# Supersymmetry - ATLAS

**Xuanhong Lou** (Stockholm University)

**on behalf of the ATLAS Collaboration**

11th Edition of the Large Hadron Collider Physics Conference

22nd – 26th May 2023, Belgrade, Serbia

Stockholms universitet

ATLAS EXPERIMENT

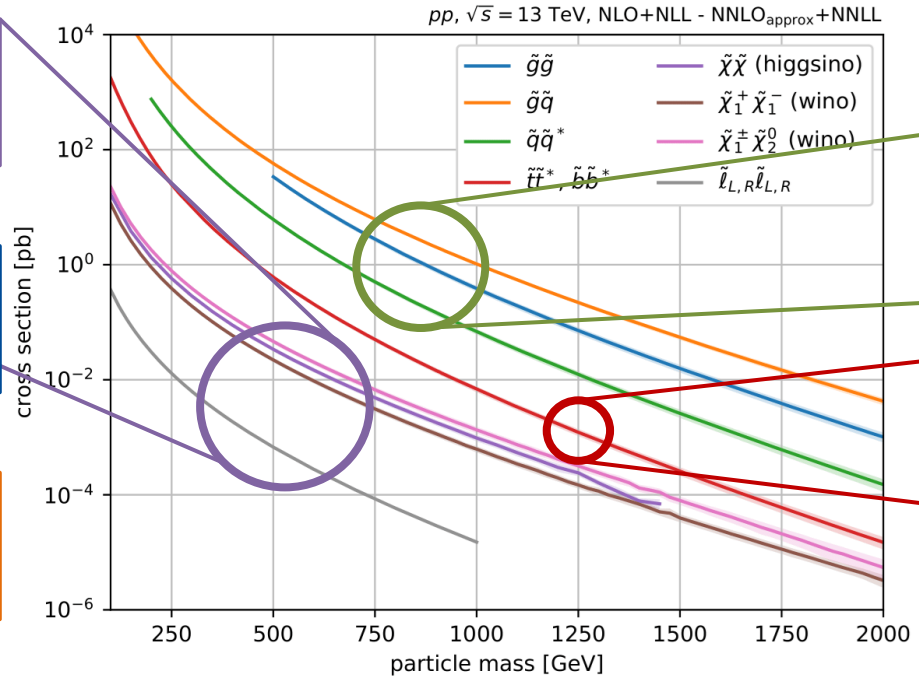
# Introduction

- An overview of the Supersymmetry (SUSY) searches in ATLAS
  - Results covered in this talk all based on the ATLAS full Run 2 data (139 fb$^{-1}$)

**Electroweak Production**
Relatively low XS
small mass splitting

**Long-lived Particles**
Displaced jets, leptons...
Covered in Mohsen's talk

***R*-Parity Violation (RPV)**
High jet/lepton multiplicity
(Often) low $p^{T}_{miss}$

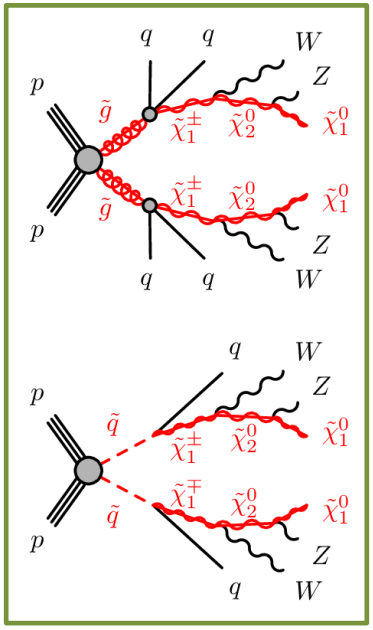



**Strong Production**
Relatively high XS
(Mostly) inclusive searches

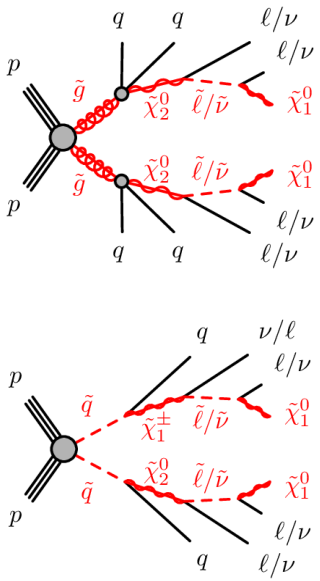
**Third Generation**
1st and 2nd generation
squarks can be too heavy

# Gluino and Squark Production: Same-Sign (SS) / 3L

**ATLAS-CONF-2023-017**

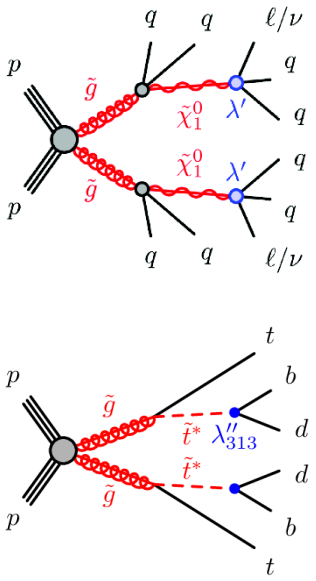


electroweak gauginos to LSP via cascade decays



electroweak gauginos to SM leptons + LSP

direct LSP decay to SM lepton via non-zero RPV



lightest stop decay to tbq via non-zero RPV

**Key Discriminant: Effective Mass**

$$m_{\text{eff}} = \sum p_{\text{T}}^{\text{jet}} + \sum p_{\text{T}}^{\ell} + E_{\text{T}}^{\text{miss}}$$

**SRGG(gluino)/SS(squark)WZ**

Suffix "L", "M", "H" denotes mass splitting between gluino/squark and the LSP

In **SRSSWZ**, "M" is further split into "ML" and "MH"

| SR name | $n_{\text{Sig}}(\ell)$ ($n_{\text{BL}}(\ell)$) | $n_{b\text{-jets}}$ | $n_{\text{jets}}$ | $p_{\text{T}}^{\text{jet}}$ [GeV] | $E_{\text{T}}^{\text{miss}}$ [GeV] | $m_{\text{eff}}$ [GeV] | $\Delta\phi(\ell 1\ell 2, \mathbf{p}_{\text{T}}^{\text{miss}})$ | $\text{Sig}(E_{\text{T}}^{\text{miss}})$ |
|---|---|---|---|---|---|---|---|---|
| SRGGWZ-L | $\geq 2$ ($\geq 3$) | 0 | $\geq 6$ | $> 25$ | $> 200$ | $> 8 \times \sum p_{\text{T}}^{\ell}$ | $> 0.2$ | $> 6$ |
| SRGGWZ-M | $\geq 2$ (–) | | $\geq 6$ | $> 40$ | $> 190$ | $> 1300$ | $> 0.8$ | – |
| SRGGWZ-H | $\geq 2$ (–) | | $\geq 6$ | $> 40$ | $> 150$ | $> 2100$ | – | – |

| SR name | $n_{\text{Sig}}(\ell)$ | $n_{b\text{-jets}}$ | $n_{\text{jets}}$ | $p_{\text{T}}^{\text{jet}}$ [GeV] | $E_{\text{T}}^{\text{miss}}$ [GeV] | $m_{\text{eff}}$ [GeV] | $E_{\text{T}}^{\text{miss}}/\sum p_{\text{T}}^{\ell}$ | $\sum p_{\text{T}}^{\ell}/\sum p_{\text{T}}^{\text{jet}}$ | $n_{Z\to\ell^+\ell^-}$ |
|---|---|---|---|---|---|---|---|---|---|
| SRSSWZ-L | $\geq 3$ | 0 | $\geq 4$ | $> 25$ | $> 0.2 \times m_{\text{eff}}$ | – | – | $< 0.2$ | $0^{\dagger}$ |
| SRSSWZ-ML | | | $\geq 6$ | $> 25$ | $> 150$ | $> 800$ | $> 1.2$ | $< 0.3$ | $\geq 1^{\dagger}$ |
| SRSSWZ-MH | | | $\geq 5$ | $> 40$ | $> 200$ | $> 900$ | $> 1.1$ | $< 0.4$ | $\geq 1^{\dagger}$ |
| SRSSWZ-H | | | $\geq 5$ | $> 40$ | $> 250$ | $> 1500$ | $> 0.3$ | $< 0.7$ | – |

$^{\dagger}$: based on number of SFOS pairs with $81 < m_{\text{SFOS}} < 101$ GeV

**Z filter based on same-flavor opposite-sign (SFOS) leptons**

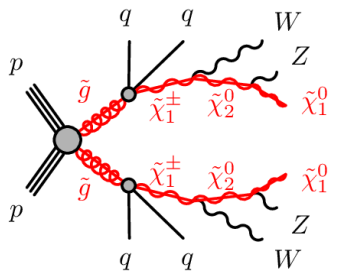
Stockholms universitet



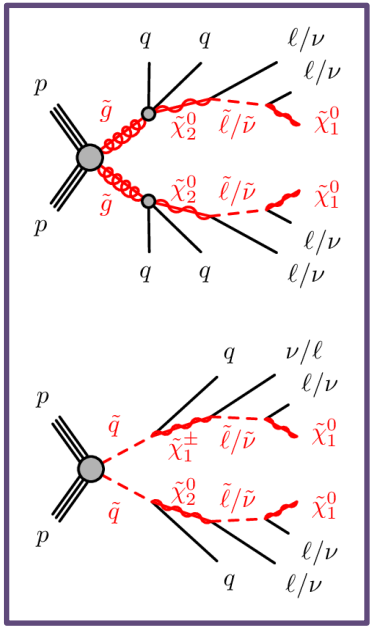
ATLAS EXPERIMENT

# Gluino and Squark Production: Same-Sign (SS) / 3L

**ATLAS-CONF-2023-017**

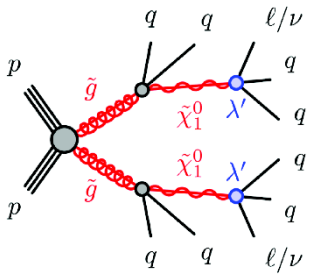


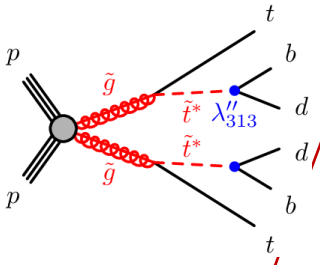
electroweak gauginos to LSP via cascade decays



electroweak gauginos to SM leptons + LSP

direct LSP decay to SM lepton via non-zero RPV





lightest stop decay to tbq via non-zero RPV

**SRGG(gluino)/SS(squark)Slep**

Same suffix denotation as **SRGG/SSWZ**

In **SRSSSlep**, additional "H (loose)" region defined with relaxed $m_{\text{eff}}$ cut, allowing for binned fit

| SR name | $n_{\text{Sig}}(\ell)$ | $n_{b\text{-jets}}$ | $n_{\text{jets}}$ | $p_{\text{T}}^{\text{jet}}$ [GeV] | $E_{\text{T}}^{\text{miss}}$ [GeV] | $E_{\text{T}}^{\text{miss}}/\sum p_{\text{T}}^{\text{jet}}$ | $p_{\text{T}}^{\ell 2}$ [GeV] | other |
|---|---|---|---|---|---|---|---|---|
| SRGGSlep-L | $\geq 3^{\dagger}$ | 0 | $\geq 4$ | $\geq 40$ | – | $> 0.4$ | $> 30$ | $E_{\text{T}}^{\text{miss}}/\sum p_{\text{T}}^{\ell} > 1.4$ |
| SRGGSlep-M | | | | | $> 150$ | $> 0.3$ | $> 70$ | $\Delta\phi(\ell 1\ell 2, \mathbf{p}_{\text{T}}^{\text{miss}}) > 0.7$ |
| SRGGSlep-H | | | | | $> 100$ | – | – | $\sum p_{\text{T}}^{\text{jet}} > 1200\,\text{GeV}$ |

†: SFOS pairs with $81 < m_{\text{SFOS}} < 101$ GeV are not allowed

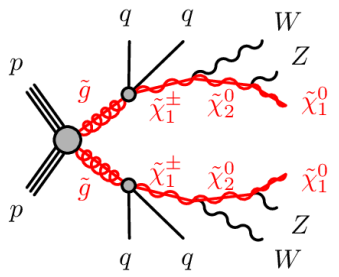
| SR name | $n_{\text{Sig}}(\ell)$ | $p_{\text{T}}^{\ell}$ [GeV] | $n_{b\text{-jets}}$ | $n_{\text{jets}}$ | $p_{\text{T}}^{\text{jet}}$ [GeV] | $E_{\text{T}}^{\text{miss}}$ [GeV] | $m_{\text{eff}}$ [GeV] | $\Delta\phi(\ell 1\ell 2, \mathbf{p}_{\text{T}}^{\text{miss}})$ |
|---|---|---|---|---|---|---|---|---|
| | other requirements | | | | | | | |
| SRSSSlep-L | 3* | $< 60$ | 0 | $\geq 3$ | $> 60, 60, 25$ | $> 100$ | $> 600$ | $> 1.4$ |
| | $\sum p_{\text{T}}^{\ell}/\sum p_{\text{T}}^{\text{jet}} < 0.6$ | | | | | | | |
| SRSSSlep-ML | 3* | $> 30$ | 0 | $\geq 3$ | $> 60, 60, 25$ | $> 100$ | $> 700$ | $> 1.4$ |
| | $E_{\text{T}}^{\text{miss}}/\sum p_{\text{T}}^{\ell} > 0.7$, $\sum p_{\text{T}}^{\ell}/\sum p_{\text{T}}^{\text{jet}} < 0.6$ | | | | | | | |
| SRSSSlep-MH | 3* | $> 40$ | 0 | $\geq 2$ | $> 60$ | $> 200$ | $> 1000$ | $> 0.5$ |
| | $E_{\text{T}}^{\text{miss}}/\sum p_{\text{T}}^{\ell} > 0.7$, $\Delta R(\ell 1, \ell 2) > 0.2$ | | | | | | | |
| SRSSSlep-H | 3* | $> 40$ | 0 | $\geq 2$ | $> 60$ | $> 200$ | $> 2000$ | $> 0.3$ |
| | $\Delta R(\ell 1, \ell 2) > 0.5$ | | | | | | | |
| SRSSSlep-H (loose) | 3* | $> 40$ | 0 | $\geq 2$ | $> 60$ | $> 200$ | $> 1000$ | $> 0.3$ |
| | $\Delta R(\ell 1, \ell 2) > 0.5$ | | | | | | | |

*: additional baseline leptons are not allowed, nor SFOS pairs with $81 < m_{\text{SFOS}} < 101$ GeV

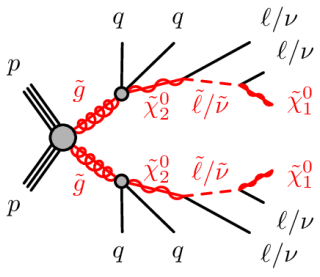
**Z veto**

# Gluino and Squark Production: Same-Sign (SS) / 3L

**ATLAS-CONF-2023-017**

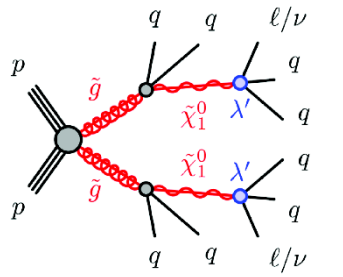


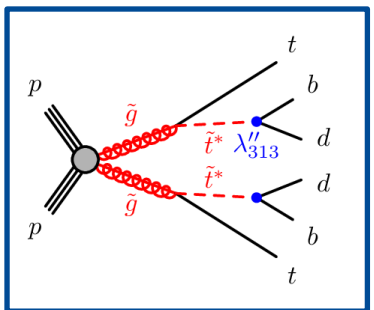
electroweak gauginos to LSP via cascade decays



electroweak gauginos to SM leptons + LSP

direct LSP decay to SM lepton via non-zero RPV





lightest stop decay to tbq via non-zero RPV

$$W_{\text{MSSM}} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d$$
$$+ \frac{1}{2}\lambda^{ijk}L_iL_j\overline{e}_k + \lambda'^{ijk}L_iQ_j\overline{d}_k + \mu'^iL_iH_u + \frac{1}{2}\lambda''^{ijk}\overline{u}_i\overline{d}_j\overline{d}_k$$

**SRLQD**

RPV coupling of LQD type

2 SS leptons, high $m_{\text{eff}}$, no requirement on $p^{\text{T}}_{\text{miss}}$

| SR name | $n_{\text{Sig}}(\ell)$ | $n_{b\text{-jets}}$ | $n_{\text{jets}}$ | $p_{\text{T}}^{\text{jet}}$ [GeV] | $m_{\text{eff}}$ [GeV] |
|---|---|---|---|---|---|
| SRLQD | 2 | – | ≥ 5 | > 50 | > 2600 |

**SRUDD**

RPV coupling of UDD type

Suffix denotes $b$-jet multiplicity

2 SS leptons, no requirement on $p^{\text{T}}_{\text{miss}}$

| SR name | $n_{\text{Sig}}(\ell)$ | $n_{b\text{-jets}}$ | $n_{\text{jets}}$ | $p_{\text{T}}^{\text{jet}}$ [GeV] | $m_{\text{eff}}$ [GeV] | $\sum p_{\text{T}}^{\text{jet}}$ [GeV] |
|---|---|---|---|---|---|---|
| SRUDD-1b | 2 | 1 | ≥ 6 | > 50 | – | > 1600 |
| SRUDD-2b | | 2 | ≥ 2 | > 25 | – | > 1700 |
| SRUDD-ge2b | | ≥ 2 | ≥ 5 | > 50 | – | > 1600 |
| SRUDD-ge3b | | ≥ 3 | ≥ 4 | > 50 | > 1600 | – |

Stockholms universitet

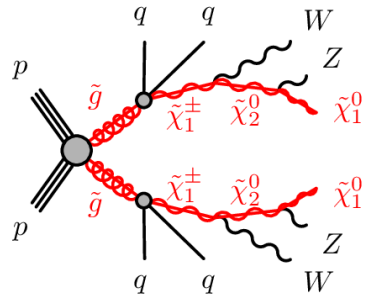


ATLAS EXPERIMENT

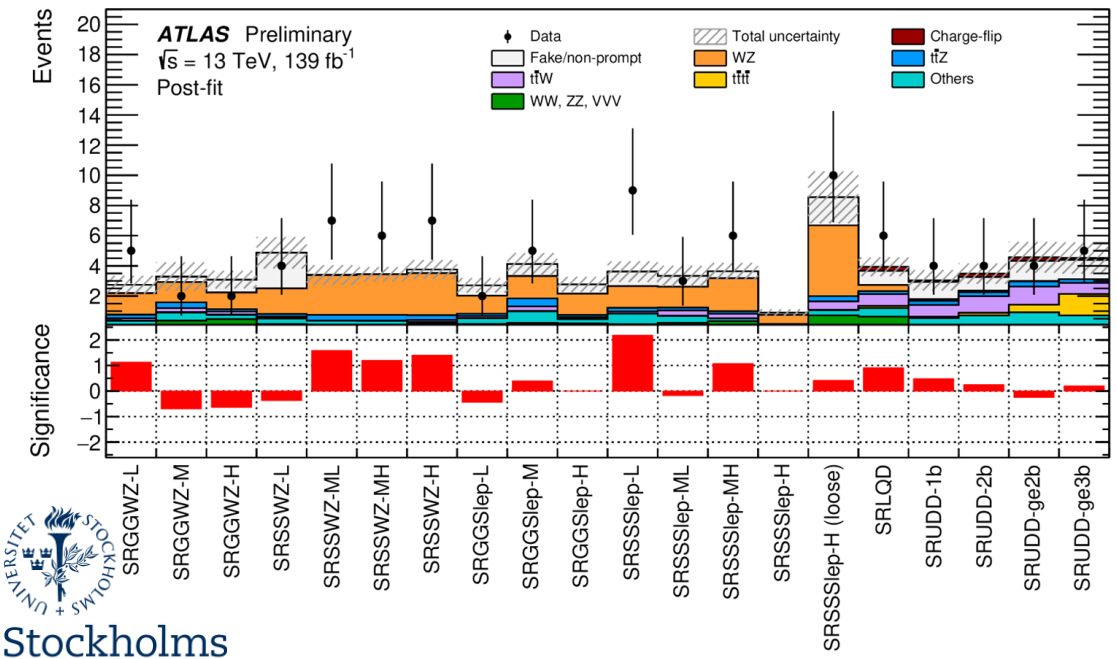
# Gluino and Squark Production: Same-Sign (SS) / 3L

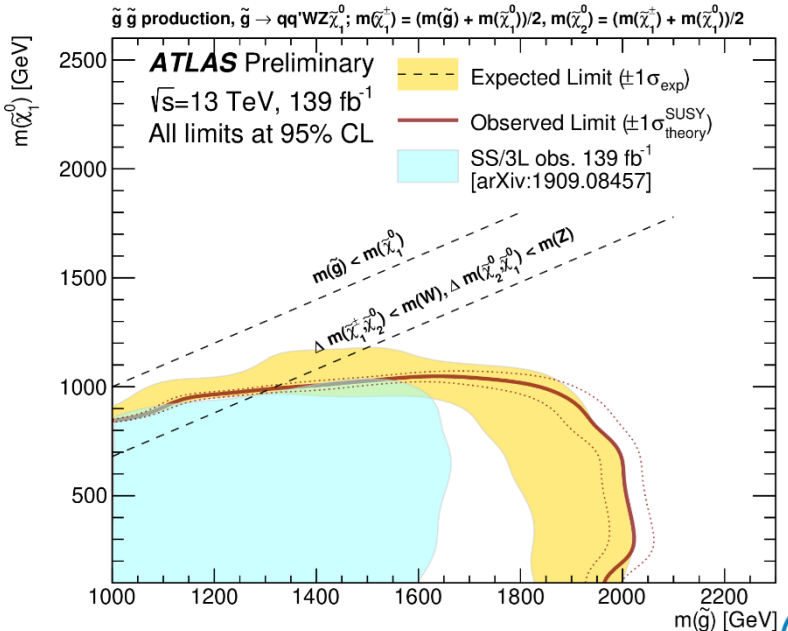
**ATLAS-CONF-2023-017**

- Background estimation
  - SM WZ (RPC only) – constrained in dedicated control region (CR)
  - Charge-flip, fake/non-prompt (F/NP) leptons
- No significant excess over the SM prediction in all SRs




**exclusions for other scenarios in backup**

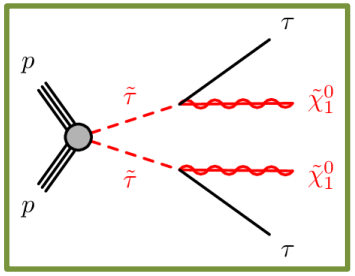


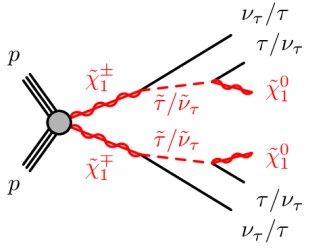



# Stau and Gaugino Production: 2 Tau Final State

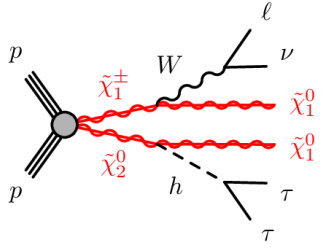
**ATLAS-CONF-2023-029**

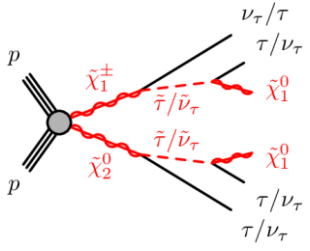
direct production of stau pair to tau + LSP




electroweak gauginos to SM tau + LSP via intermediate Wh




electroweak gauginos to SM tau + LSP via intermediate stau

**Key Discriminant: Stransverse Mass** [arXiv:hep-ph/0304226]

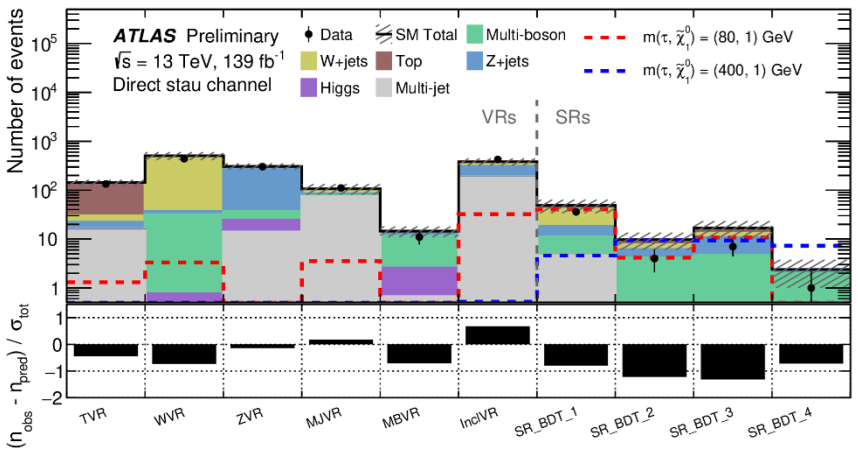
$$m_{T2} = \min_{\mathbf{q}_T} \left[ \max \left( m_{T1}(\mathbf{p}_{T1}, \mathbf{q}_T), m_{T2}(\mathbf{p}_{T2}, \mathbf{p}_T^{miss} - \mathbf{q}_T) \right) \right]$$

$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}$$

For events where two massive pair produced particles each decay to two objects, a kinematic endpoint can be seen in the $m_{T2}$ spectrum

**SR-BDT**

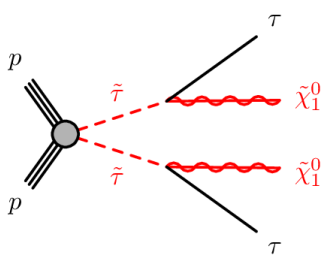
4 overlapping SRs defined based on the BDT score Among them, the SR with the best expected sensitivity will be chosen for interpretations



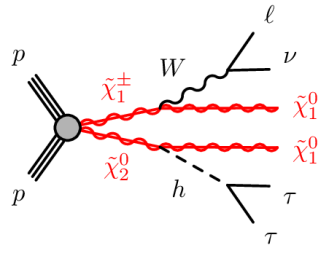
# Stau and Gaugino Production: 2 Tau Final State

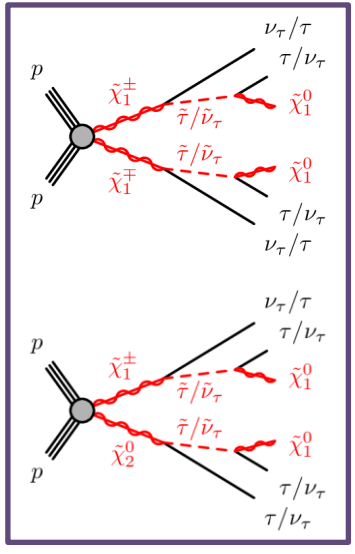
**ATLAS-CONF-2023-029**

direct production of stau pair to tau + LSP




electroweak gauginos to SM tau + LSP via intermediate Wh




electroweak gauginos to SM tau + LSP via intermediate stau

**Key Discriminant: Stransverse Mass** [arXiv:hep-ph/0304226]

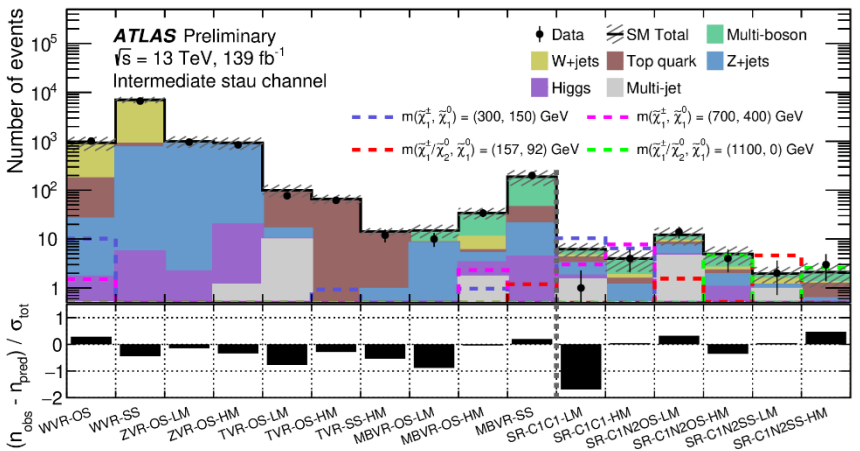
$$m_{T2} = \min_{\mathbf{q}_T} \left[ \max \left( m_{T1}(\mathbf{p}_{T1}, \mathbf{q}_T), m_{T2}(\mathbf{p}_{T2}, \mathbf{p}_T^{miss} - \mathbf{q}_T) \right) \right]$$

$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}$$

For events where two massive pair produced particles each decay to two objects, a kinematic endpoint can be seen in the $m_{T2}$ spectrum

**SR-C1C1/C1N2**

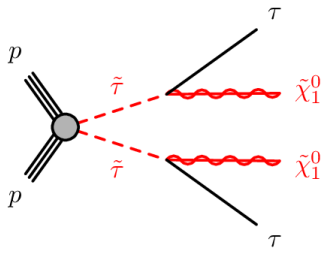
**SRC1N2** divided into opposite-sign (OS) and same-sign (SS) base on the charge of tau pair SRs further separated into LM and HM regions

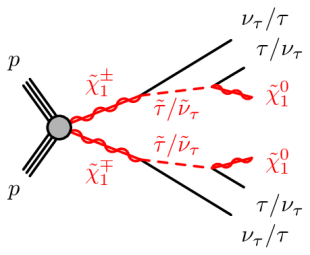


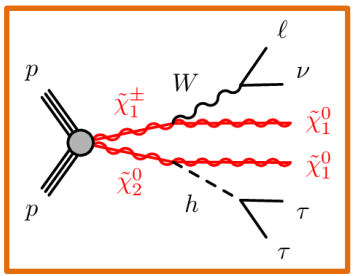
# Stau and Gaugino Production: 2 Tau Final State

**ATLAS-CONF-2023-029**

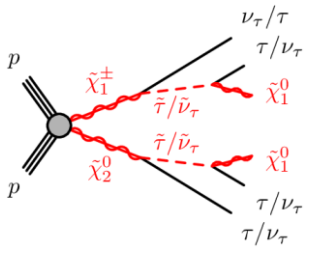
direct production of stau pair to tau + LSP




electroweak gauginos to SM tau + LSP via intermediate Wh




electroweak gauginos to SM tau + LSP via intermediate stau

**Key Discriminant: Stransverse Mass** [arXiv:hep-ph/0304226]

$$m_{T2} = \min_{\mathbf{q}_T} \left[ \max \left( m_{T1}(\mathbf{p}_{T1}, \mathbf{q}_T), m_{T2}(\mathbf{p}_{T2}, \mathbf{p}_T^{miss} - \mathbf{q}_T) \right) \right]$$

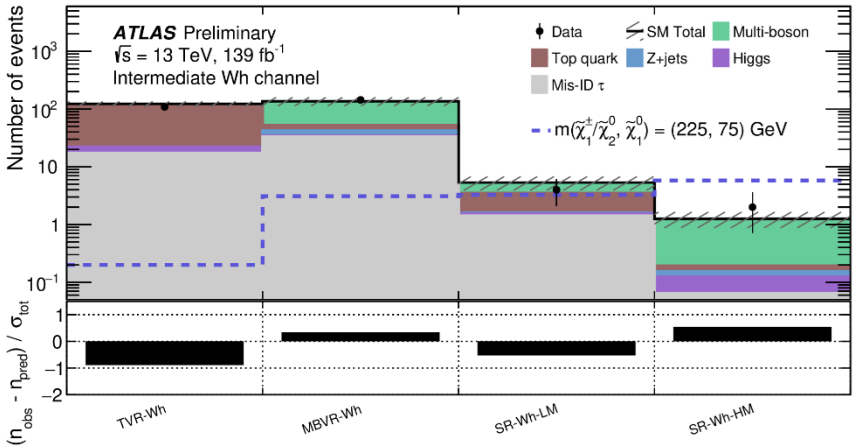
$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}$$

For events where two massive pair produced particles each decay to two objects, a kinematic endpoint can be seen in the $m_{T2}$ spectrum

**SR-Wh-LM/HM**

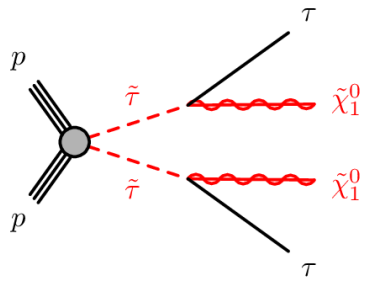
Invariant mass of the 2 tau leptons fall within the Higgs mass range

Apply high $m_{T2}$ requirement to reject the SM backgrounds



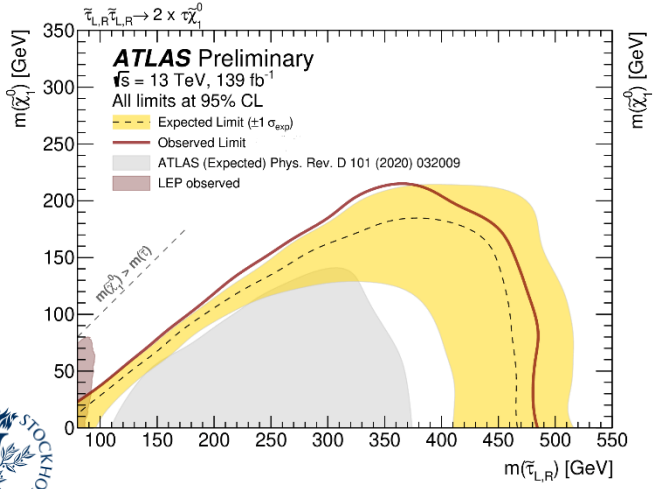
# Stau and Gaugino Production: 2 Tau Final State

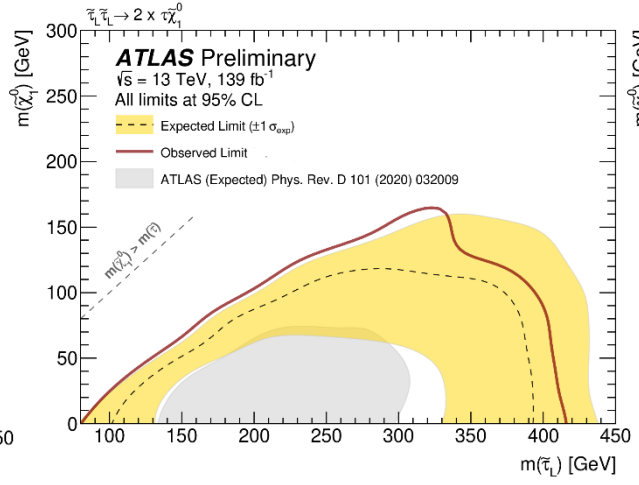
**ATLAS-CONF-2023-029**

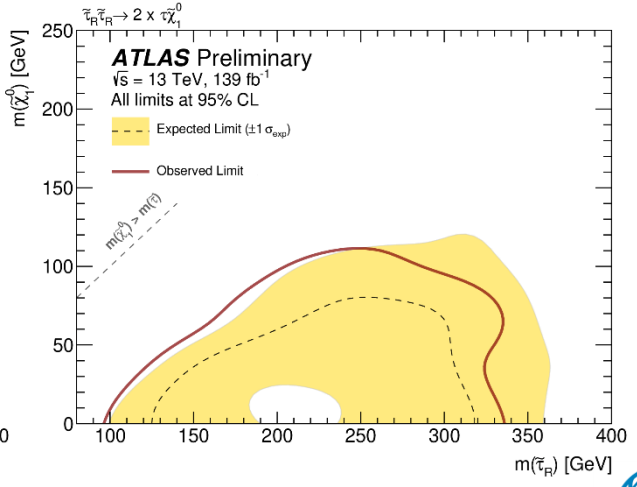



- Background estimation
  - Multijet – constrained using ABCD method
  - SM top, W/Z+jets – constrained in dedicated CRs
  - Other irreducible background – validated in VRs
- No significant excess over the SM prediction in all SRs
- First sensitivity to right-handed stau pair production at the LHC!

**exclusions for other scenarios in backup**



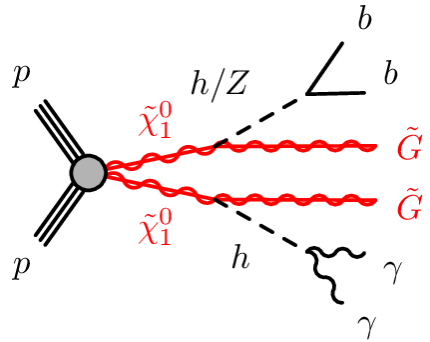

Stockholms universitet



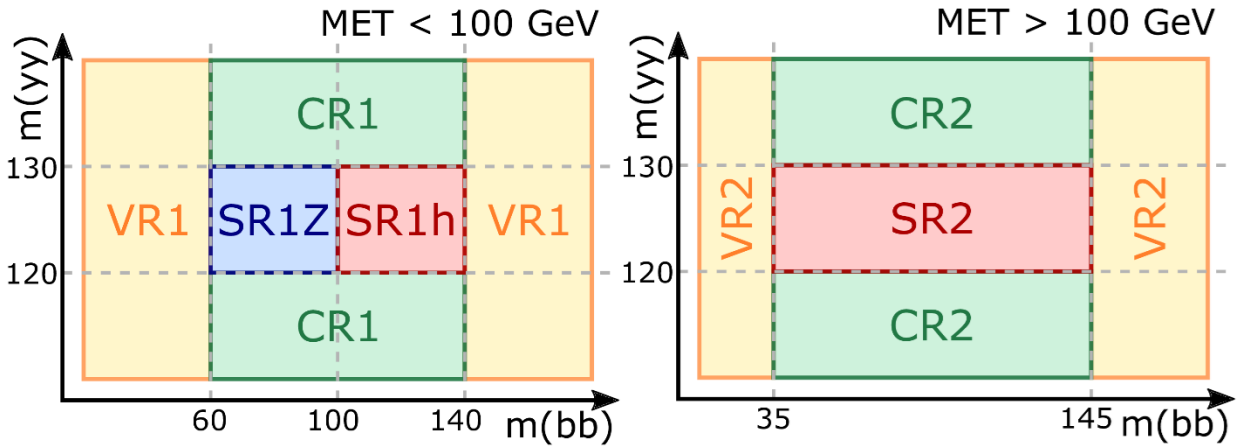
ATLAS EXPERIMENT

# Higgsino Production: 2 Photons + 2 b-jets Final State

**ATLAS-CONF-2023-009**



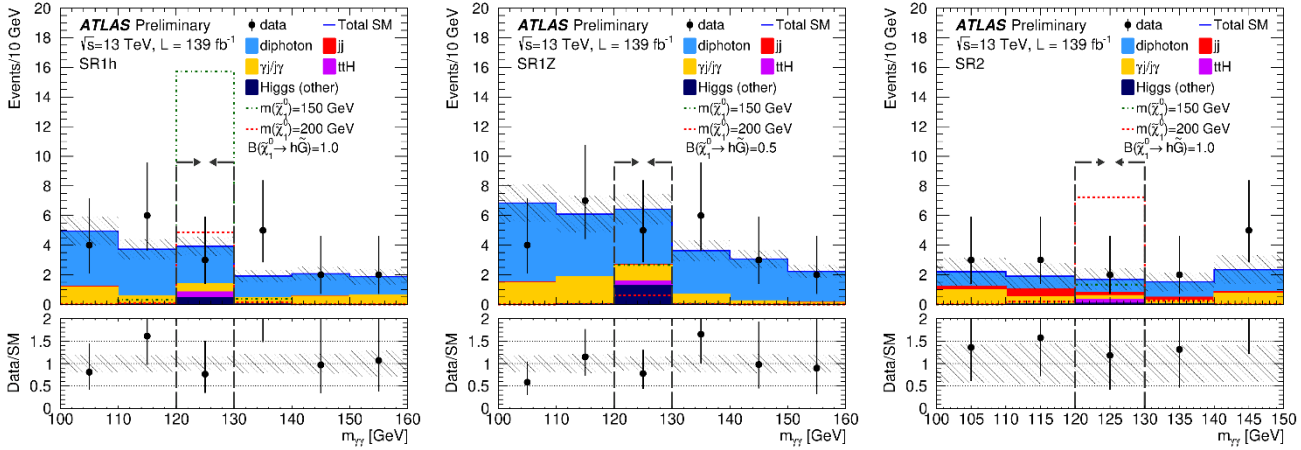

**gravitino mass negligible (1 MeV)**

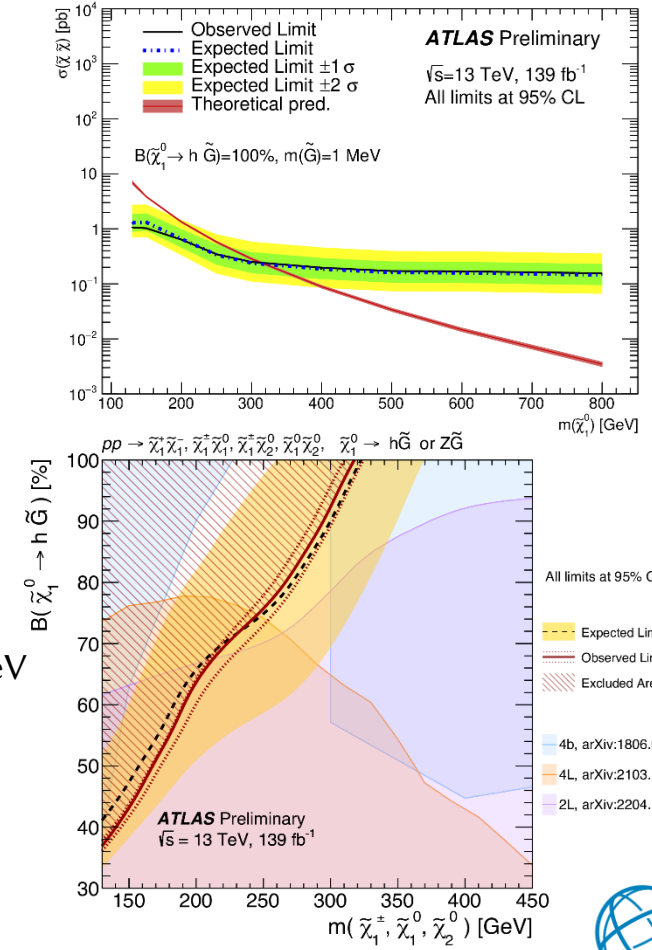



- Events selected by diphoton trigger
- Preselection to reduce fake photons:
  - Invariant mass $m_{yy} \in [90, 160]$ GeV
  - $p_T/m_{yy} > 0.2$ for each signal photon
- 3 non-overlapping SRs
- Major backgrounds
  - Resonant – determined by MC
  - Non-resonant (F/NP photons) – determined by the "2×2D sideband method" [arXiv:1107.0581]

# Higgsino Production: 2 Photons + 2 b-jets Final State

**ATLAS-CONF-2023-009**




- No significant excess over the SM prediction in all SRs
- Assuming $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G}) = 100\%$ :
  - Theoretical prediction excluded at 95% CL for neutralino mass < 320 GeV
- Assuming $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G}) + \mathcal{B}(\tilde{\chi}_1^0 \to Z\tilde{G}) = 100\%$ :
  - **Limits** set as a function of Higgsino mass and branching fraction
  - Exclusion down to $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G}) = 36\%$ for neutralino mass = 130 GeV

# Summary and Outlook

- Newest result in search of Supersymmetry from the ATLAS Collaboration:
  - Strong SS/3L
  - Electroweak ττ (*first sensitivity to right-handed stau pair production at the LHC*)
  - Electroweak yybb

- Data observations consistent with the SM prediction

- With the accumulation of Run 3 data, larger statistics expected, allowing for searches targeting even more challenging region in SUSY parameter space!

Stockholms universitet

ATLAS EXPERIMENT

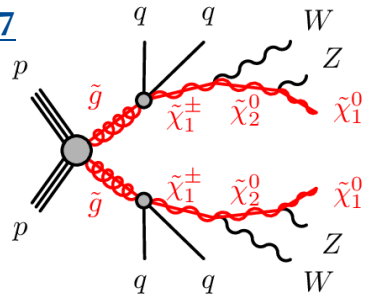
# Backup Materials

Stockholms universitet

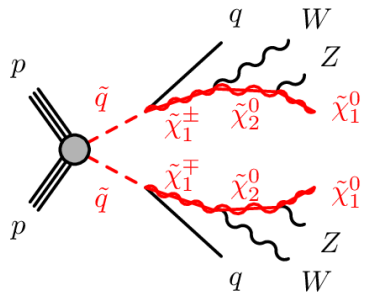
ATLAS EXPERIMENT

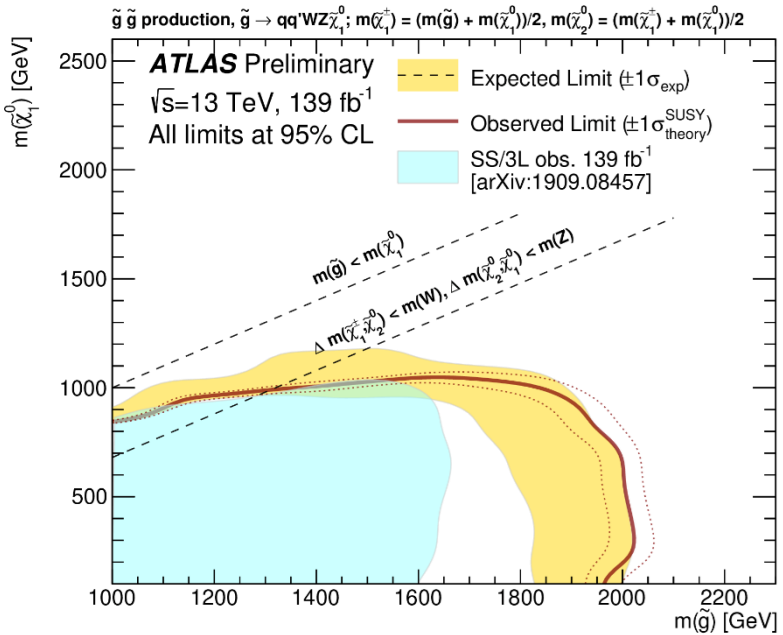
# Gluino and Squark Production: Same-Sign (SS) / 3L

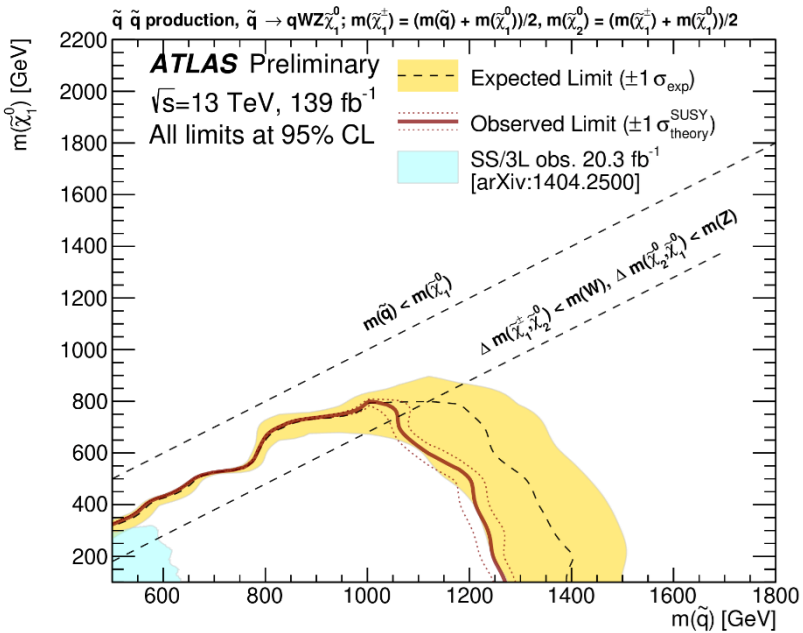
ATLAS-CONF-2023-017




electroweak gauginos to LSP via cascade decays

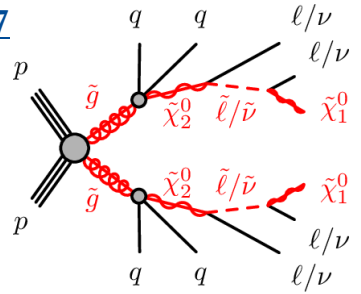


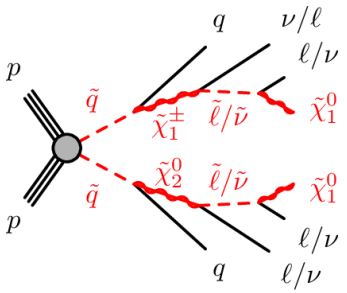



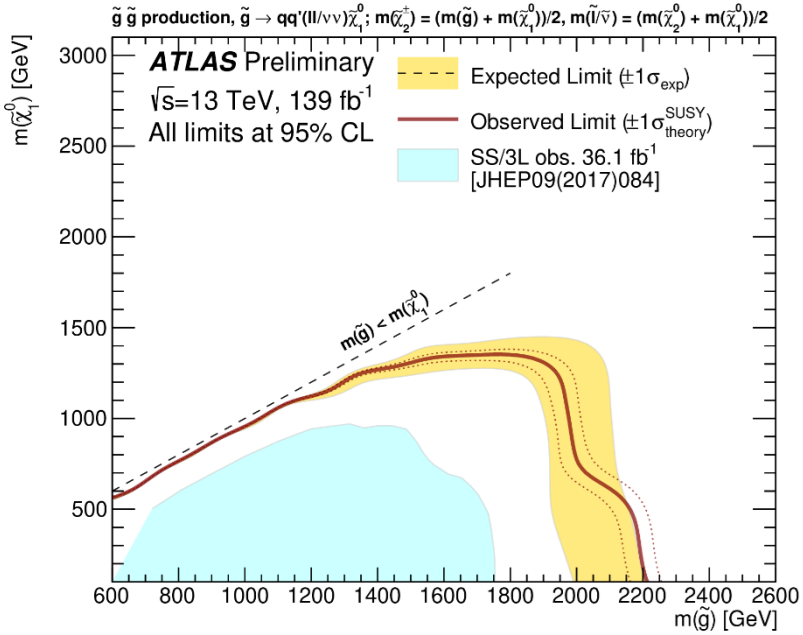
# Gluino and Squark Production: Same-Sign (SS) / 3L

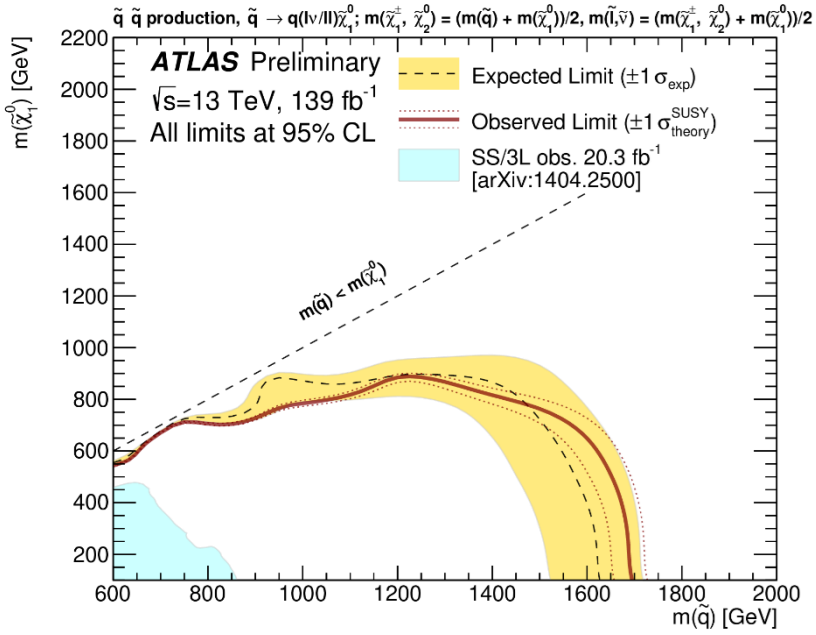
**ATLAS-CONF-2023-017**




electroweak gauginos to SM leptons + LSP



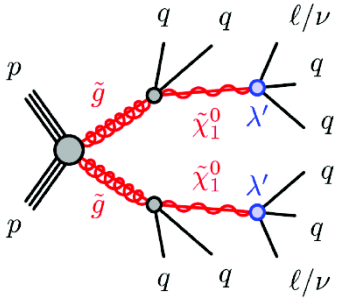



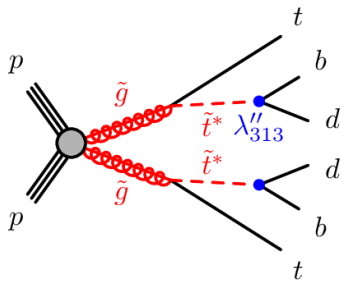



# Gluino and Squark Production: Same-Sign (SS) / 3L

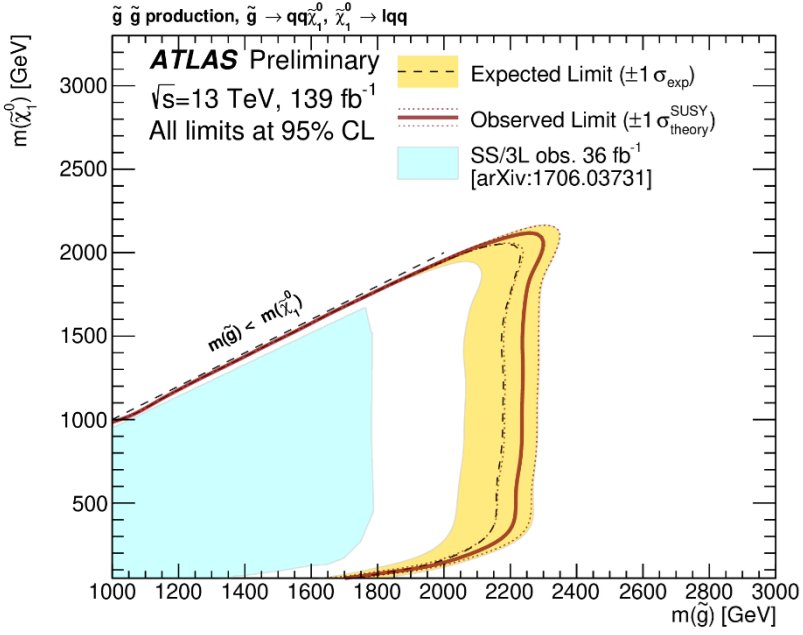
**ATLAS-CONF-2023-017**

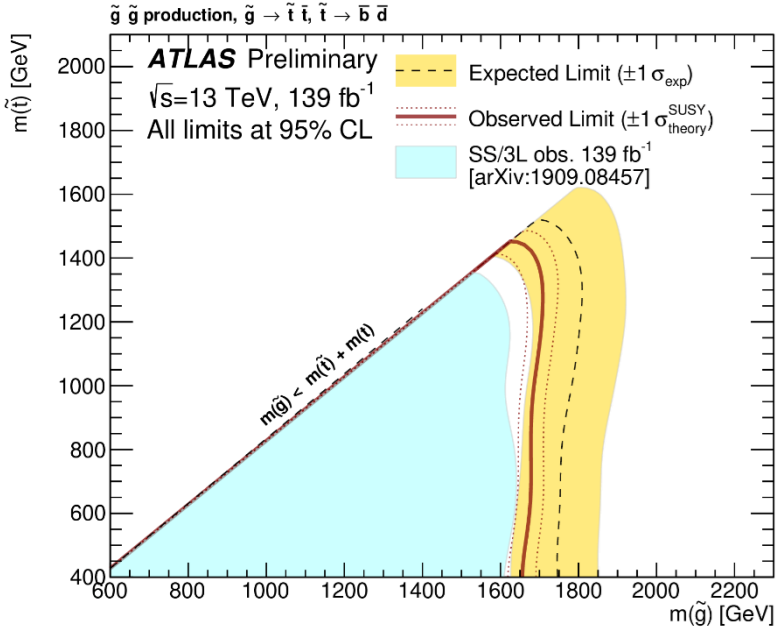
direct LSP decay to SM lepton via non-zero RPV



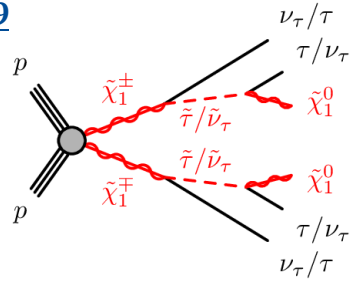

lightest stop decay to tbq via non-zero RPV



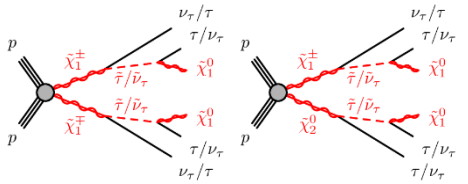



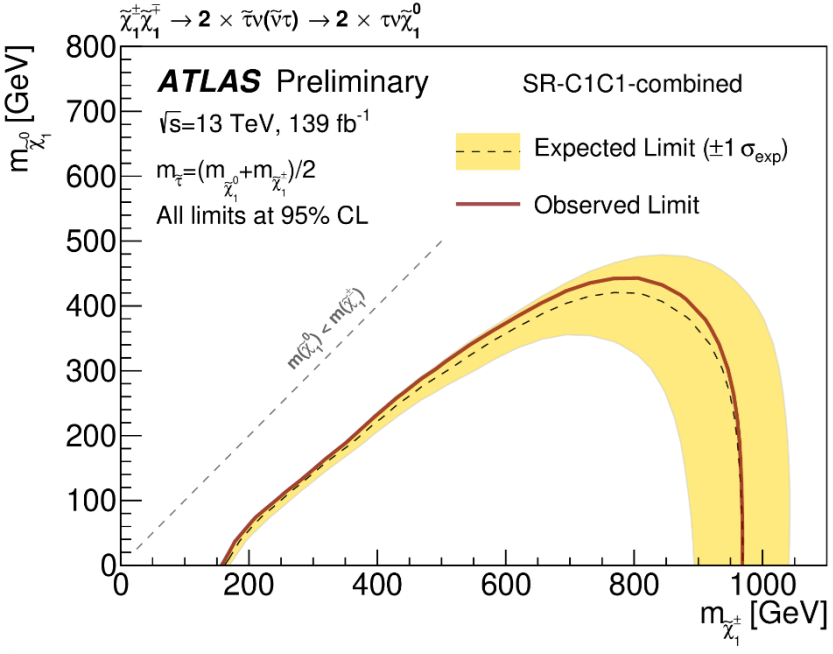
# Stau and Gaugino Production: 2 Tau Final State

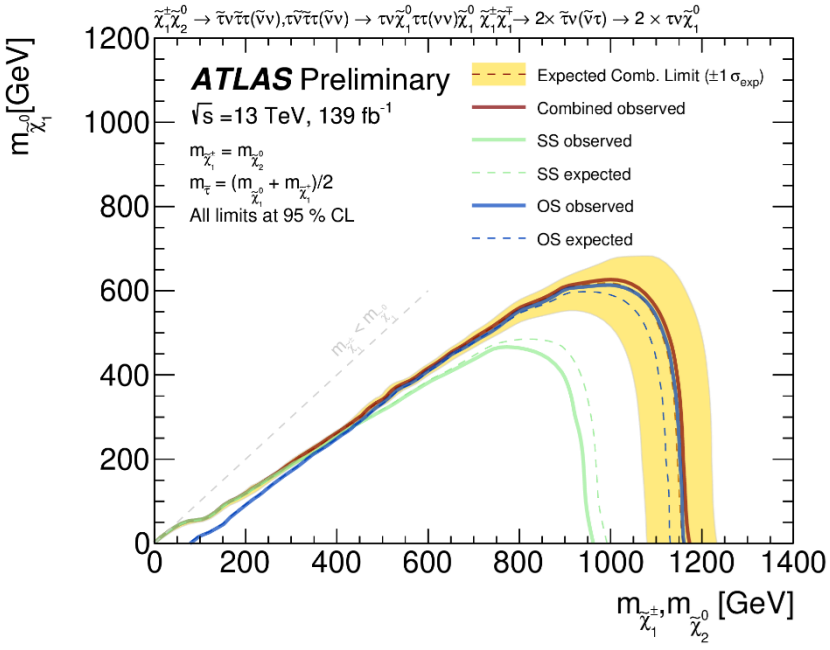
**ATLAS-CONF-2023-029**




electroweak gauginos to SM tau + LSP via intermediate stau

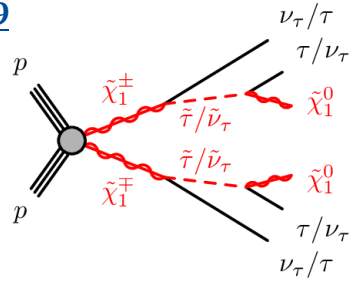


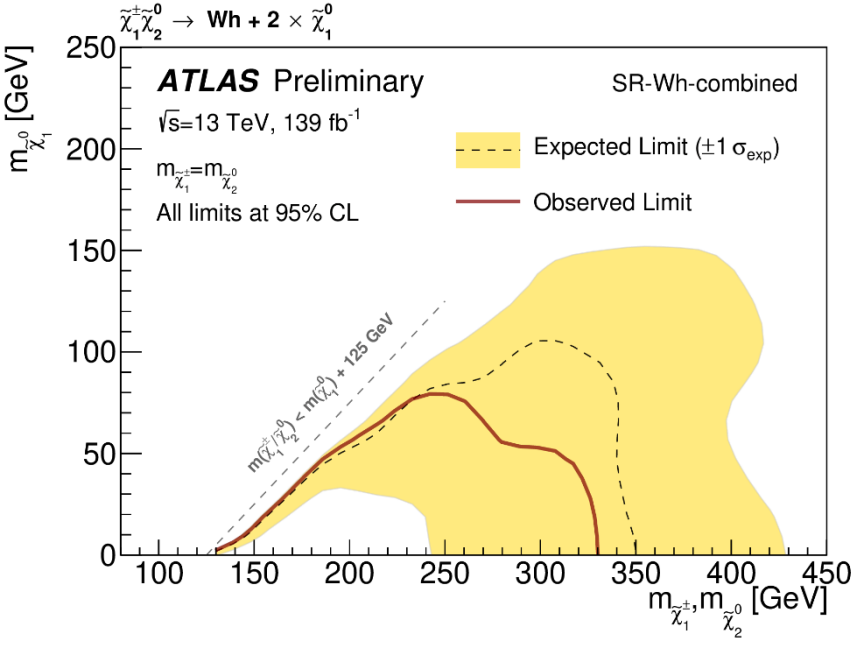



# Stau and Gaugino Production: 2 Tau Final State

**ATLAS-CONF-2023-029**

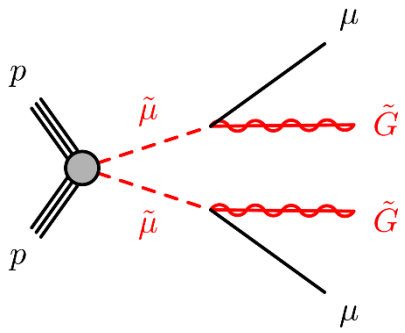



electroweak gauginos to SM tau + LSP via intermediate Wh



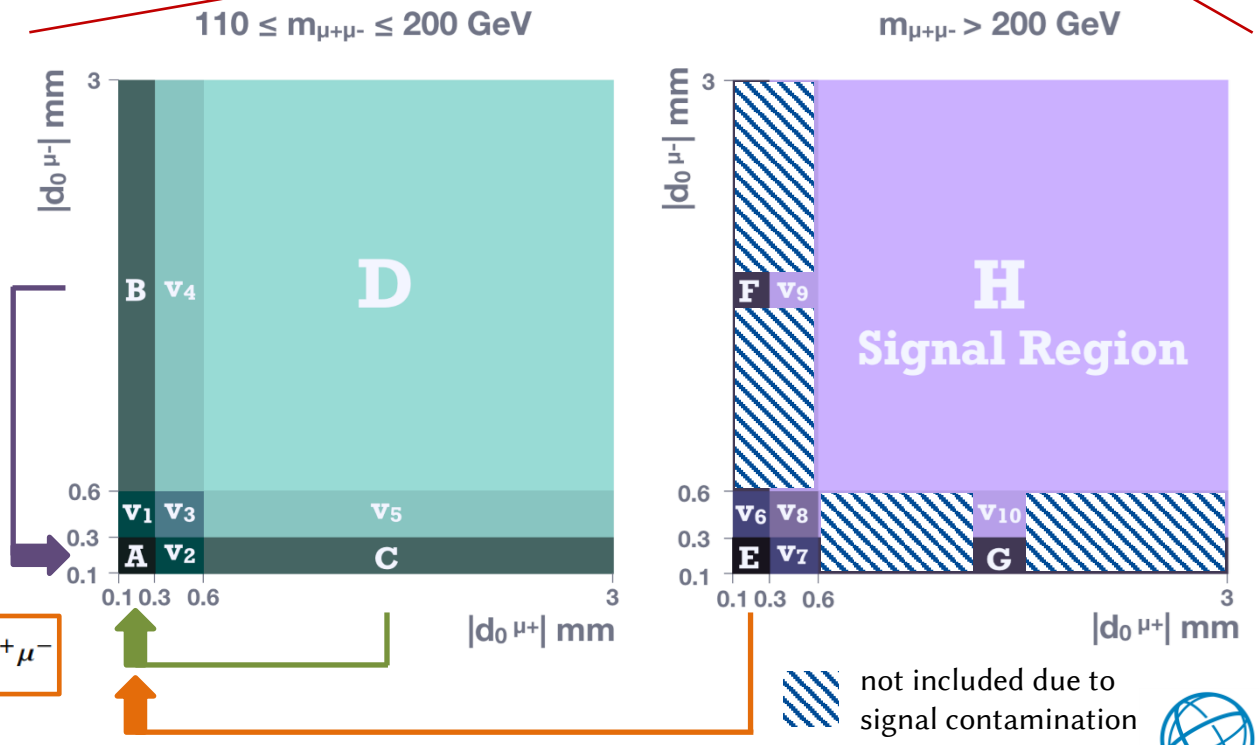
# Smuon Production: Micro-displaced Muons

arXiv:2305.02005, submitted to *Phys.Lett. B*




- Transverse impact $|d_0|$ > 0.1 mm
  - Major background – semileptonic *b*-hadron decays
  - Other SM processes with prompt leptons negligible based on MC
- Extended ABCD method used to estimate background in the SR

| Set of Regions | Lower displacement region | Higher displacement region | Threshold $m_{\mu^+\mu^-}$ | Additional cut |
|---|---|---|---|---|
| 1 | $0.1 \le \lvert d_0 \rvert < 0.3$ | $0.6 \le \lvert d_0 \rvert < 3$ mm | 200 GeV | - |
| 2 | $0.1 \le \lvert d_0 \rvert < 0.3$ | $0.6 \le \lvert d_0 \rvert < 3$ mm | 140 GeV | - |
| 3 | $0.1 \le \lvert d_0 \rvert < 0.3$ | $0.6 \le \lvert d_0 \rvert < 1.3$ mm | 125 GeV | $\Delta R_{\mu^+\mu^-} > 3$ rad. |




$$N_H^{\text{est. bkg.}} = N_A^{\text{data}} \cdot r^{d_0^+} \cdot r^{d_0^-} \cdot r^{m_{\mu^+\mu^-}}$$

# Smuon Production: Micro-displaced Muons

arXiv:2305.02005, submitted to *Phys.Lett. B*

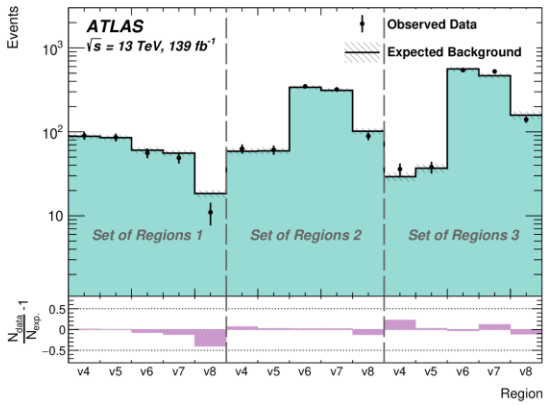
$$N_H^{\text{est. bkg.}} = N_A^{\text{data}} \cdot r^{d_0^+} \cdot r^{d_0^-} \cdot r^{m_{\mu^+\mu^-}}$$

**ABCD Method Validation**

The variables $r^{d_0^+}$, $r^{d_0^-}$, $r^{m_{\mu^+\mu^-}}$ should be uncorrelated

Validation regions v4 – v8 defined, using regions A, B, C, E and v1 – v3 for ratio computation

Data/Exp consistent in VRs




- No significant excess over the SM prediction in all SRs

| Set of Regions | Expected $N_H^{\text{bkg}}$ | Observed $N_H^{\text{data}}$ | $\langle A\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb] | $S_{\text{obs}}^{95}$ | $S_{\text{exp}}^{95}$ | $CL_B$ | $p(s=0)$ $(Z)$ |
|---|---|---|---|---|---|---|---|
| 1 | $2.1 \pm 0.8$ | 1 | 0.02 | 3.3 | $4.2^{+2.5}_{-1.4}$ | 0.27 | 0.50 (0.00) |
| 2 | $12.5 \pm 5.2$ | 7 | 0.04 | 5.2 | $8.5^{+4.0}_{-2.7}$ | 0.08 | 0.50 (0.00) |
| 3 | $17.2 \pm 7.4$ | 14 | 0.06 | 8.9 | $10.5^{+5.0}_{-3.1}$ | 0.26 | 0.50 (0.00) |