Searches for Strong Production of Supersymmetric Particles

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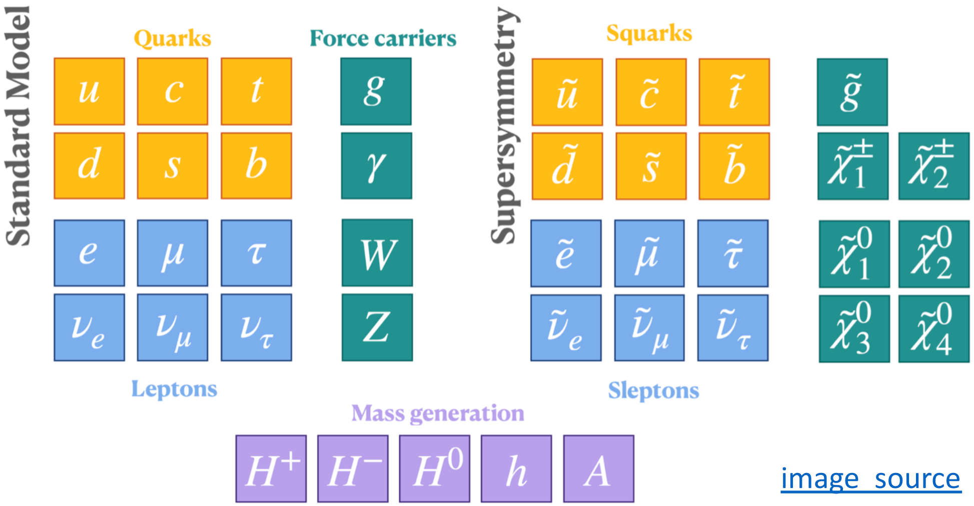
Outline

- Supersymmetry – general concept.
- Strong production of supersymmetric particles at LHC.
- Analyses:
  - Gluino pair production with large E_T^{miss}, 3 or more *b*-jets in the final state: arXiv:2211.08028
  - Gluino pair production with large E_T^{miss}, photons, jets in the final state: arXiv:2206.06012
  - Gluino or squark pair production with two same sign or three leptons in the final state: arXiv:2307.01094
- Summary.

Supersymmetry

- **Supersymmetry (SUSY)** is a promising extension to the Standard Model (SM):
  - **Introduces new fermionic/bosonic partners to each of the SM bosons/fermions.**
  - The Minimal Supersymmetric Standard Model (MSSM) is an extension to the SM that realizes SUSY with the minimum number of new particle states and interactions.
  - A natural **solution for the hierarchy problem**.
  - **Unification of** the electromagnetic, weak and strong **forces**.
  - In R-parity $P_R = (-1)^{3(B-L)+2s}$ conserved models (RPC), the lightest supersymmetric particle (LSP) is stable; **LSP is** a perfect candidate for **the Dark matter.**
- No evidence of SUSY in searches at ATLAS and other experiments so far.



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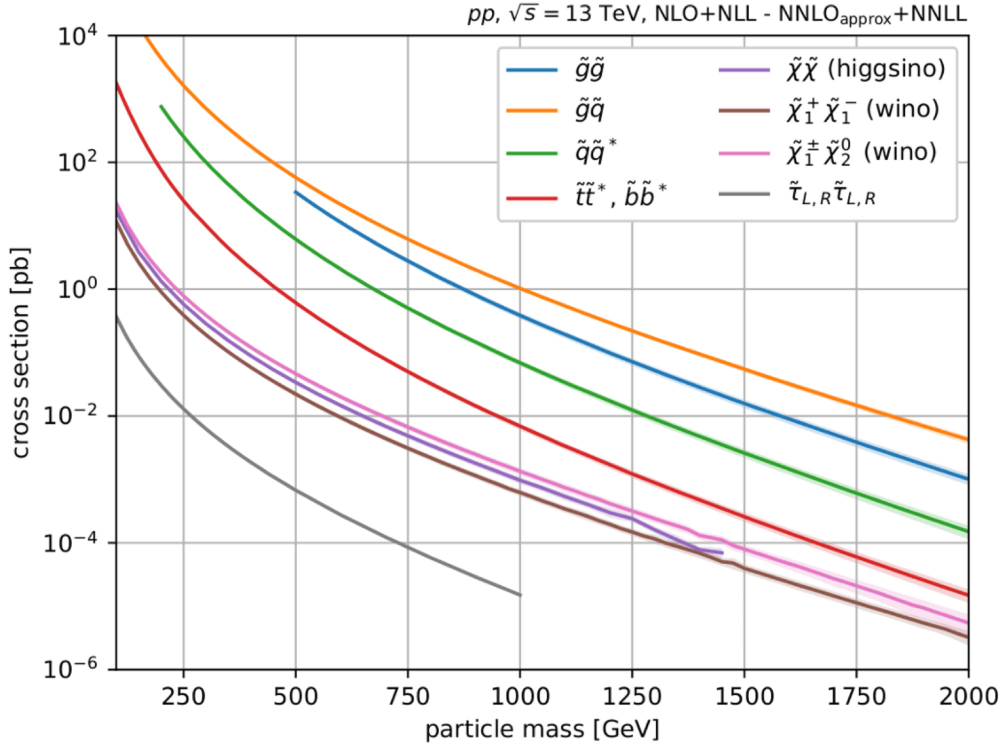
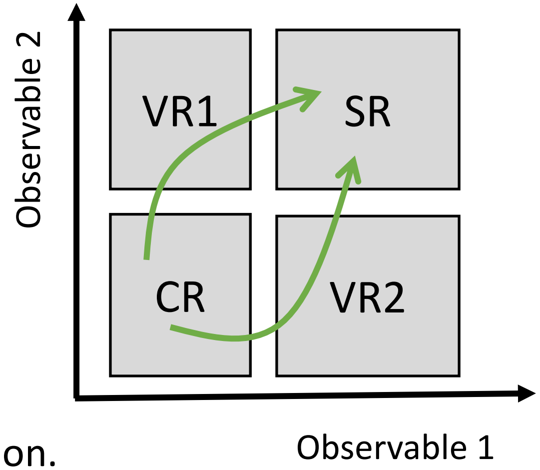
Strong Production of SUSY Particles at LHC

- In Run-2, LHC delivered *pp* collisions at $\sqrt{s} = \mathbf{13}$ **TeV**.
- After the standard data quality selection, ATLAS selected $\mathbf{140}\ \boldsymbol{fb^{-1}}$ of data for physics analyses.
- Searches are based on prediction cross-section.
- Many SUSY searches at ATLAS:
  - With E_T^{miss} and additional objects in the final states.
  - Various channels, RPC and RPV.

LHC SUSY Cross-Sections



Common BSM Analysis Strategy



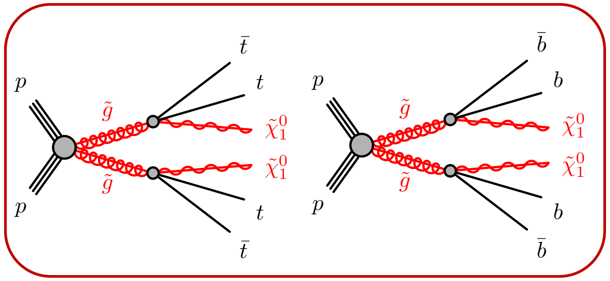
- General strategy for any beyond the standard model (BSM) searches:
  - **Maximize BSM signal significance.**
- **Signal region (SR):**
  - Enrich with SUSY events and minimize background contamination.
- **Control region (CR):**
  - Maximize background event yields and minimize SUSY contamination.
  - Keep kinematically close to SR.
  - Use to derive MC background normalization factors.
- **Validation region (VR):**
  - Validate MC prediction with normalization factors before applying them in the SR.
- **Statistical interpretation:**
  - If no significant excess of data over the SM prediction is observed in the SR, run a combined fit over CR+SR to set exclusion limit at 95% CL.

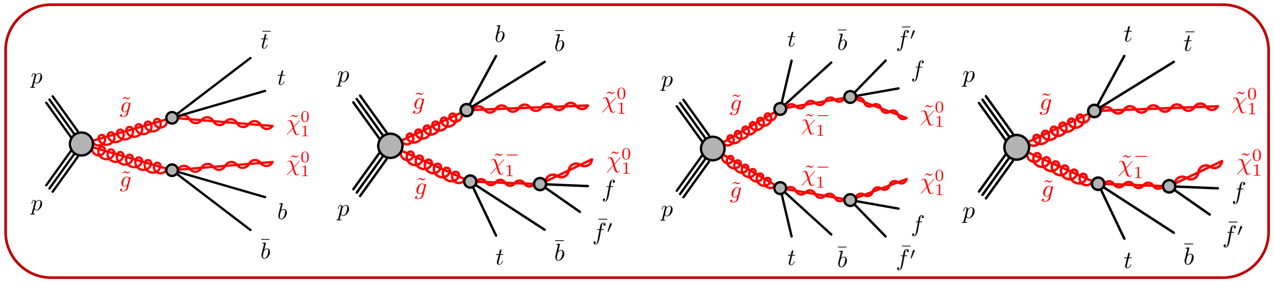
Search for supersymmetry in final states with missing transverse momentum and three or more b-jets in $139\ fb^{-1}$ of proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

arXiv:2211.08028

Multi b-jets: Analysis Setup

- Interpretations are provided in context of **several models**:
  - $\tilde{g}t\bar{t}$ and $\tilde{g}b\bar{b}$ models with 100% branching ratios in corresponding channel (left).
  - $\tilde{g}tb$ models with variable gluino branching ratio (right).
  - All models feature large E_T^{miss} and multiple jets with at least 3 *b*-tagged in the finals state.

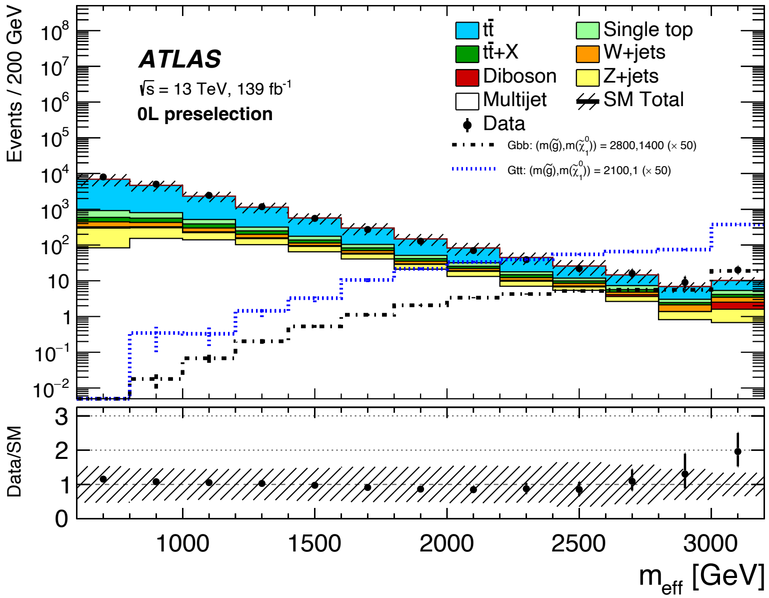


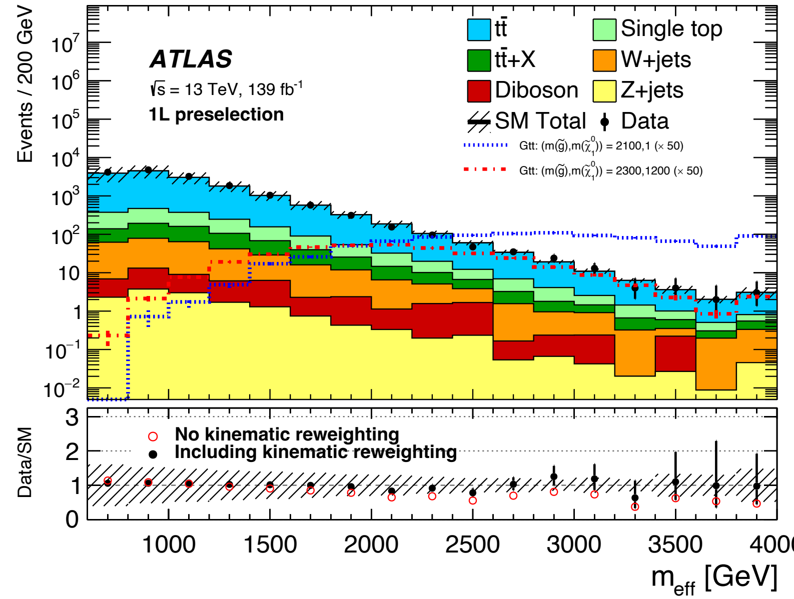


- **Analysis strategy:**
  - Using two event selection approaches: **cut-and-count** (CCA) and **neural network** (NN).
  - **In two channels**: with exactly zero (**0L**) and at least one (**1L**) signal leptons in the final state.

- **Background estimate:**
  - From MC: $t\bar{t}$, single top, $t\bar{t} + X$, $W + jets$, diboson, $Z + jets$.
    - Kinematic reweighing (reshaping) for all MC processes is derived.
    - Normalization factors extracted from CRs for $t\bar{t}$ in all regions and $Z + jets$ in $\tilde{g}\bar{b}b$ NN.
  - Multi-jet : data-driven method.

Multi *b*-jets: Background Kinematic Reweighing





arXiv:2211.08028

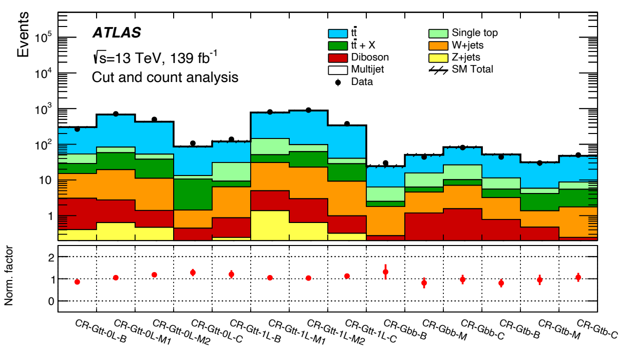
- The 1L channel (right) suffers from p_T-related distributions mismodeling, while no such issue in the 0L channel (left) was observed.
- Kinematic reweighing with respect to $\boldsymbol{m_{eff}} = \sum_{i \leq n} p_T^{jet_i} + \sum_{j \leq m} p_T^{lep_j} + E_T^{miss}$ was derived.
- The new weights correct modeling of m_{eff} and its components independently in the 1L channel.
- Kinematic reweighing only affect shape and does not renormalize MC predictions.

Multi b-jets: Fit Regions

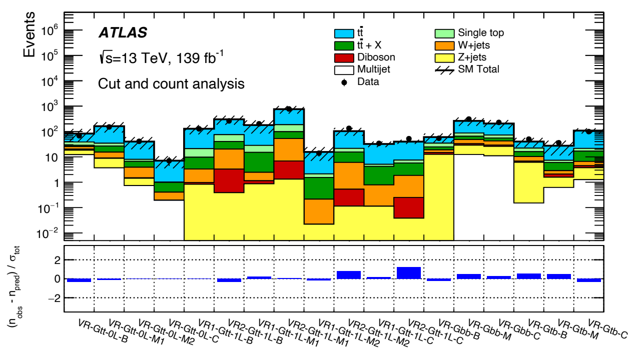
- Pull plots for CCA (top row) and NN (bottom row) analyses.
- $t\bar{t}$ / $Z + jets$ MC normalization factors are derived in CRs and validated in VRs.
  - Renormalized MC describes data well in all VRs.
- No significant excess of data over the SM prediction is observed in any of the SRs of the analysis.
- Exclusion limits and model independent upper limits are derived.

arXiv:2211.08028

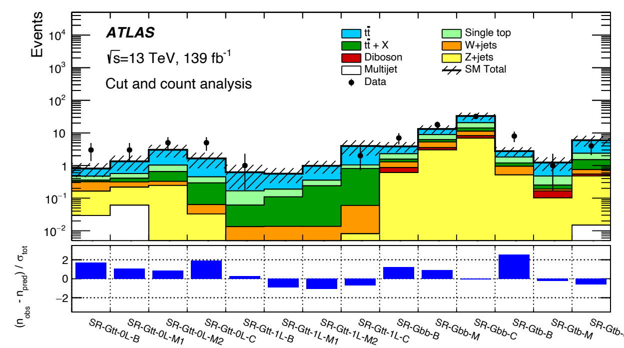
CRs pulls: MC normalization factors

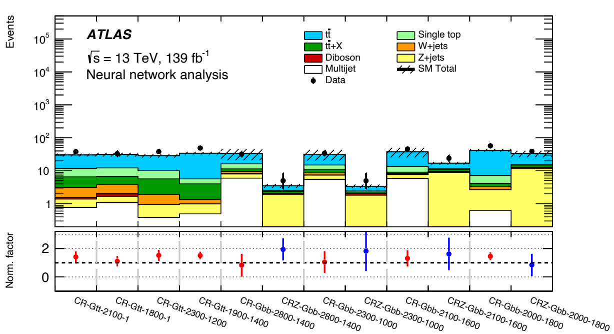


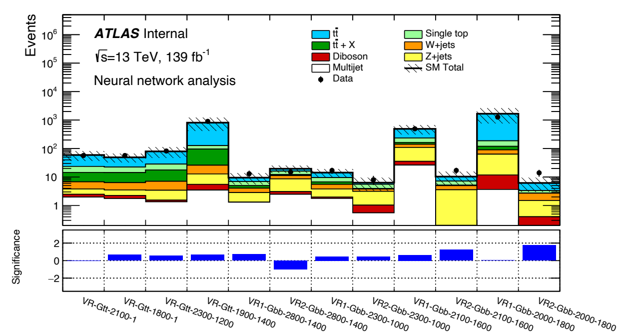
VRs pulls: validating

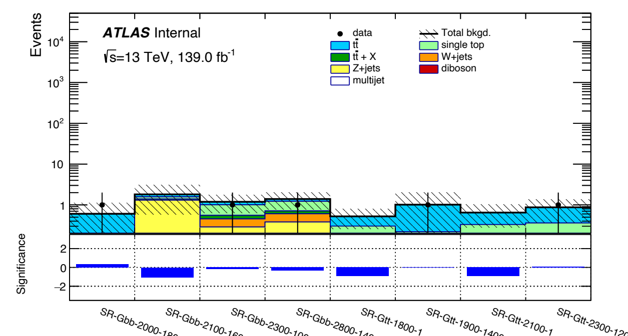


SRs pulls: no significant excess of data

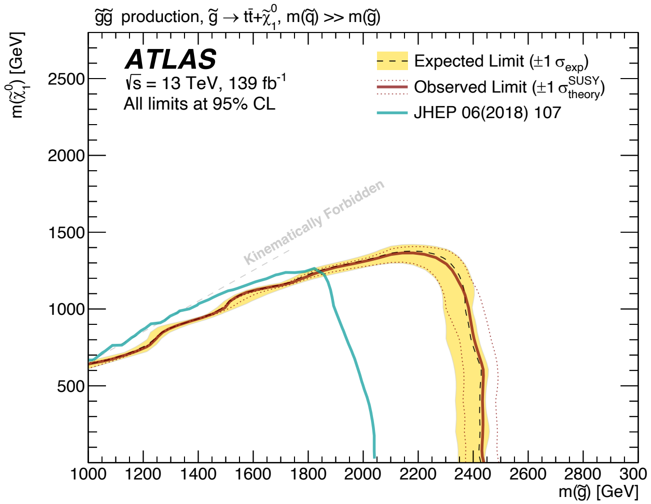


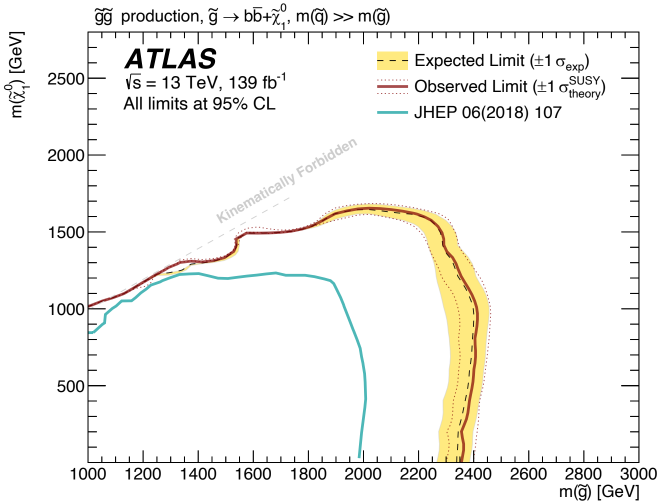






Multi b-jets: $\tilde{g}\bar{t}t$ and $\tilde{g}\bar{b}b$ Interpretations





arXiv:2211.08028

Model-independent upper limits in each SR of the analysis

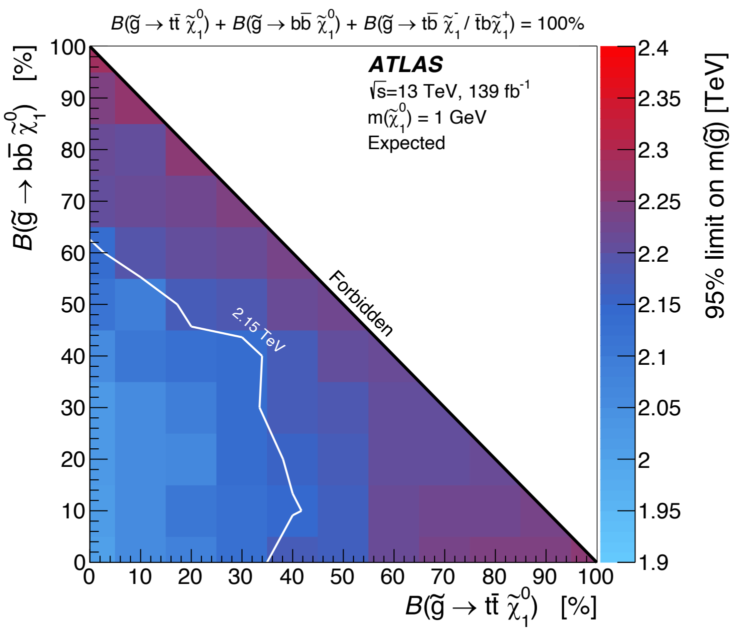
Signal Region	p_0 (Z)	σ_{vis}^{95} [fb]	S_{obs}^{95}	S_{exp}^{95}
SR-Gtt-0L-B	0.03 (1.82)	0.05	6.4	$3.7^{+1.2}_{-0.4}$
SR-Gtt-0L-M1	0.13 (1.13)	0.04	6.1	$4.3^{+1.6}_{-1.0}$
SR-Gtt-0L-M2	0.18 (0.91)	0.06	7.7	$5.7^{+2.2}_{-1.2}$
SR-Gtt-0L-C	0.03 (1.83)	0.06	8.5	$4.9^{+2.0}_{-1.0}$
SR-Gtt-1L-B	0.29 (0.56)	0.03	3.9	$3.3^{+1.2}_{-0.2}$
SR-Gtt-1L-M1	0.5 (0.0)	0.02	3.0	$3.1^{+1.2}_{-0.1}$
SR-Gtt-1L-M2	0.5 (0.0)	0.02	2.9	$3.4^{+1.3}_{-0.4}$
SR-Gtt-1L-C	0.5 (0.0)	0.03	4.6	$5.3^{+2.2}_{-1.5}$
SR-Gbb-B	0.11 (1.22)	0.07	9.5	$6.2^{+2.6}_{-1.4}$
SR-Gbb-M	0.18 (0.93)	0.11	16.0	$11.4^{+5.0}_{-2.7}$
SR-Gbb-C	0.5 (0.0)	0.14	19.4	$19.5^{+5.5}_{-4.6}$
SR-Gtb-B	0.01 (2.30)	0.08	11.3	$5.4^{+2.2}_{-1.3}$
SR-Gtb-M	0.5 (0.0)	0.03	3.7	$3.8^{+1.5}_{-0.5}$
SR-Gtb-C	0.5 (0.0)	0.04	5.7	$6.7^{+2.6}_{-1.8}$
SR-Gtt-2100-1	0.5 (0.0)	0.02	3.0	$3.1^{+1.1}_{-0.2}$
SR-Gtt-1800-1	0.5 (0.0)	0.02	3.0	$3.0^{+1.1}_{-0.1}$
SR-Gtt-2300-1200	0.40 (0.26)	0.03	3.8	$3.5^{+1.4}_{-0.3}$
SR-Gtt-1900-1400	0.5 (0.0)	0.03	4.2	$4.1^{+1.5}_{-1.1}$
SR-Gbb-2800-1400	0.5 (0.0)	0.03	3.7	$3.9^{+1.4}_{-0.8}$
SR-Gbb-2300-1000	0.5 (0.0)	0.03	3.8	$3.8^{+1.3}_{-0.7}$
SR-Gbb-2100-1600	0.36 (0.35)	0.02	3.0	$3.2^{+1.3}_{-0.1}$
SR-Gbb-2000-1800	0.29 (0.55)	0.03	4.0	$3.4^{+1.2}_{-0.6}$

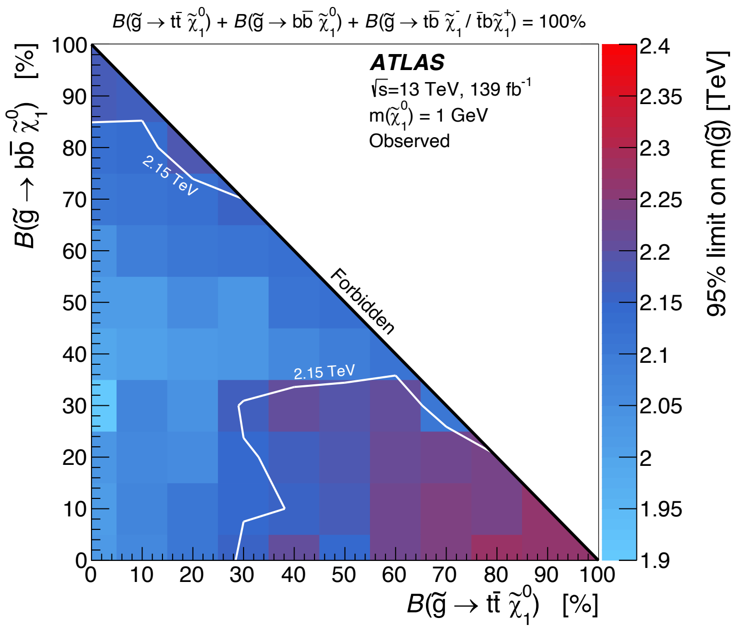
- Exclusion limits derived for NN and CCA analyses independently; the NN exclusion limits are stronger for both $\tilde{g}\bar{t}t$ and $\tilde{g}\bar{b}b$.
- **Excluded gluinos** with masses below **2.44 TeV** and **2.35 TeV** at 95% CL for massless neutralinos in $\tilde{g}\bar{t}t$ (left) and $\tilde{g}\bar{b}b$ (right) models.
- The strongest **neutralino exclusion** limits:
  - $\tilde{g}\bar{t}t$: **1.35 TeV** at $m_{\tilde{g}} = 2.20$ TeV
  - $\tilde{g}\bar{b}b$: **1.65 TeV** at $m_{\tilde{g}} = 2.10$ TeV

Multi b-jets: $\tilde{g}tb$ Interpretations

- $\tilde{\boldsymbol{g}}\boldsymbol{tb}$ exclusion limits are presented as a function of branching ratios for $\mathcal{B}(\tilde{g} \to b\bar{b}\tilde{\chi}_1^0)$ (vertical) and $\mathcal{B}(\tilde{g} \to t\bar{t}\tilde{\chi}_1^0)$ (horizontal) for expected (left) and observed (right).
- Results for $m(\tilde{\chi}_1^0) = 1$ GeV, 600 GeV and 1000 GeV are derived.
- The exclusion limits are the strongest when either of two $\mathcal{B}(\tilde{g} \to b\bar{b}\tilde{\chi}_1^0)$ and $\mathcal{B}(\tilde{g} \to t\bar{t}\tilde{\chi}_1^0)$ saturate the total sum, and weaker when the two $\mathcal{B}$s are mixed.
- Expected and observed exclusion limits for $m(\tilde{\chi}_1^0) = 1$ GeV :

arXiv:2211.08028



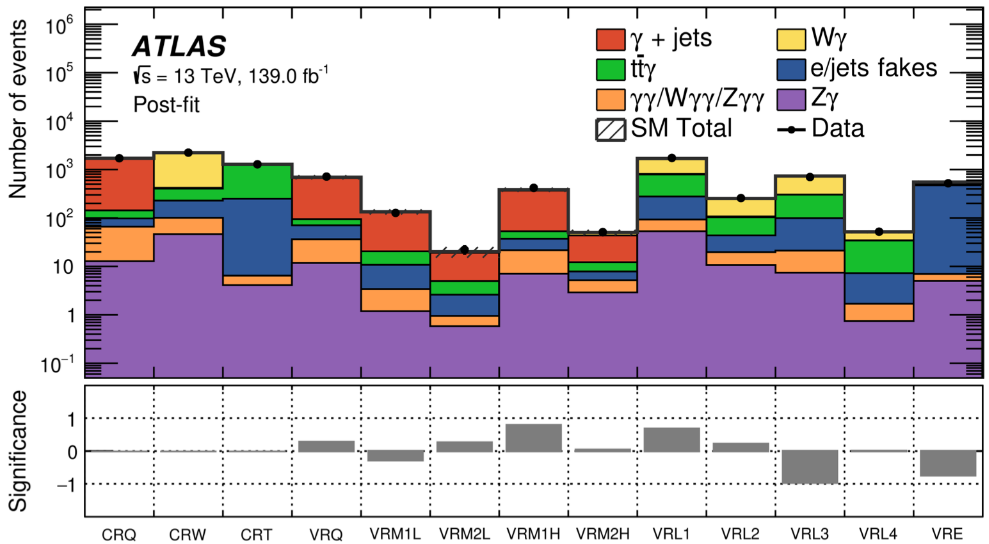


Search for new phenomena in final states with photons, jets and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

arXiv:2206.06012

Gravitino: Analysis Setup

- **Two models** with escaping gravitinos $\tilde{G}$ are considered:
  - With the γ/Z or γ/h boson in the final state.
  - Both featuring large E_T^{miss}, and multiple jets in the final states.
- **Background estimate:**
  - $t\bar{t}\gamma$, $W\gamma$, QCD $\gamma + jets$ (fake large E_T^{miss}): from MC with normalization factors extracted from CRs.
  - $W\gamma\gamma/Z\gamma\gamma/Z\gamma/\gamma\gamma$ directly from MC.
  - Misidentified jets or electrons as photons – data driven method.



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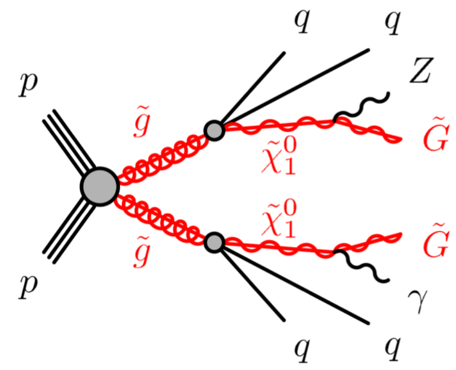
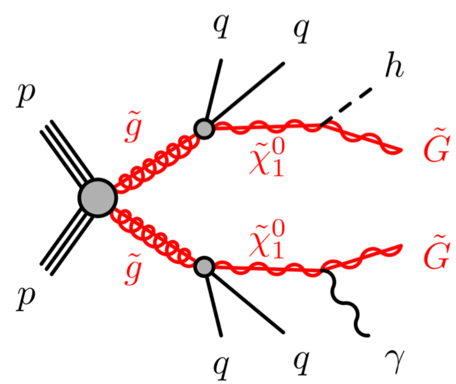


(a) γ/Z model

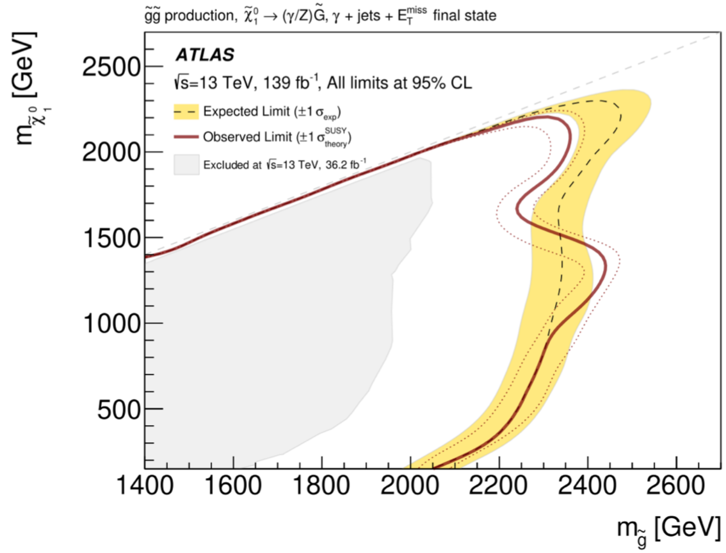


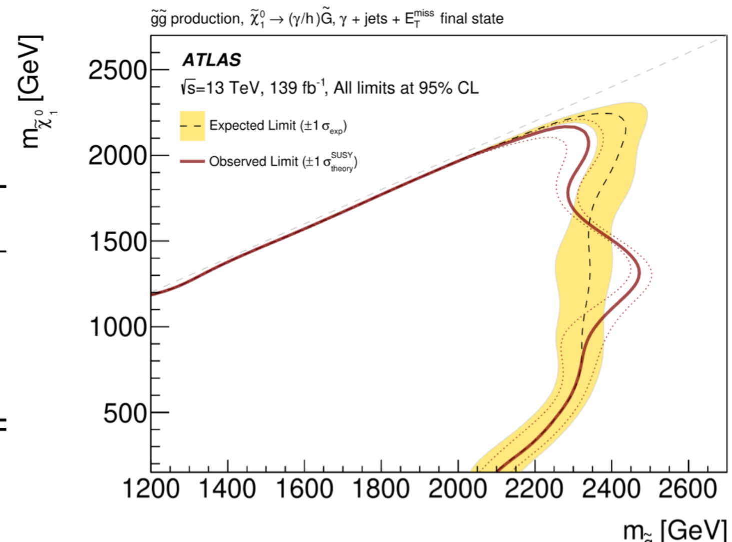
(b) γ/h model

Gravitino: Results

arXiv:2206.06012

- No excess of data over the SM prediction in any of the SRs of the analysis is observed.
- **Exclusion limits** for both models with the γ/Z (top figure) or γ/h (bottom figure) are derived:
  - The strongest limit on $\boldsymbol{m_{\tilde{g}} = 2.4}$ **TeV** corresponding to $\boldsymbol{m(\tilde{\chi}_1^0) = 1.3 - 1.4}$ **TeV** for both models.
  - Due to low signal acceptance in $m(\tilde{\chi}_1^0) < 150$ GeV and $m(\tilde{\chi}_1^0) = 2050 - 2100$ GeV, the limits on $m_{\tilde{g}}$ in the regions are softer.





- Model independent upper limits:

Signal Region	$\langle\epsilon\sigma\rangle_{obs}^{95}$ [fb]	$\langle\epsilon\sigma\rangle_{exp}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}	p_0 (Z)
SRL	0.034	$0.034^{+0.016}_{-0.009}$	4.7	$4.7^{+2.2}_{-1.2}$	0.50 (0.00)
SRM	0.022	$0.033^{+0.013}_{-0.008}$	3	$4.6^{+1.8}_{-1.1}$	0.50 (0.00)
SRH	0.054	$0.035^{+0.014}_{-0.010}$	7.6	$4.8^{+1.9}_{-1.4}$	0.09 (1.32)

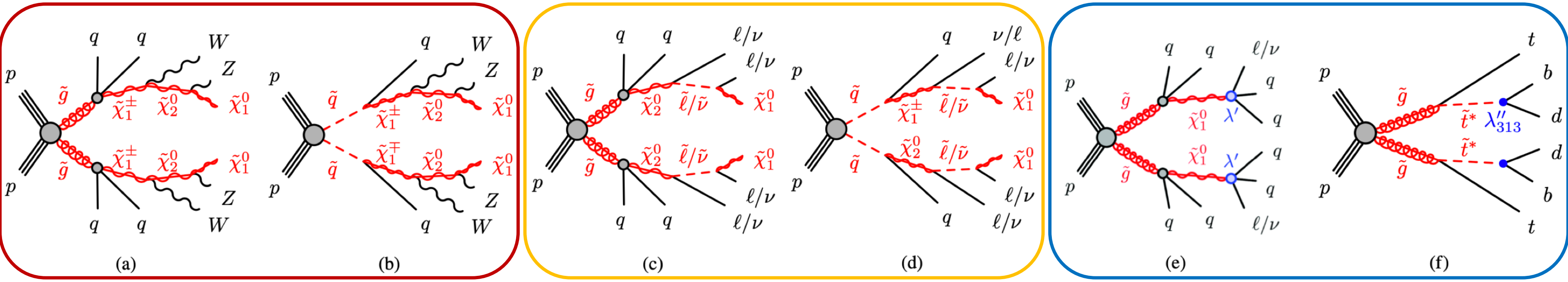
L, M, H = Low, Medium, High mass splitting regions

Search for pair production of squarks or gluinos decaying via sleptons or weak bosons in final states with two same-sign or three leptons with the ATLAS detector

arXiv:2307.01094

SS/3Lep: Analysis Setup

- **Several signal models are studies:**
  - Gluino (a,c,e,f) or squark (b,d) pair productions.
  - SUSY fermions cascade decays (a, b).
  - SUSY fermions cascade decay with intermediate sleptons (c,d).
  - RPV models with non-zero couplings to the SM leptons and quarks (e,f).
  - Final states vary depending on the channel, common feature: 2 (SS) or ≥3 (any) leptons.



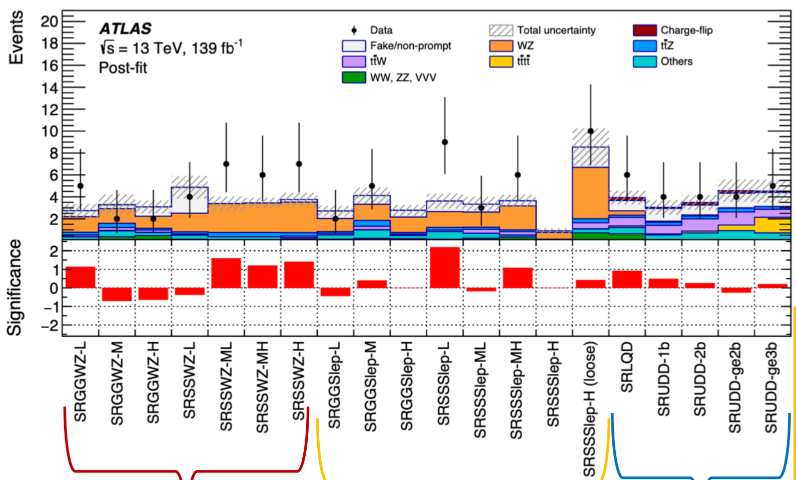
- **Background estimate:**
  - $WZ + jets$: from MC with normalization factors extracted from CRs.
  - Directly form MC: $t\bar{t} + V$, $t\bar{t}t\bar{t}$, $WW/ZZ/VVV$, $t\bar{t} + X$, single top $+X$, tW.
  - Events with electrons with incorrect charge – data driven method.
  - Events with fake and non-prompt leptons – using matrix method.

SS/3Lep: SRs Fit and Upper Limits

- No significant excess of data over the SM prediction is observed in any of the analysis SRs.
- Exclusion limits for each model as well and independent upper limits for each SR are derived.

[arXiv:2307.01094](https://arxiv.org/abs/2307.01094)

Signal regions pulls



Fermions cascade decays

Fermions cascade decays with intermediate leptons

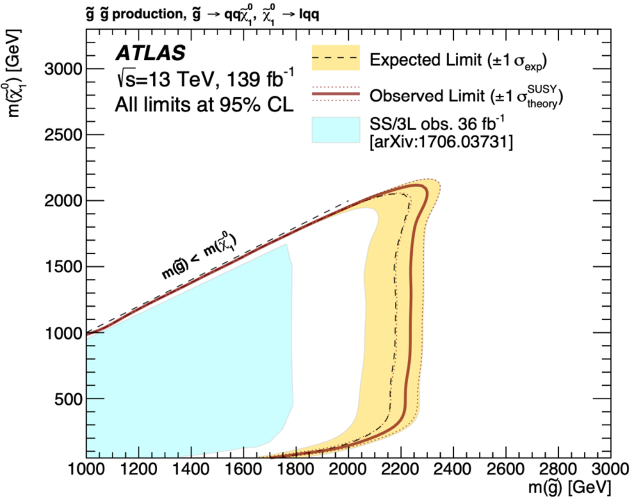
RPV

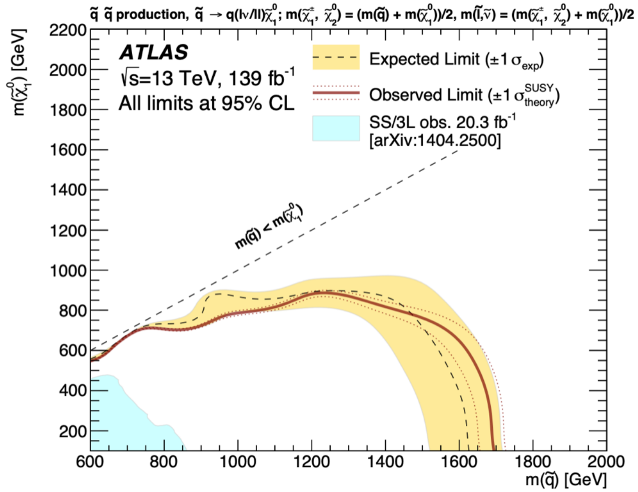
Model independent upper limits

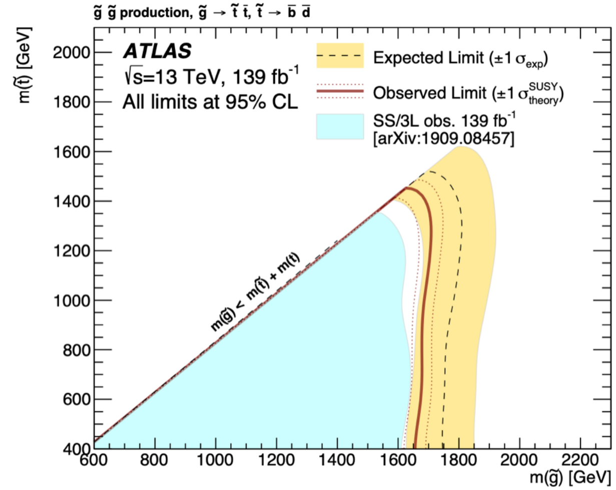
(L, M, H = Low, Medium, High mass splitting regions)

SR	σ_{vis}[fb]	S^{95}_{obs}	S^{95}_{exp}	CL_b	$p(s=0)$ (Z)
SRGGWZ-L	0.06	8.1	$5.2^{+2.2}_{-1.1}$	0.91	0.05 (1.64)
SRGGWZ-M	0.03	4.5	$5.2^{+2.1}_{-1.3}$	0.32	0.50 (0.00)
SRGGWZ-H	0.03	3.9	$5.0^{+2.0}_{-1.4}$	0.23	0.50 (0.00)
SRSSWZ-L	0.04	5.7	$6.1^{+2.3}_{-1.6}$	0.41	0.50 (0.00)
SRSSWZ-ML	0.07	10.4	$6.5^{+2.3}_{-1.5}$	0.94	0.02 (2.04)
SRSSWZ-MH	0.06	8.6	$5.3^{+2.0}_{-1.4}$	0.93	0.04 (1.74)
SRSSWZ-H	0.06	8.6	$5.4^{+2.5}_{-1.1}$	0.91	0.09 (1.32)
SRGGSlep-L	0.03	4.0	$4.7^{+2.0}_{-1.2}$	0.33	0.50 (0.00)
SRGGSlep-M	0.04	6.2	$5.8^{+2.2}_{-1.7}$	0.60	0.43 (0.17)
SRGGSlep-H	0.02	2.9	$4.7^{+2.0}_{-1.1}$	0.00	0.35 (0.39)
SRSSSlep-L	0.08	11.7	$5.6^{+2.4}_{-1.3}$	0.99	0.01 (2.33)
SRSSSlep-ML	0.03	4.8	$5.1^{+2.2}_{-1.3}$	0.43	0.50 (0.00)
SRSSSlep-MH	0.06	7.9	$5.4^{+2.3}_{-1.4}$	0.85	0.15 (1.06)
SRSSSlep-H	0.02	2.9	$3.5^{+1.3}_{-0.5}$	0.04	0.36 (0.35)
SRSSSlep-H (loose)	0.07	9.9	$8.1^{+3.3}_{-2.0}$	0.70	0.32 (0.46)
SRLQD	0.05	7.3	$5.3^{+2.3}_{-1.2}$	0.82	0.21 (0.81)
SRUDD-1b	0.05	6.6	$5.1^{+2.3}_{-1.1}$	0.77	0.21 (0.80)
SRUDD-2b	0.05	6.4	$5.2^{+2.4}_{-1.1}$	0.69	0.26 (0.66)
SRUDD-ge2b	0.04	5.8	$6.1^{+2.4}_{-1.4}$	0.44	0.50 (0.00)
SRUDD-ge3b	0.05	6.8	$6.1^{+2.4}_{-1.7}$	0.62	0.40 (0.24)

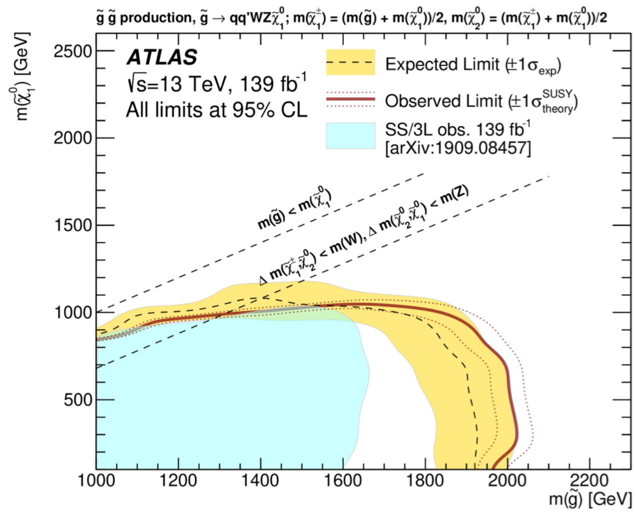
SS/3Lep: Exclusion Limits







- The strongest exclusion limits are:
  - (left) For **gluino and the LSP** corresponding to a point:
    - $m_{\tilde{g}} \approx 2.2$ **TeV** , $m(\tilde{\chi}_1^0) = 2.0$ **TeV**
  - (center) For **squark** is $m_{\tilde{q}} = 1.7$ **TeV** corresponding to a massless LSP.
  - (right) For stop quark is $m_{\tilde{t}} = 1.4$ **TeV** corresponding to $m_{\tilde{g}} \approx 1700$ GeV.
- Right bottom: $\tilde{g} \rightarrow qq'WZ\tilde{\chi}_1^0$ channel of the analysis made significant improvement compared to previous result with the same 139 fb^{-1} dataset.



arXiv:2307.01094

Summary

- **SUSY searches at ATLAS cover many models**:
  - Different productions with varieties of final states.
  - RPV, RPC, long lived particles.
  - Many Run2 results are available.

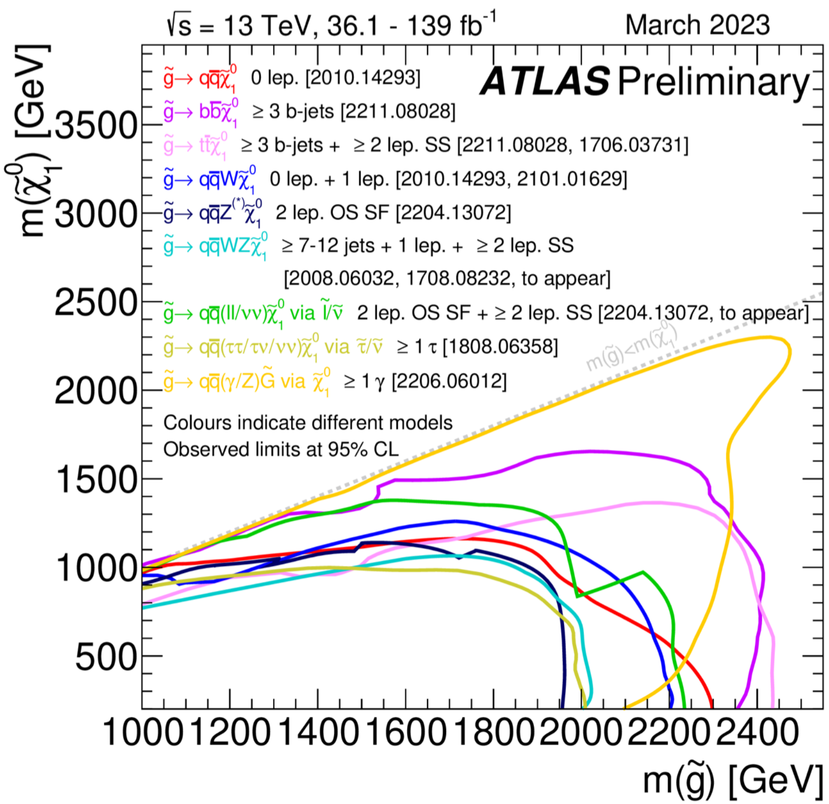
- **Presented recent results for strong production**.

- **No evidence of SUSY in nature has been found yet**. ATLAS interprets the results as:
  - **exclusion limits** on SUSY particles' masses,
  - and **model-independent upper limits** for particular signal regions.

- More studies to come with the Run3 data!

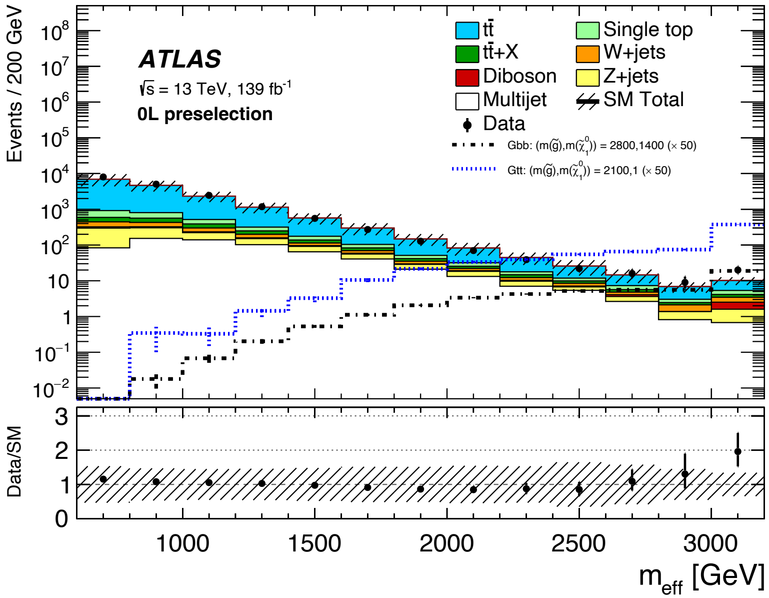
Exclusion limits at 95% CL

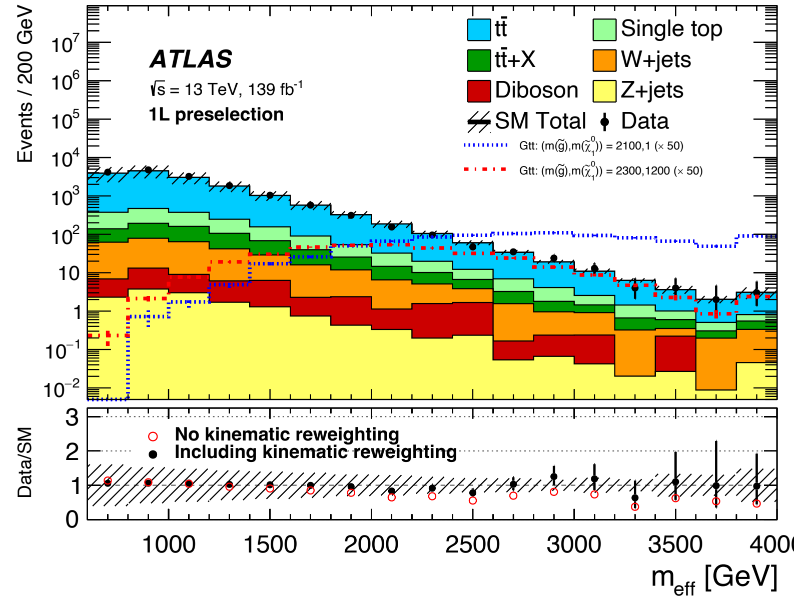
ATL-PHYS-PUB-2023-005



Backup

Multi *b*-jets: Background Kinematic Reweighing





arXiv:2211.08028

- The 1L channel (right) suffers from p_T-related distributions mismodeling, while no such issue in the 0L channel (left) was observed.
- Kinematic reweighing with respect to $\boldsymbol{m_{eff}} = \sum_{i\leq n} p_T^{jet_i} + \sum_{j\leq m} p_T^{lep_j} + E_T^{miss}$ was derived.
- The new weights correct modeling of m_{eff} and its components independently in the 1L channel.
- Kinematic reweighing only affect shape and does not renormalize MC predictions.

Multi b-jets: NN Analysis Event Selection

- Keras - tensorflow. Parametrized: knows signal mass point and discrimination between background Gtt or Gbb.
- NN returns probability for an event to be signal $\left(P(Gtt) or\ P(Gbb)\right)$, a $t\bar{t}$ background event $P(t\bar{t})$, or a $Z + jets$ background event $P(Z)$.
- To reduce the large number of potential SRs, a set-cover algorithm was used to iteratively select the SR which excludes the most as-yet non-excluded model points until all such points are exhausted

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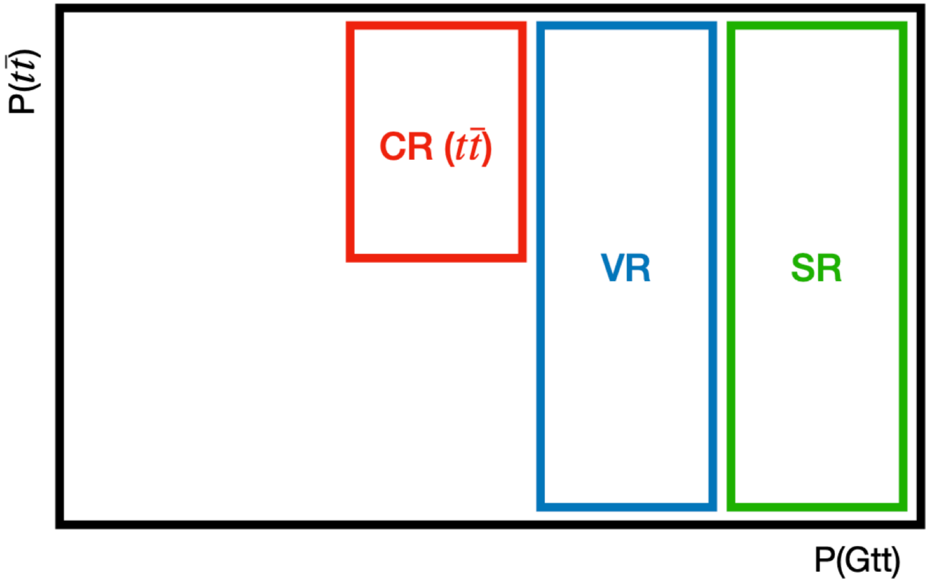
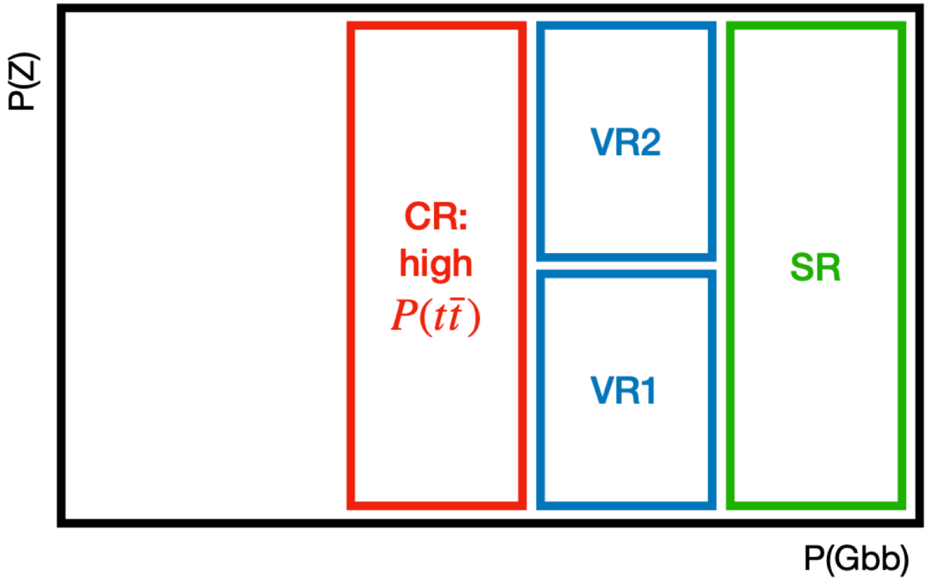
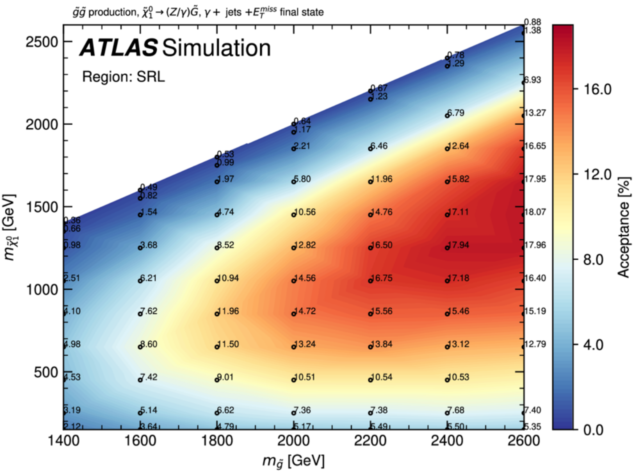
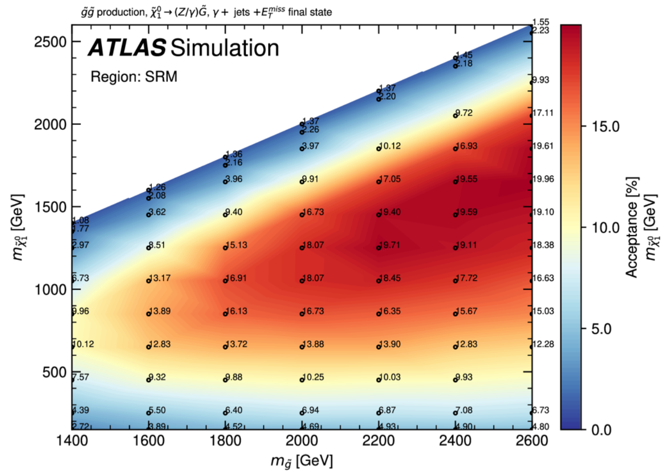


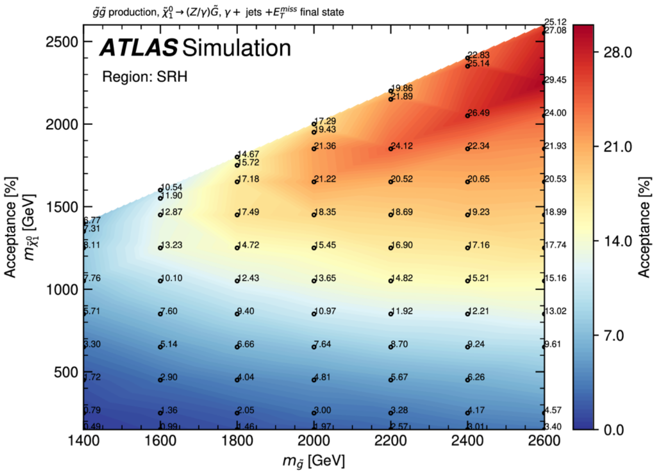


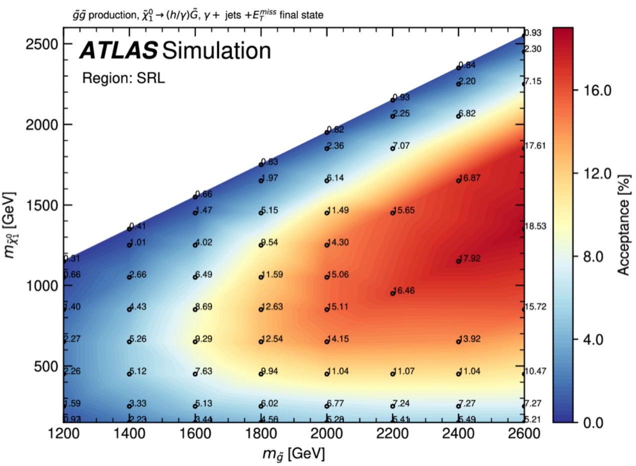
Gravitino: Signal Acceptance Plots

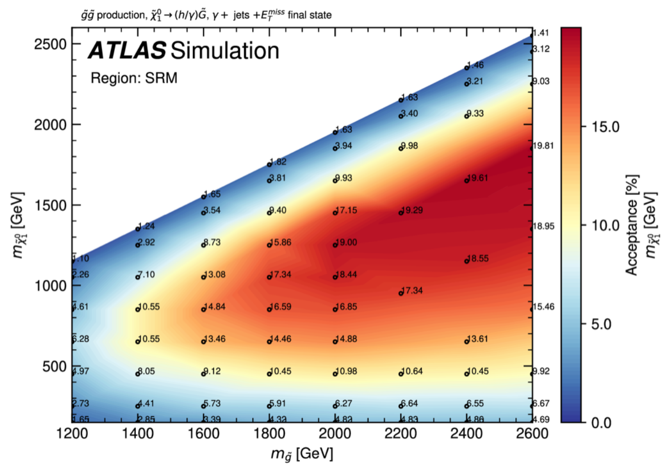
arXiv:2307.01094

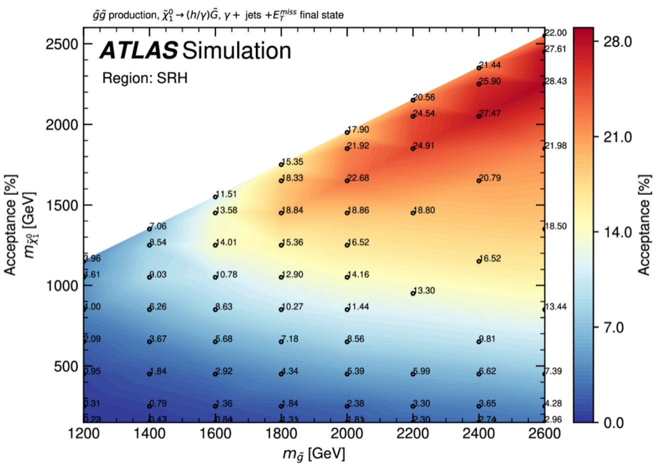




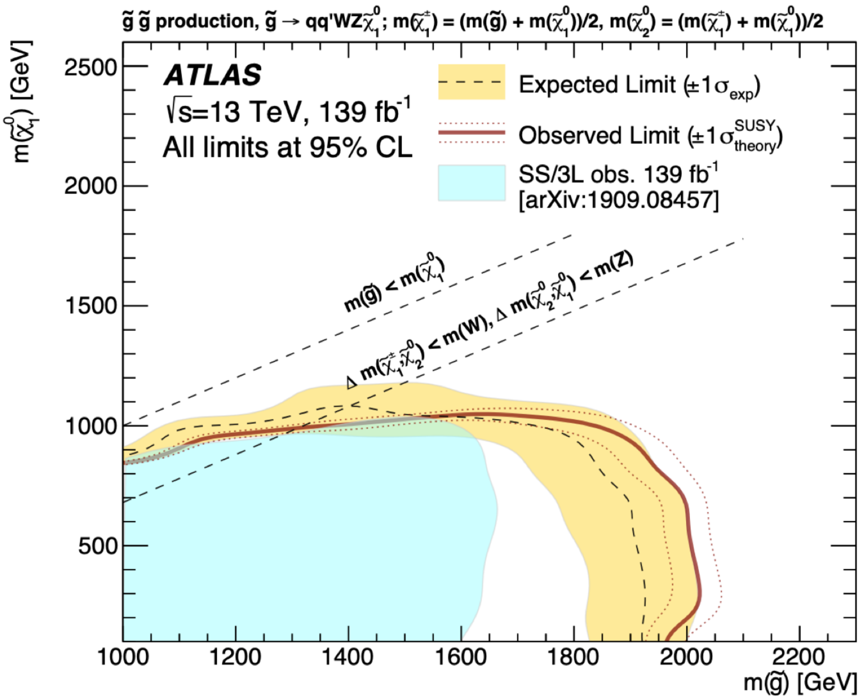






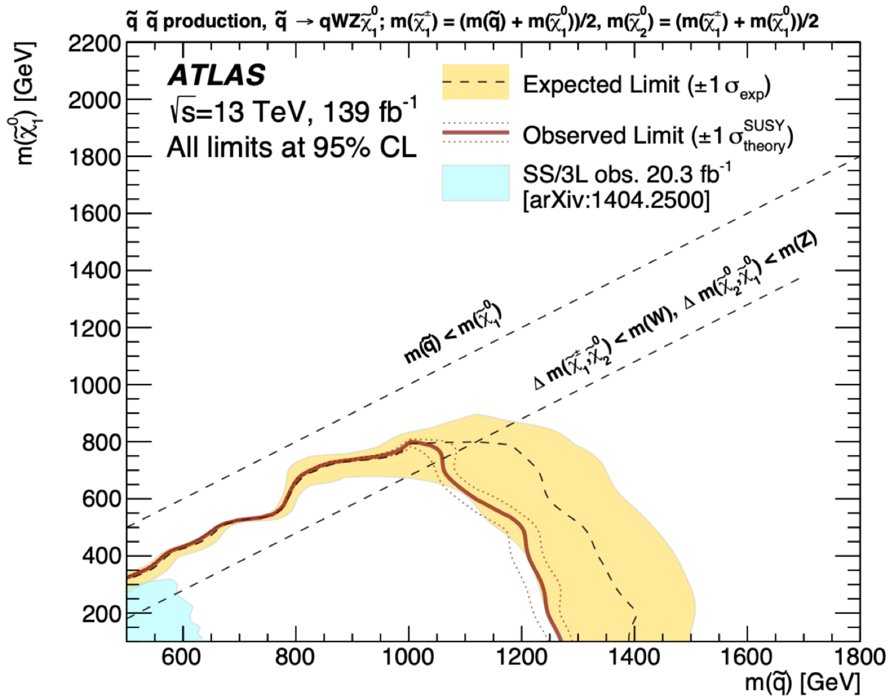


SS/3Lep : Exclusion Limits – SUSY Cascade Decay



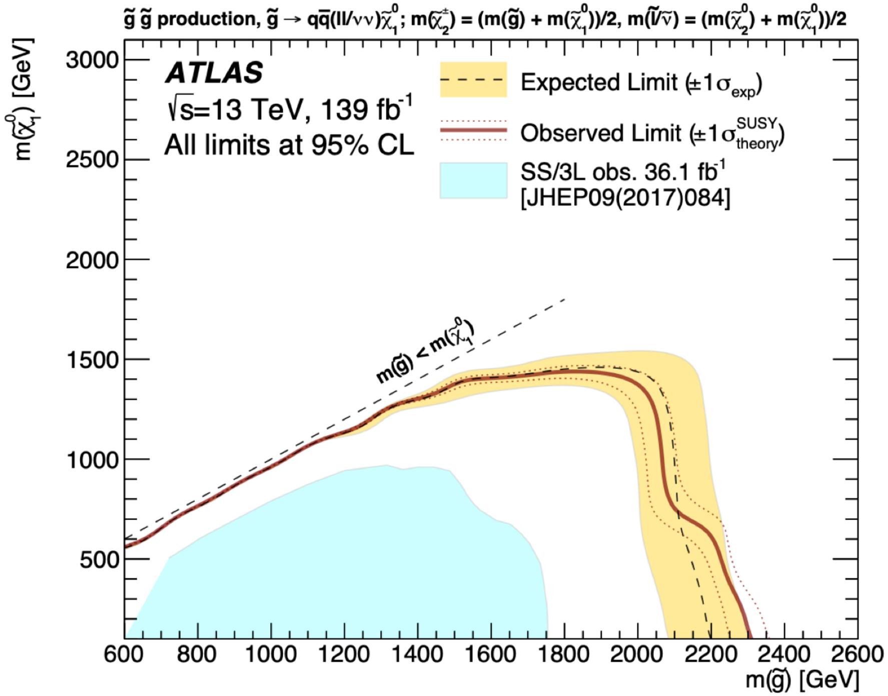
(a) $\tilde{g} \to qq'WZ\tilde{\chi}_1^0$

arXiv:2307.01094



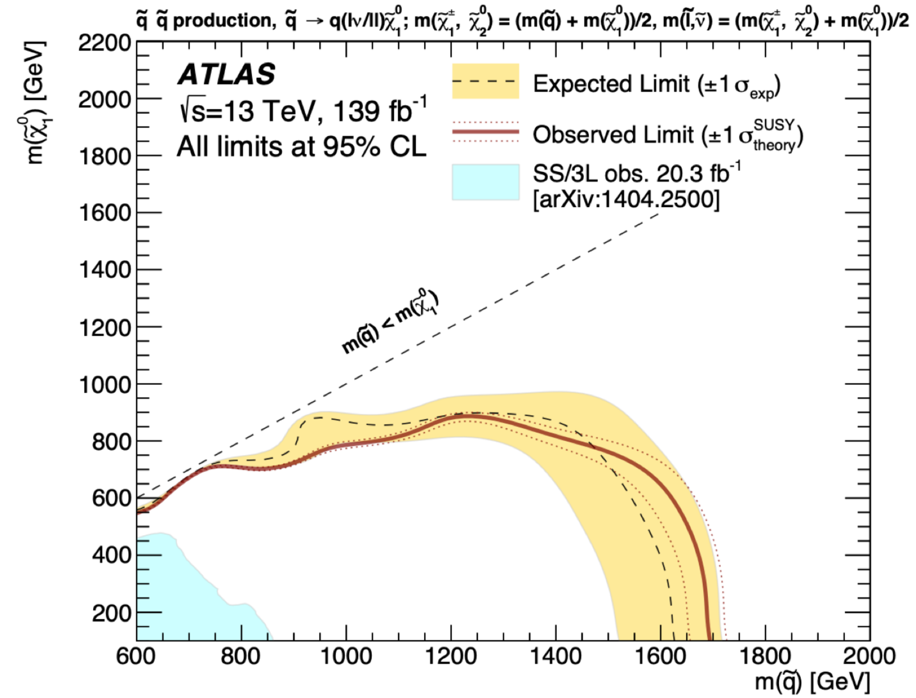
(b) $\tilde{q} \to q'WZ\tilde{\chi}_1^0$

SS/3Lep: Exclusion Limits – SUSY Cascade with Lep



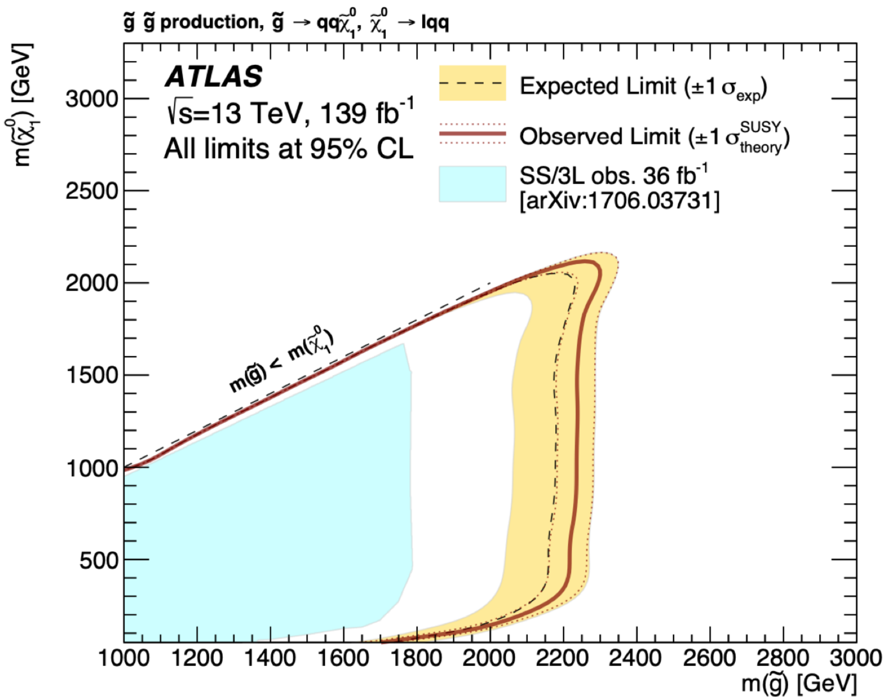
(c) $\tilde{g} \rightarrow q\bar{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$

arXiv:2307.01094



(d) $\tilde{q} \rightarrow q(\ell\nu/\ell\ell/\nu\nu)\tilde{\chi}_1^0$

SS/3Lep: Exclusion Limits RPV



(e) $\tilde{g} \longrightarrow q\bar{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \longrightarrow \ell qq$

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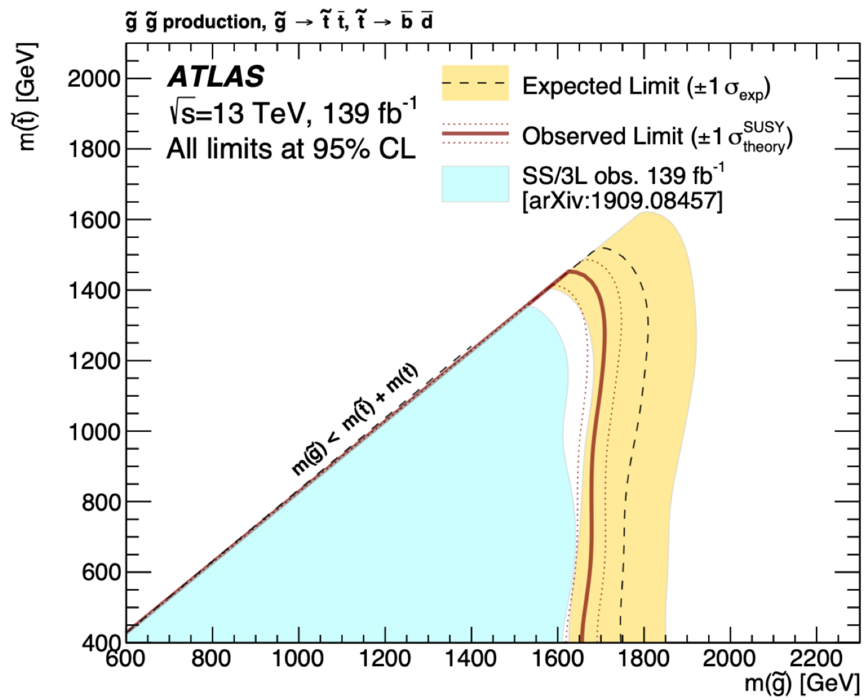

(f) $\tilde{g} \longrightarrow \tilde{t}\bar{t}, \tilde{t} \longrightarrow \bar{b}\bar{d}$