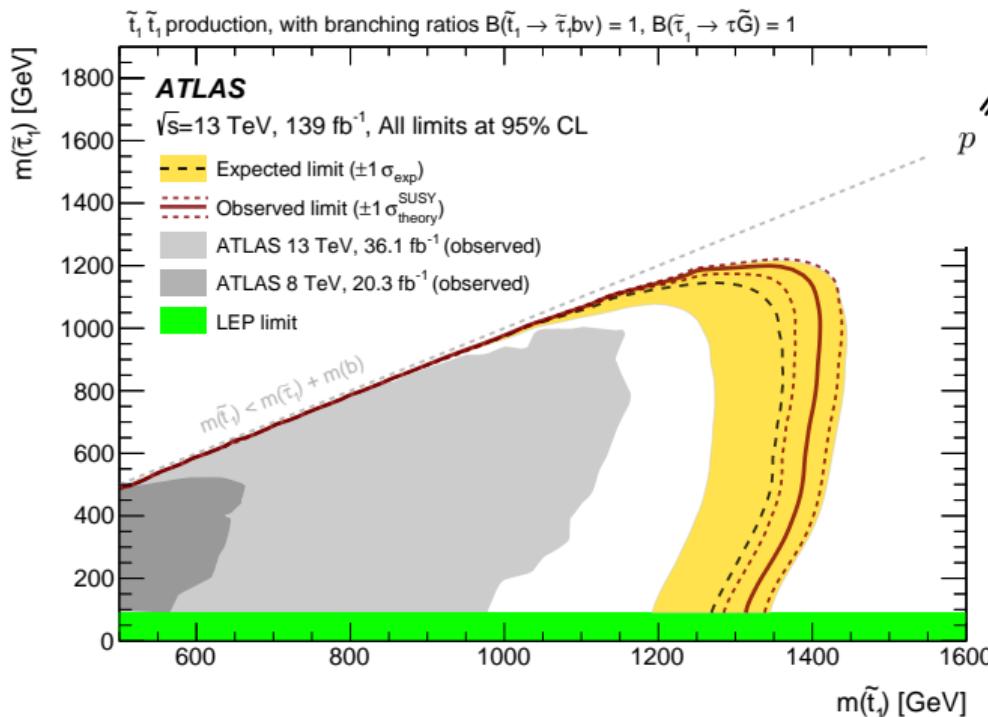
Ref: Phys. Rev. D 104, (2021) 112005



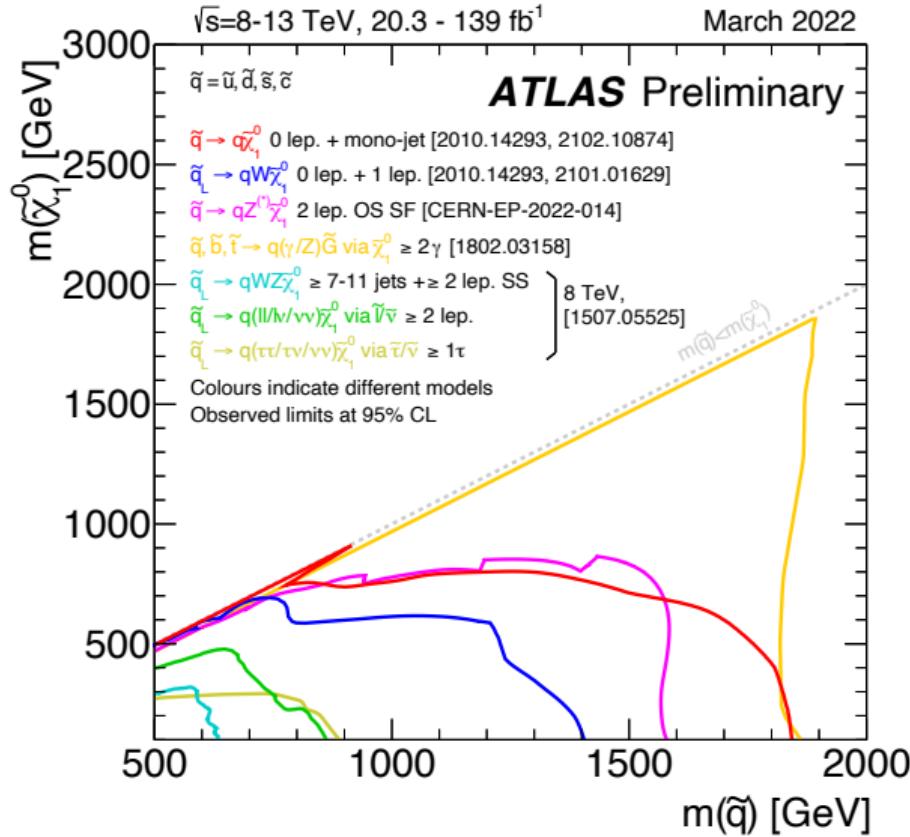
Tau leptons, b -jets and E_T^{miss} : Results

Ref: Phys. Rev. D 104, (2021) 112005

- No significant excess is found.



Summary plots for $\tilde{q} - \tilde{\chi}_1^0$ with R-parity conservation



Summary plots for $\tilde{b} - \tilde{\chi}_1^0$ with R-parity conservation

