Searches for strong production of supersymmetric particles with the ATLAS detector

Yang Liu On behalf of the ATLAS Collaboration

Nanjing University & Institute of High Energy Physics

yang.l@cern.ch

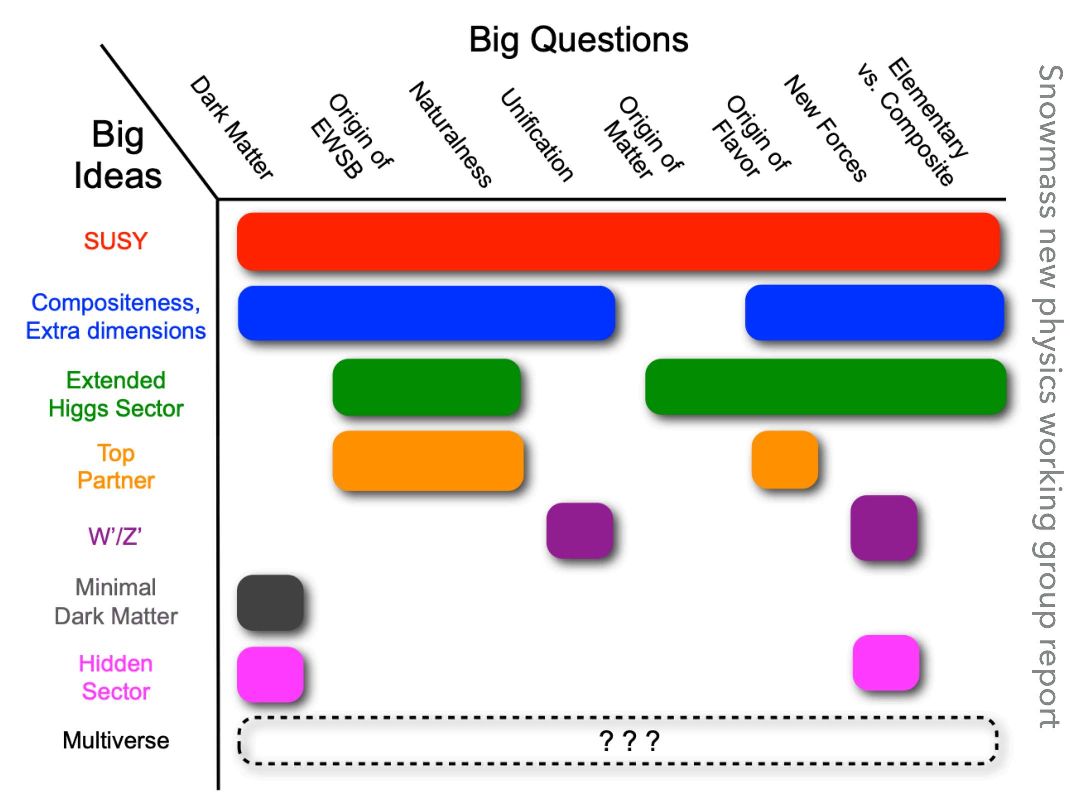
May 26 2021

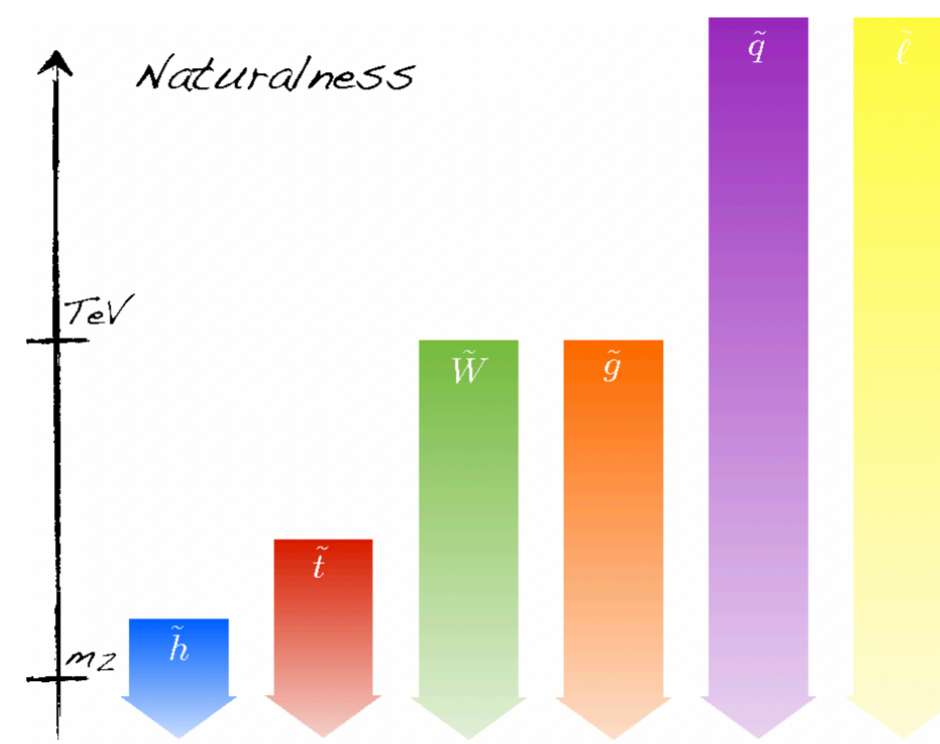
Motivation:

- Despite the huge success of the SM theory, physics beyond SM is strongly motivated:
    - hierarchy problem, dark matter, quantum description of gravity, the GUT e.t.c…
- Supersymmetry (SUSY) extend the SM and connect SM Fermions & Bosons with their super partner into a set of super-multiplets
    - Solving hierarchy problem if only soft breaking of supersymmetry (mass constraint within TeV scale, could be produced in the LHC)
    - Provide stable DM candidate (Lightest-SUSY-Particle) if R-parity is conserving (RPC)

$$P_R = (-1)^{3B+L+2S}$$

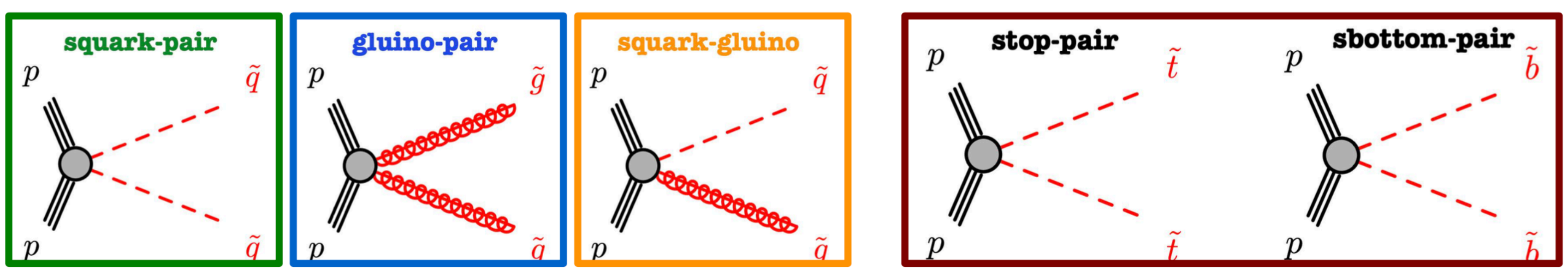
    - Including graviton & gravitino needed for the GUT…

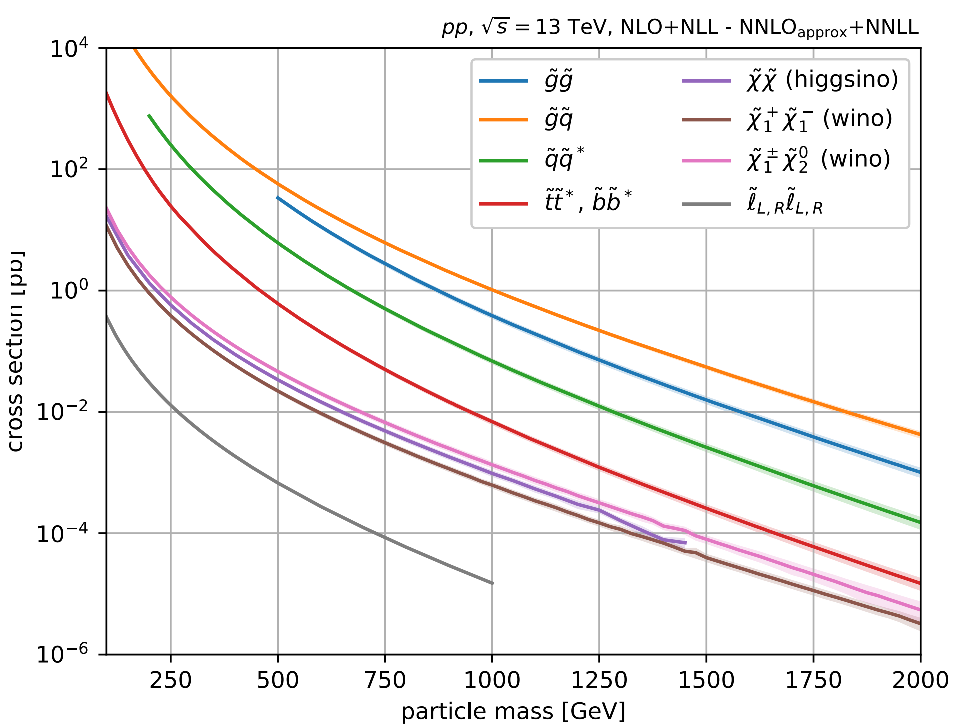




Status of SUSY search in ATLAS:

- ~40 analysis teams covering all aspects of SUSY scenarios and models including Strongly produced SUSY, EWK produced SUSY, RPC, RPV and LLP…
  - This talk will only cover the latest searches of strong production of gluino or squark^{3rd} in RPC or RPV scenarios
  - SUSY searches in EWK and LLP will be covered by Batool's talk and Jackson's talk
- Four main strong production mechanisms at LHC:





- Strong production of SUSY has relatively large production cross-sections which could probe higher mass regions but comes with more bkg contamination
- Only simplified models are used considering a few particles and decoupling the other to higher scale

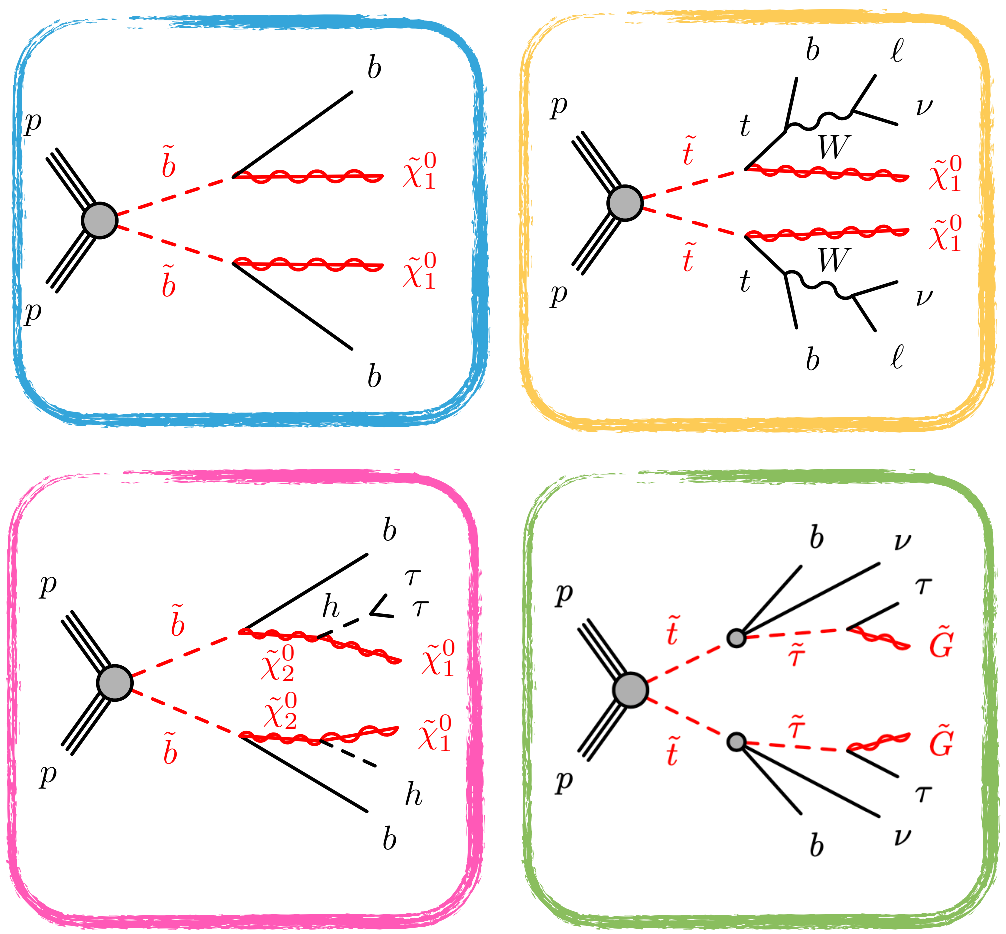
Status of Strong SUSY search in ATLAS:

- With R-parity conserving, the LSP is stable and only interacting weakly with others, providing a suitable candidate of DM (WIMP) and large E_T^{miss} as signature
- With R-parity violated, the LSP could decay to SM particles via RPV sector leaving less E_T^{miss} and SM particles in the final state:

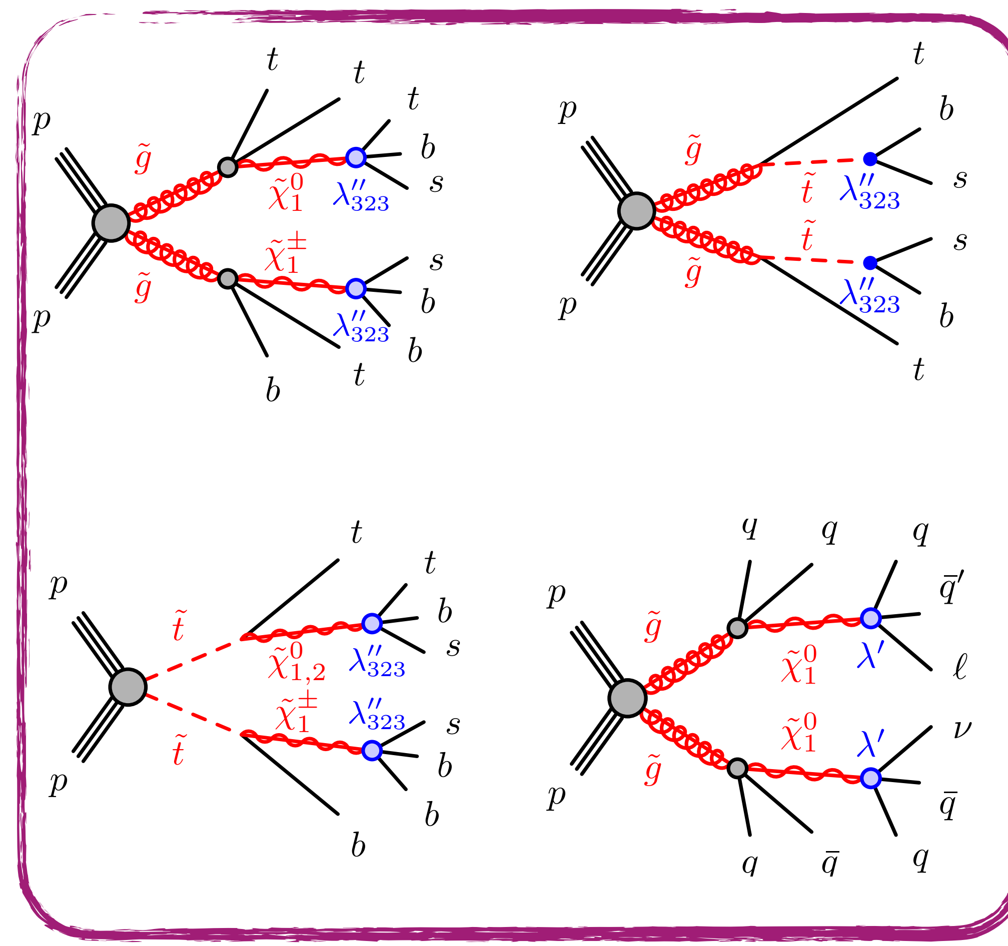
$$W = W_{MSSM} + W_R;\ \ W_R = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_iL_iH_2$$

- This talk will cover:

RPC



RPV



General strategy on Strong SUSY searches:

Finding signal regions

- Dedicated SRs are designed for targeting signal models to enhance the signal sensitivity
- Different sets of SRs are designed to target at different phase space (e.g: boost, compressed)
- “Multi-bin” strategy is applied to maximize the exclusion power
- Best CLs value for each point are chosen from those inclusively SRs

BKG estimations

- Dominant bkgs:
  - Estimated directly from data events in control regions (CRs):
    - Data-Driven (DD) methods e.g: ABCD, MxM and FakeFactor methods
  - Corrected by data in CRs
  - Estimations will be validated by comparing to data events in validation regions
- Minor bkgs: Estimated directly via MC simulations

Systematics estimations

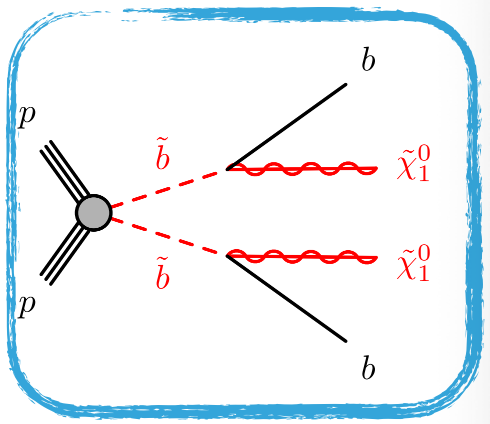
- Experimental uncertainties:
  - Uncertainties coming from the imperfection of the simulation, obtained by all kinds of correction factors e.g: Lumi, pileup …
  - Uncertainties coming from DD estimation methods
- Theoretically uncertainties:
  - Uncertainties coming from the parameter choices of used MC sample e.g: renormalization and factorization scales, PDF …

Statistical interpretations

- With estimations of BKGs and data events in SRs, excess or agreement could be seen
- 95% CLs exclusion limits will be drawn for targeted models on phase space if there is no excess observed

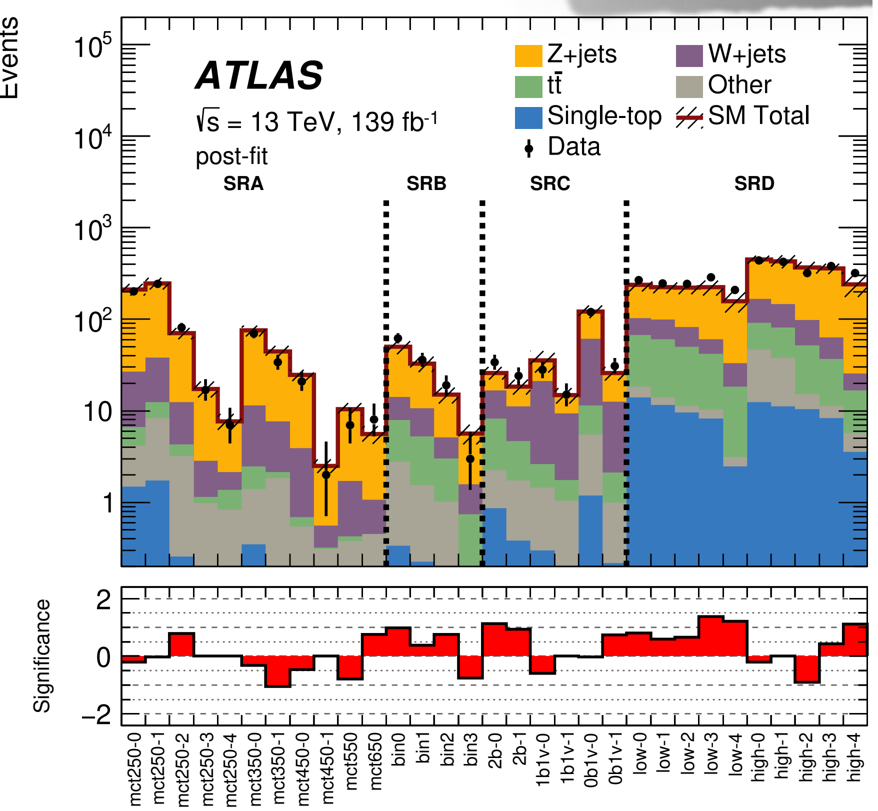
ATLAS EXPERIMENT

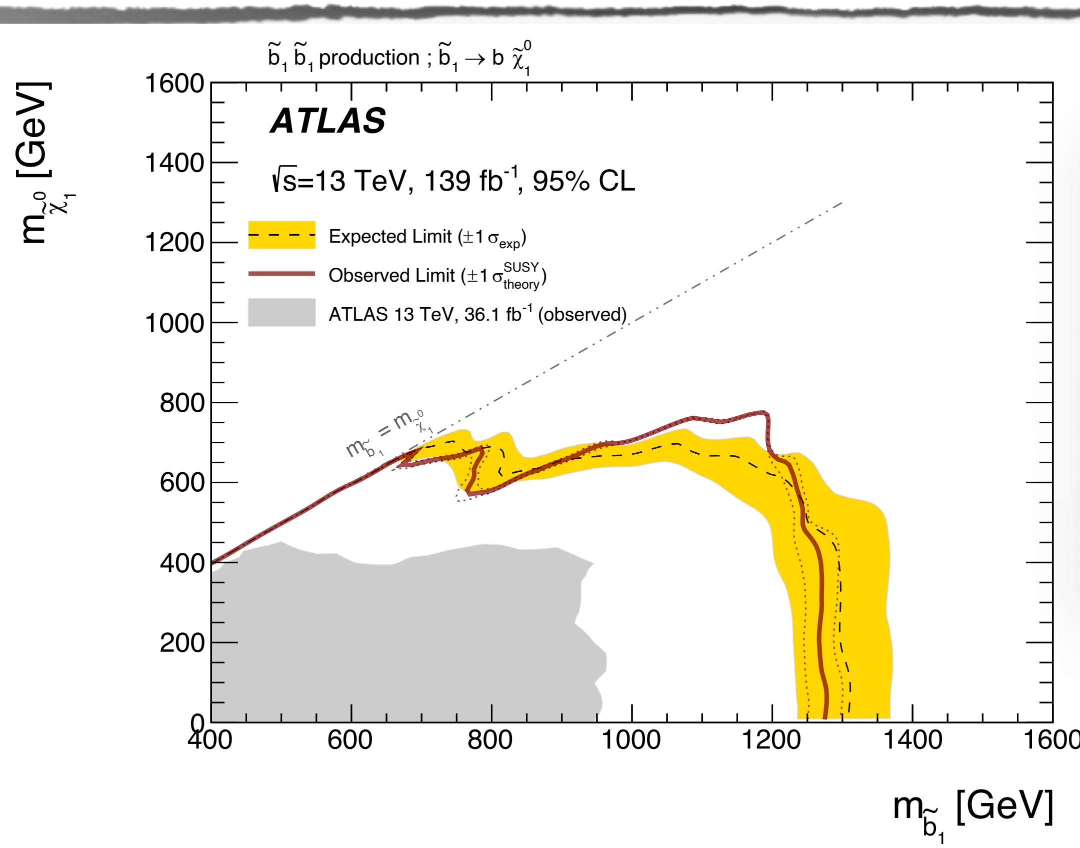
Search $\tilde{b}_1\tilde{b}_1$ with $\tilde{b}_1 \to b\tilde{\chi}_1^0$ in 2b+E_T^{miss} final state:



arXiv: 2101.12527 (sub to JHEP)

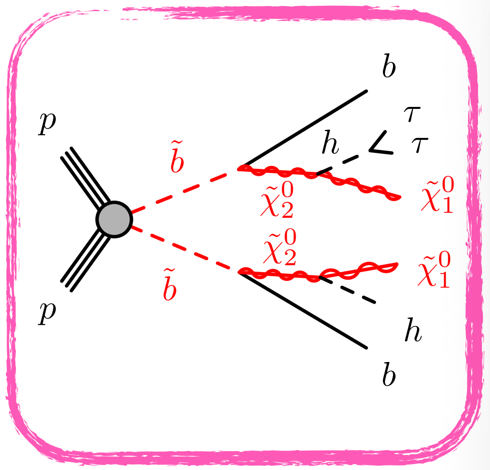
- Signal regions are designed for probing compressed & boosted regions separately:
  - SRA: Aiming @ boosted region, m_{CT} & m_{eff} is used for multi-bin strategy. Z+Jets dominant
  - SRB: Aiming @ $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) \leq 200\ GeV$, BDT technique is applied, w_{XGB} is used for multi-bin strategy. Z+Jets dominant
  - SRC: Aiming @ $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) \leq 50\ GeV$, boosted ISR Jet as signature, soft b-tagging is used to enhance the low-pt bJets sensitivity, E_T^{miss} is used for multi-bin. V+Jets & Top dominant
- Dominant bkg corrected by data in CRs





- No significant excess observed
- $m(\tilde{b}) \leq$ 1270 GeV are excluded for massless $\tilde{\chi}_1^0$
- ~ 700 GeV has been excluded for $\tilde{\chi}_1^0$

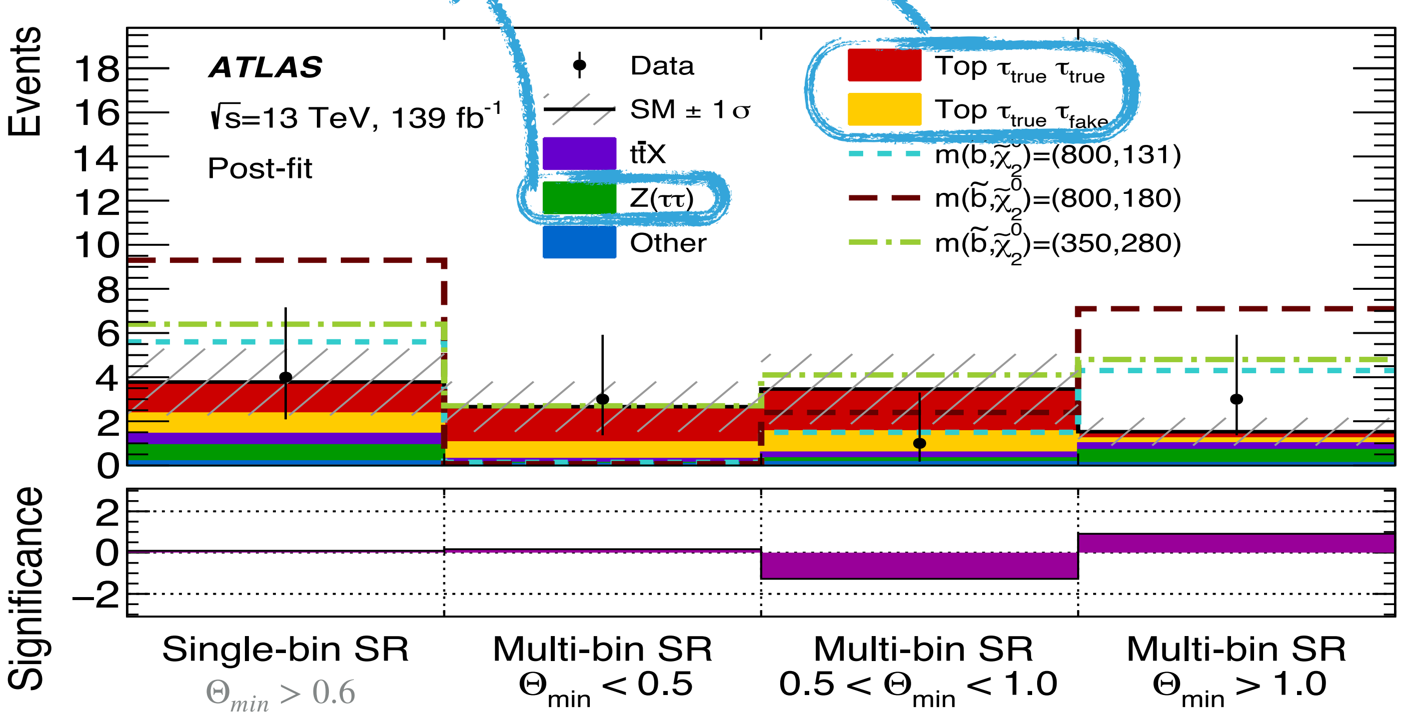
Search $\tilde{b}_1\tilde{b}_1$ with $\tilde{b}_1 \to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0$ in 2τ2b+E_T^{miss} final state:

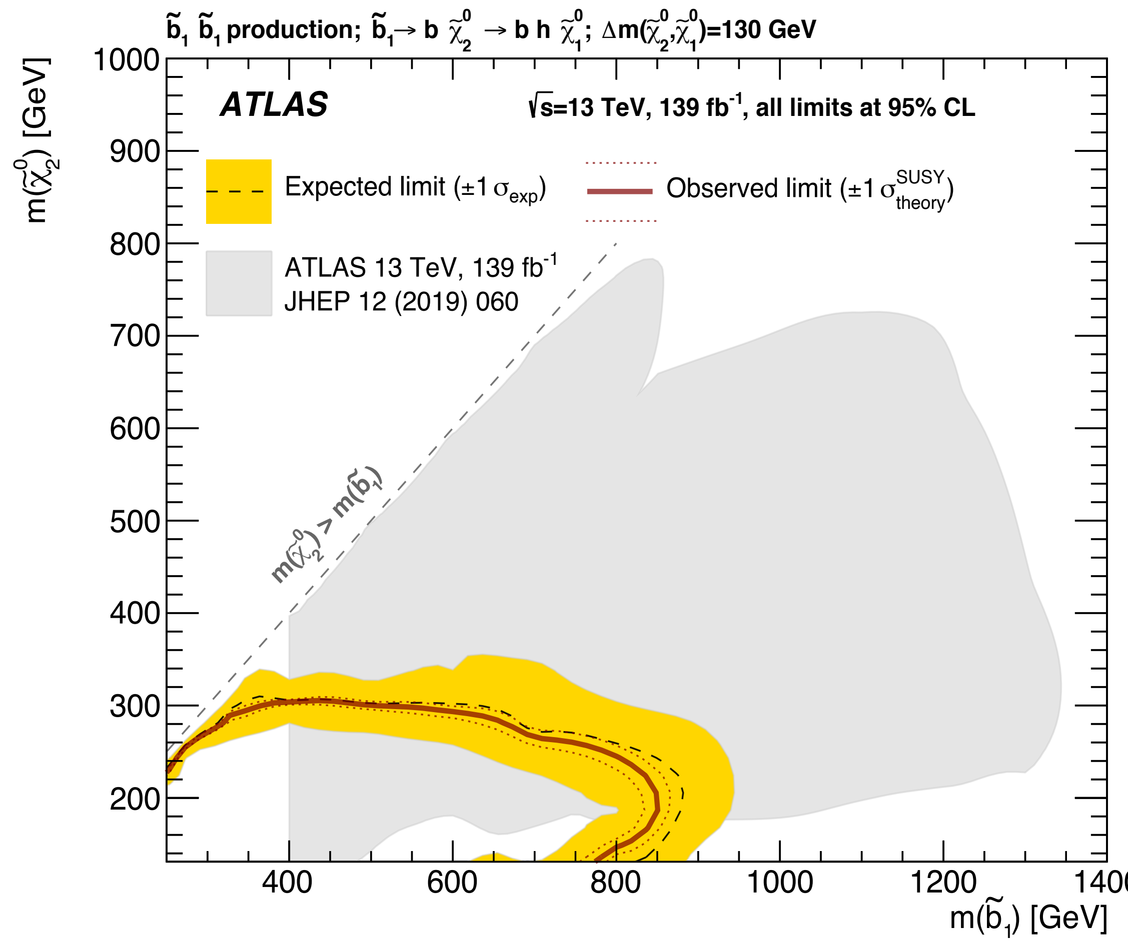


arXiv: 2103.08189 (sub to PRD)

- $B(\tilde{b} \to b\tilde{\chi}_2^0)$ is larger compared to $B(\tilde{b} \to b\tilde{\chi}_1^0)$ in "wino-bino" gaugino case
- $B(\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0)$ is enhanced when $\tilde{\chi}_2^0$ is wino-higgsino mixed and $\tilde{\chi}_1^0$ is bino case
- $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) = 130\ GeV$ to enhance the presence of on-shell Higgs
- At least one $h \to \tau\tau$ is required to be complementary to previous search:
  - Leaving 2τ2b+E_T^{miss} in the final states

ABCD method

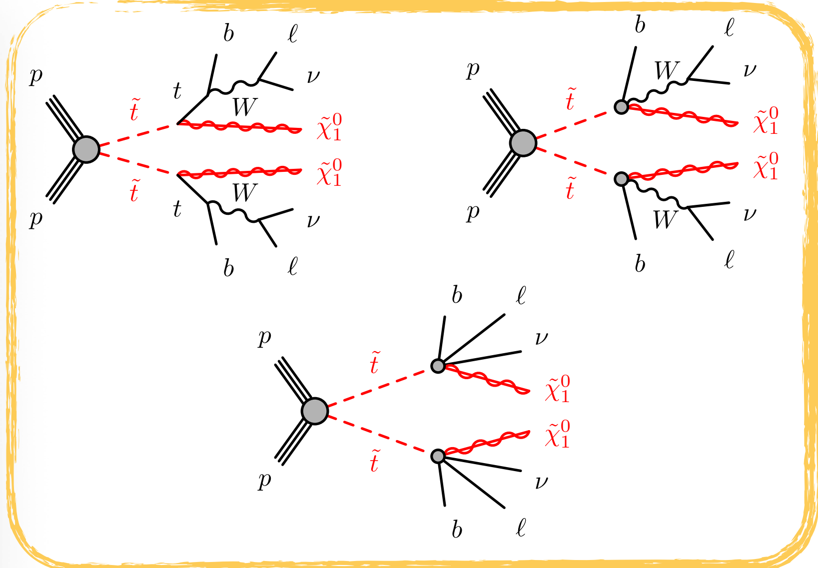




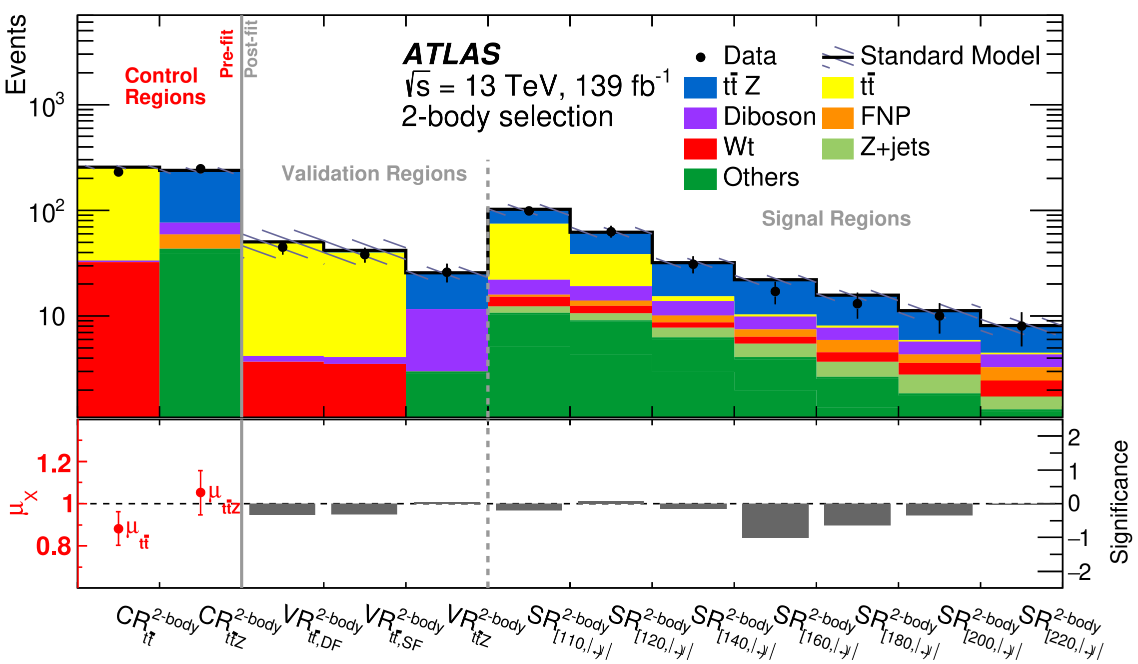
ATLAS EXPERIMENT

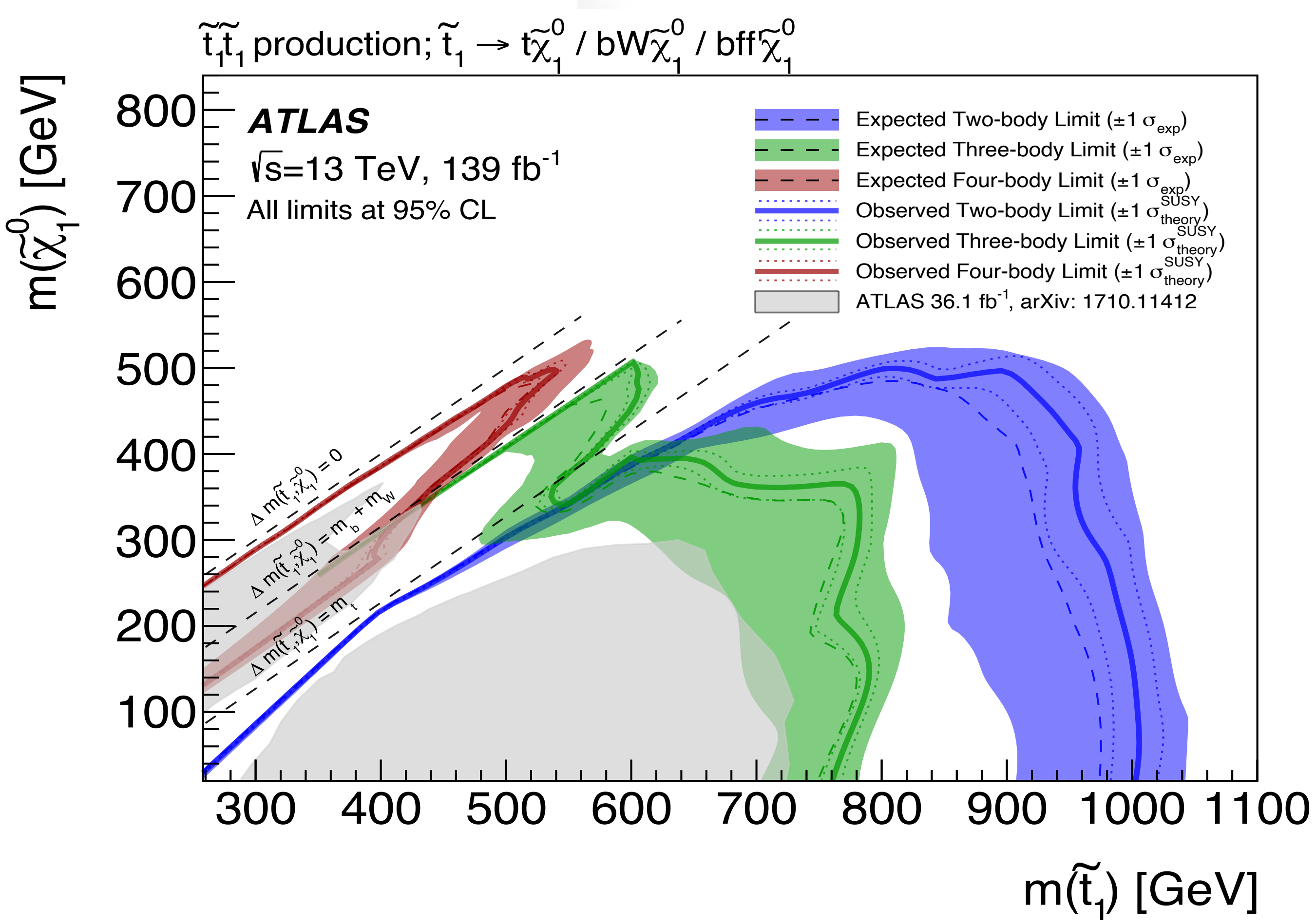
Search $\tilde{t}_1\tilde{t}_1$ with $\tilde{t}_1 \to t\tilde{\chi}_1^0$ in 2LOS + E_T^{miss} final state:

- Signal model:
  - 2-body (on-shell Top), 3-body (on-shell W) and 4-body (off-shell W) cases probed separately
- SR^{2-body}, SR_t^{3-body}, SR_W^{3-body}, $SR_{small\Delta m}^{4-body}$, $SR_{large\Delta m}^{4-body}$:
  - Binned with leptons flavor (and m_{T2}^{ll}) for 3-body (2-body) SRs to maximize the exclusion power
- $t\bar{t}$, $t\bar{t}Z$ dominant in 2 and 3-body case
- Extra large contributions from VV for 3 and 4-body case
- FNP estimated via FakeFactor method
- Dominant bkgs are corrected in CRs by data



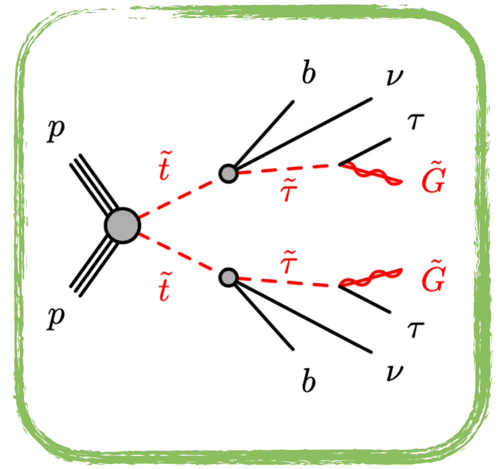
JHEP 04 (2021) 165





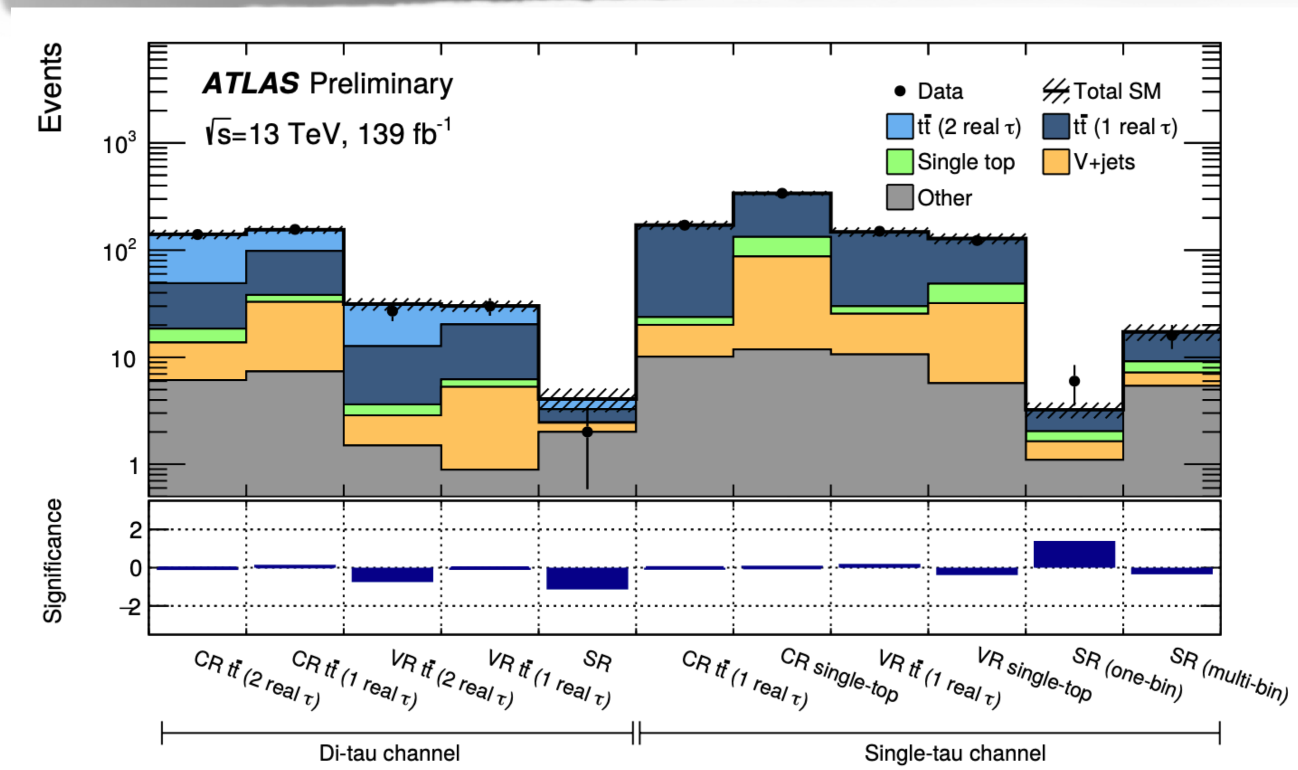
Search $\tilde{t}_1\tilde{t}_1$ with $\tilde{t}_1 \to \tilde{\tau} b\nu, \tilde{\tau} \to \tau\tilde{G}$ in 1-2τ+2Jets/1b+E_T^{miss} final state:

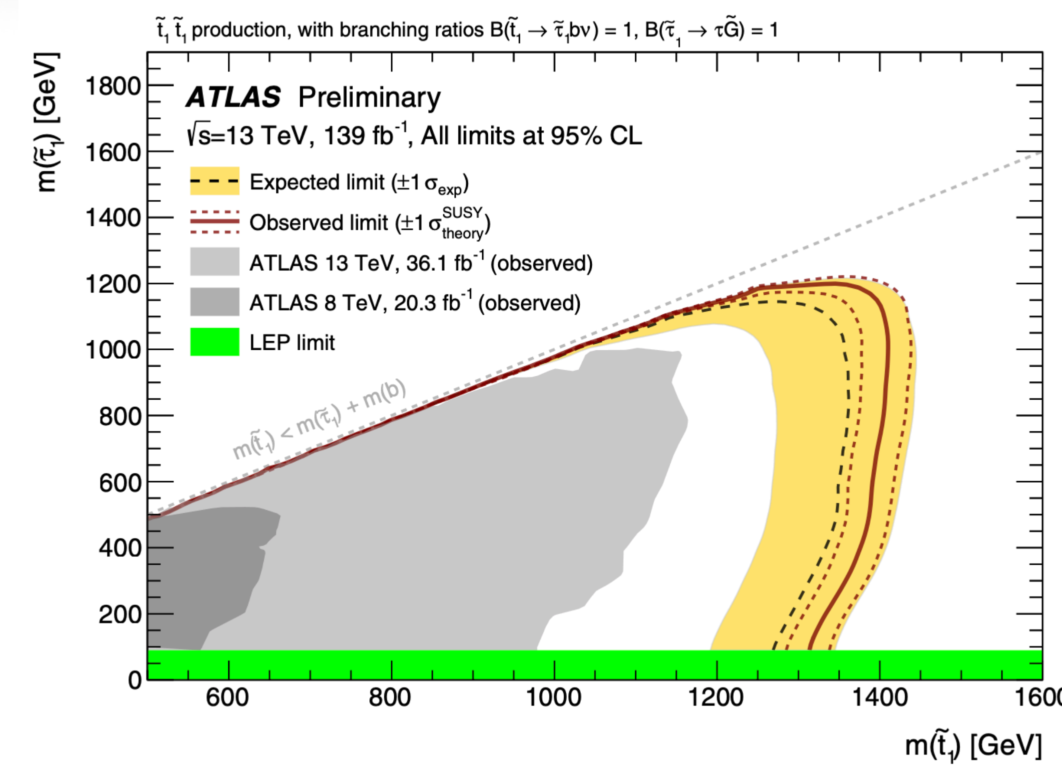
- Signal model:
  - $\tilde{t}_1\tilde{t}_1$ productions with cascade decay (off-shell $\tilde{\chi}^{\pm}$)
  - Massless $\tilde{G}$ as LSP motivated by GMSB and nGM
  - Complementary model comparing to $\tilde{t} \to t\tilde{\chi}_1^0$
- Signal regions:
  - Di-Tau SR: compressed region with soft b and boost τ
  - Single-Tau SR: boost region with boost b and soft τ, $P_T(\tau)$ bins used to maximum sensitivity
  - Statistically combined to maximize the exclusion power



ATLAS-CONF-2021-008

- Dominant by $t\bar{t}$ and single-Top process
- Corrected by data in CRs
- Results:
  - No significant excess observed
  - Extends previous exclusion limits
  - $m(\tilde{t}) \leq 1.3\ TeV$ has been excluded



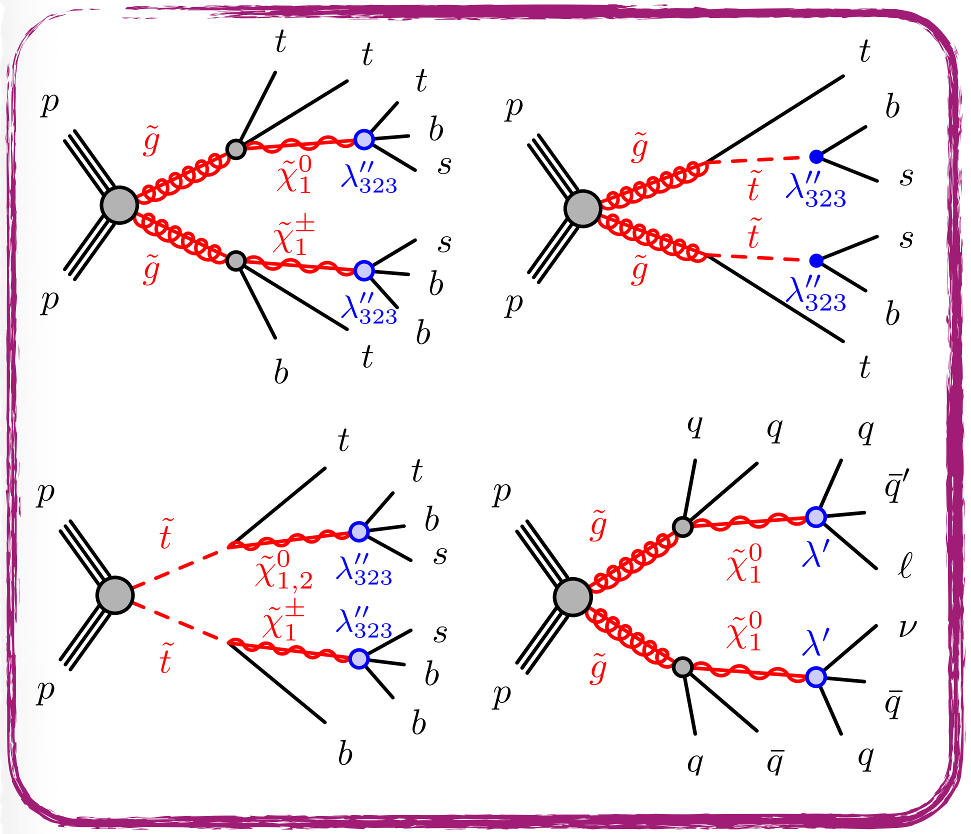


ATLAS EXPERIMENT

Search $\tilde{g}\tilde{g}$ and $\tilde{t}\tilde{t}$ in RPV with $\geq$1L+Jets final state:

- No fundamental theoretical reason for R-parity conservation
- Signal model:
  - $B(\tilde{t} \to t\tilde{\chi}^0_{1,2})$ and $B(\tilde{g} \to t\bar{t}\tilde{\chi}^0_1)$ are varied according to LSP's type (pure wino, bino or higgsino)
  - RPV couplings: Strong enough to decay promptly, weak enough to disentangled with RPC mixture
    - λ''_{323}: dominant under the minimal flavor violation hypothesis
    - λ': to be complementary for light-quark case

ATLAS-CONF-2021-007



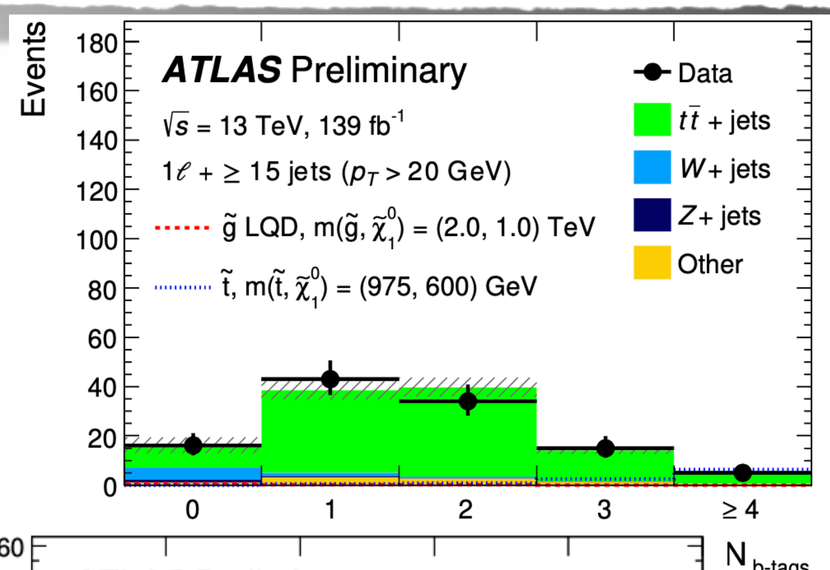
Jet counting analysis discovery SRs			
Jet p_{T} threshold	Number of jets 1ℓ category	Number of jets $2\ell^{\mathrm{sc}}$ category	Number of b-jets
20 GeV	≥ 15	≥ 10	$= 0, \geq 3$
40 GeV	≥ 12	≥ 8	$= 0, \geq 3$
60 GeV	≥ 11	≥ 7	$= 0, \geq 3$
80 GeV	≥ 10	≥ 7	$= 0, \geq 3$
100 GeV	≥ 8	≥ 6	$= 0, \geq 3$

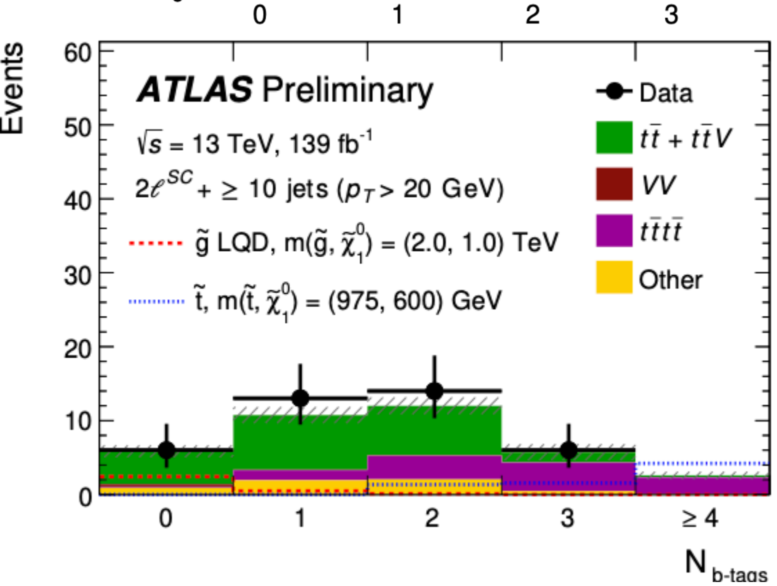
- Events are split into 2LSS case ($2l^{SC}$) and other case ($1l$ dominated)
- Statistical combined for two categories and number of b-jets bins
- Best CLs are chosen for inclusive SRs for each signal points to maximize the exclusion power

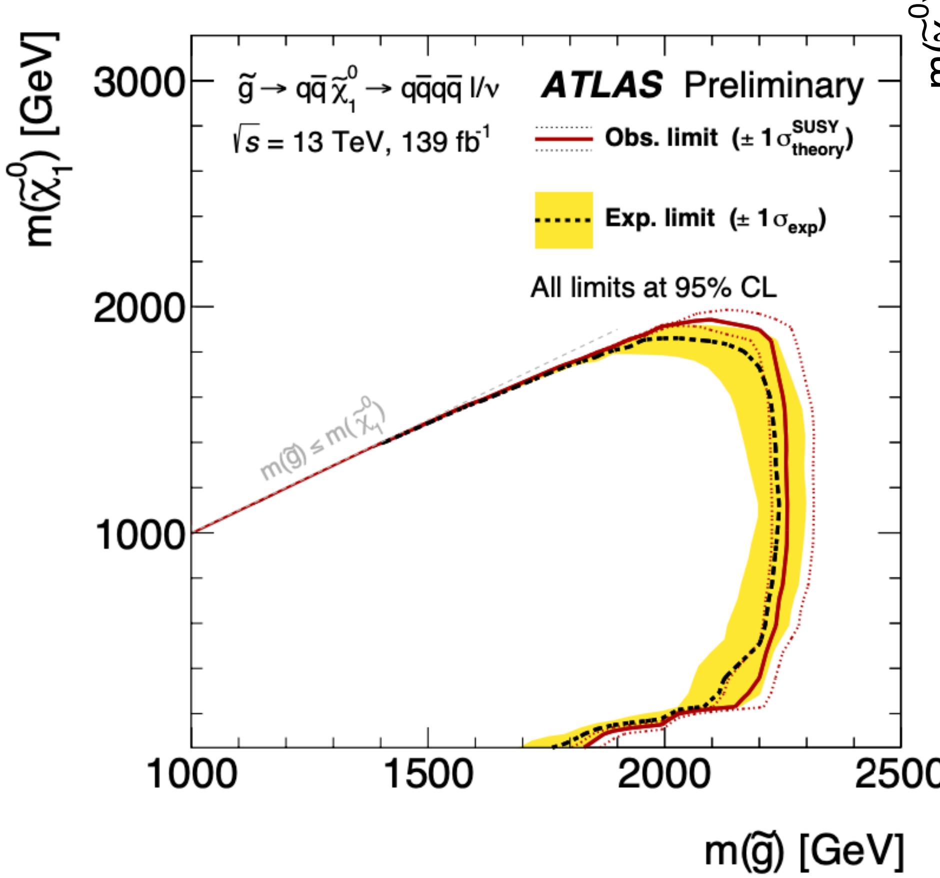
ATLAS EXPERIMENT

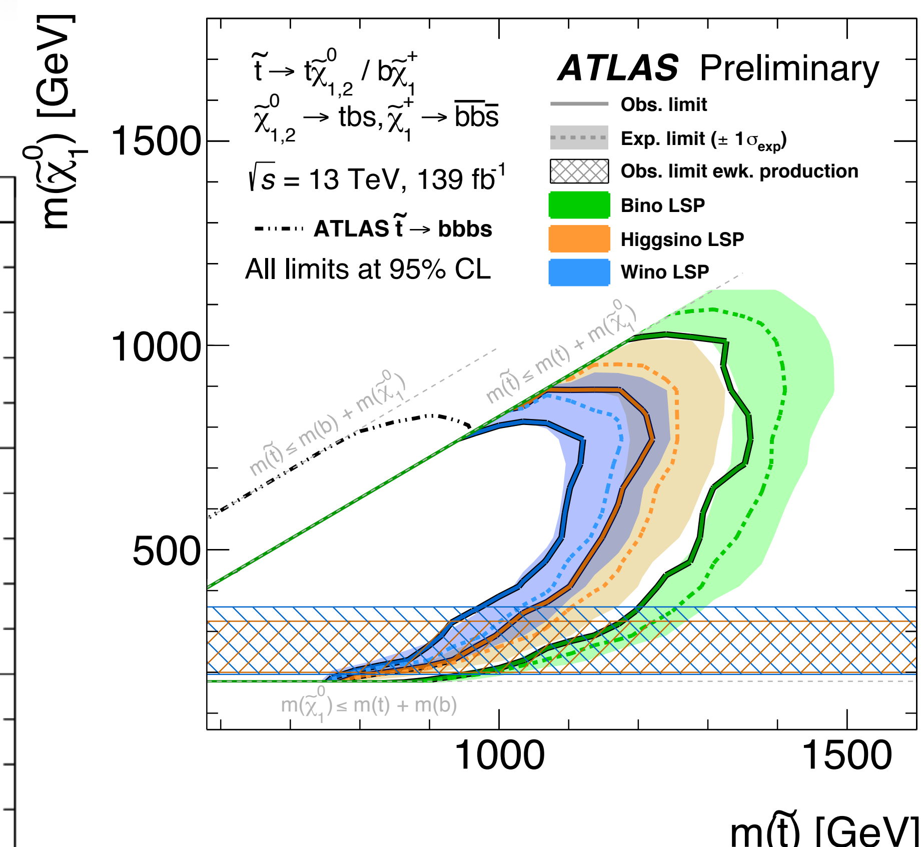
Search $\tilde{g}\tilde{g}$ and $\tilde{t}\tilde{t}$ in RPV with ≥1L+Jets final state:

- BKG estimation:
  - $W/Z + jets$ dominant for bVeto and $t\bar{t}$ for b-jet required regions for $1l$ category
  - VV dominant for bVeto and $t\bar{t}X^{SC}$ for b-jet required regions for $2l^{SC}$ category
  - Large uncertainties for high jet multiplicity, $N_{j,b}^{process}$ estimated from low-jet case which is corrected by data
  - FNP: MxM for $1l$ category, covered by $t\bar{t}X^{SC}$ in $2l^{SC}$ category
  - Other minor bkg estimated via MC simulation directly



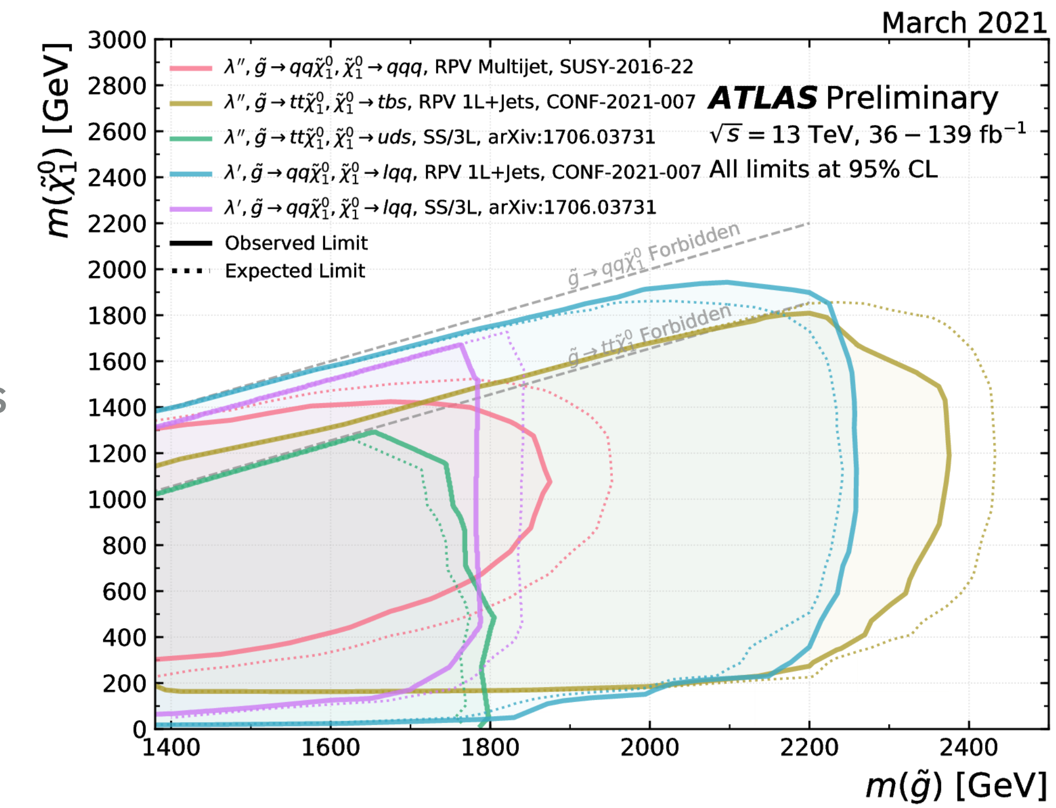


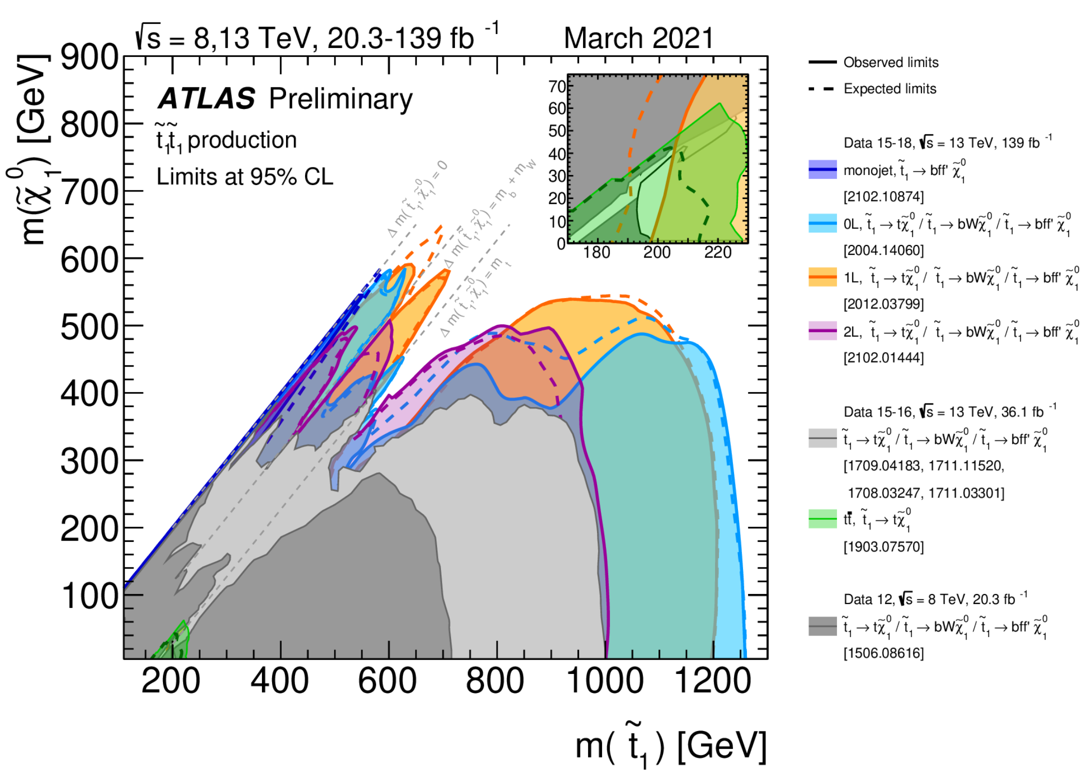


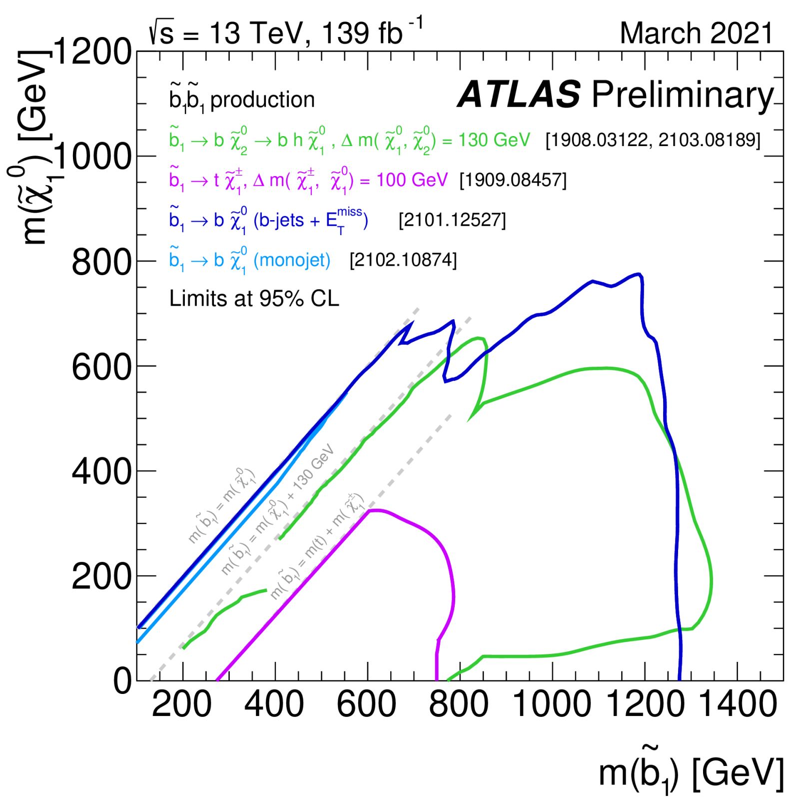


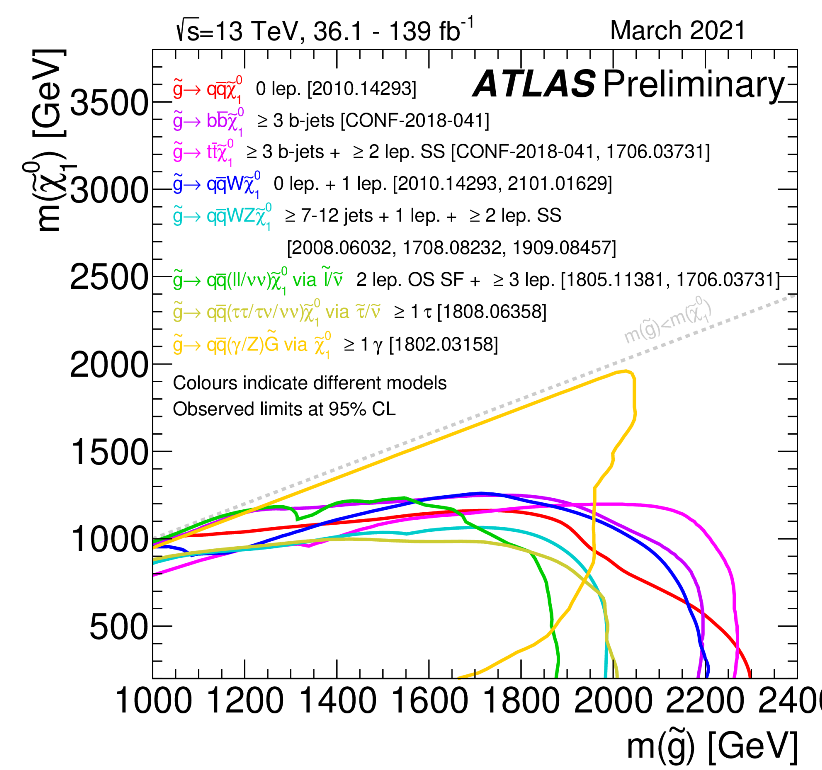
Conclusions:

- Strong SUSY searches in ATLAS have covered wide range of scenarios including both RPC and RPV and also long-lived gluino and squarks (will be covered by Jackson's talk)
- Lots of results coming out recently from searching for squark^{3rd} and gluino for direct decay or cascade decay in multiple channels
- Unfortunately, no significant excess observed yet
- Greatly extends the sensitivity to gluino and squarks under many different decay modes and assumptions



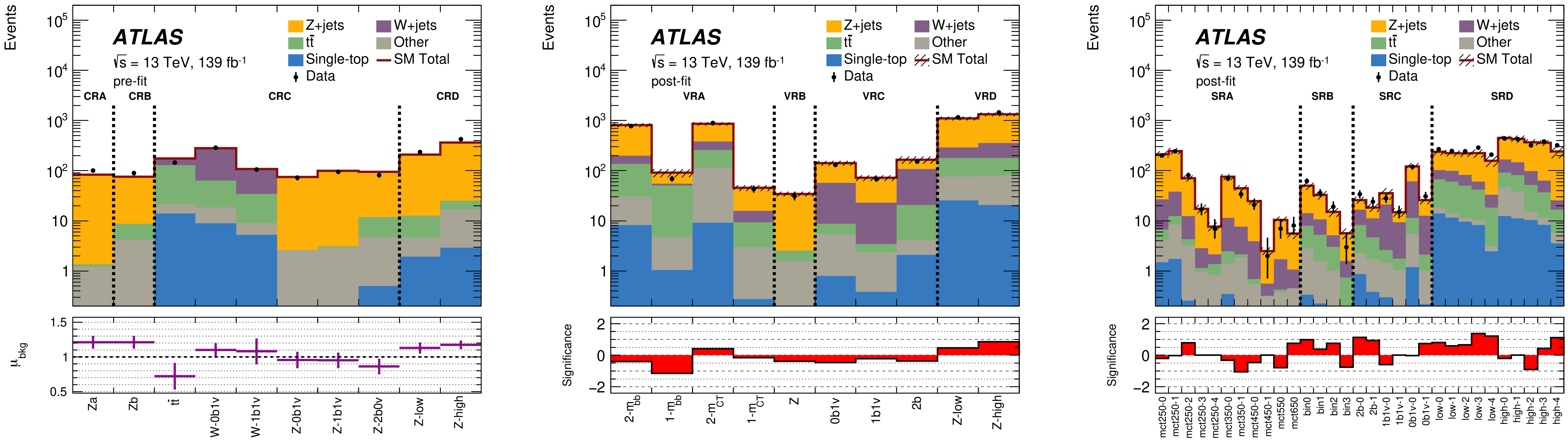


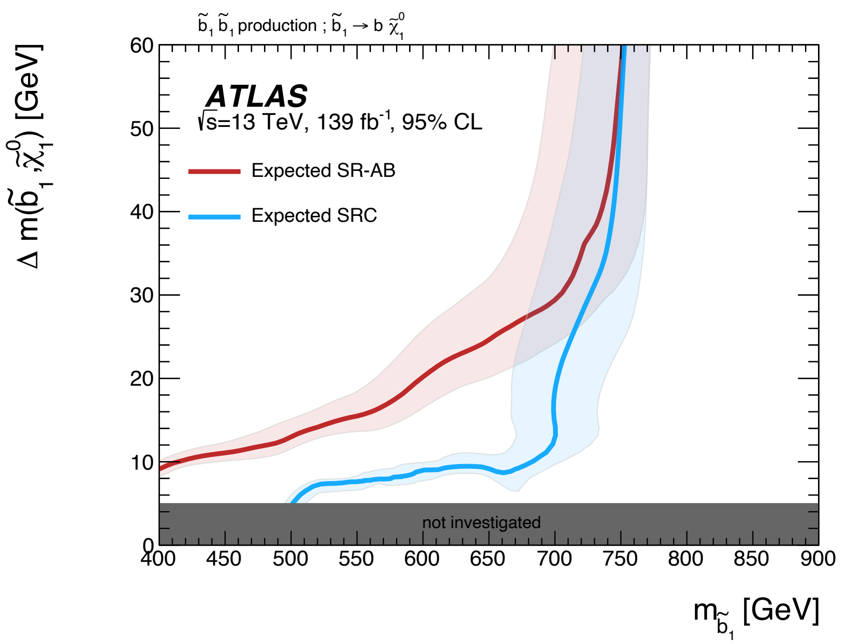




Back Ups

Search $\tilde{b}_1\tilde{b}_1$ with $\tilde{b}_1 \to b\tilde{\chi}_1^0$ in 2b+E_T^{miss} final state:

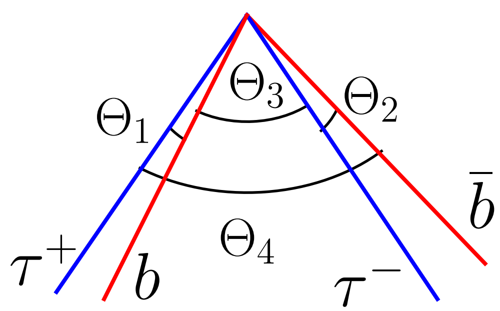


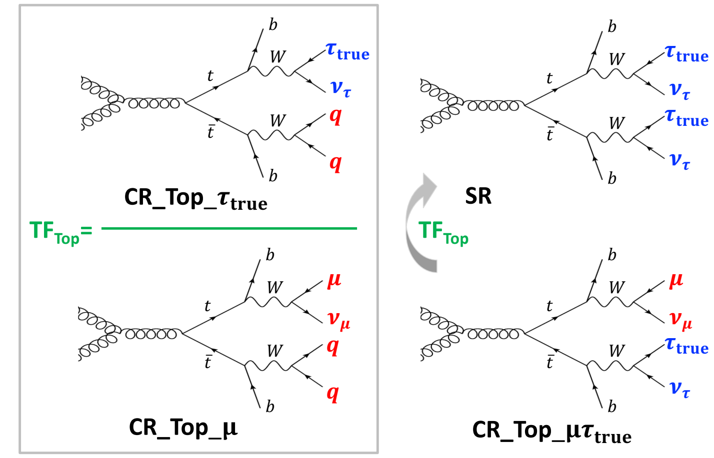


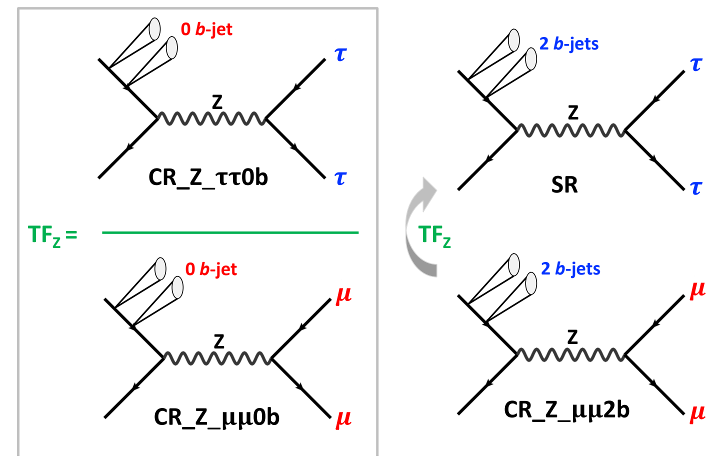
Search $\tilde{b}_1\tilde{b}_1$ with $\tilde{b}_1 \to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0$ in 2τ2b+E_T^{miss} final state:

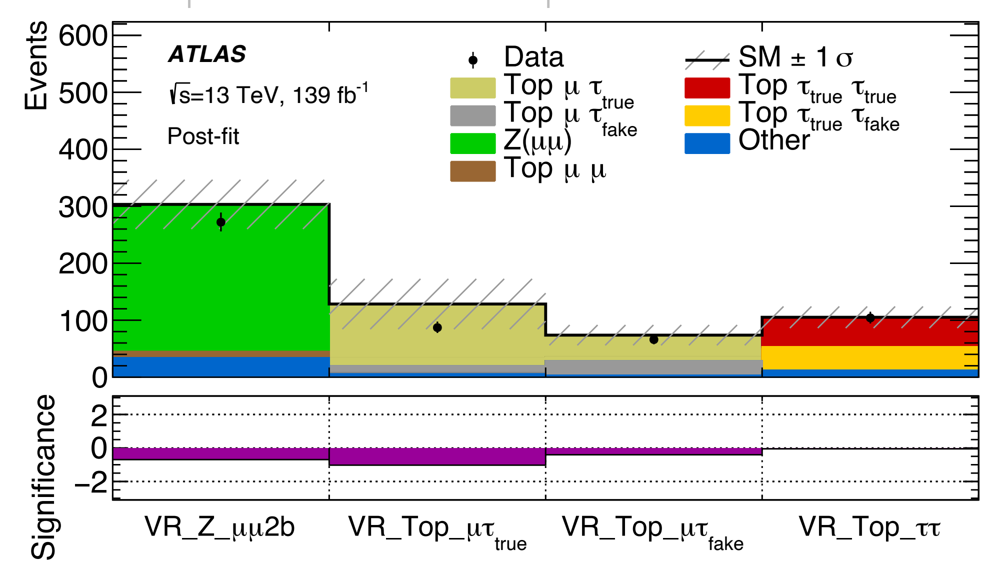
$N_\tau + N_\mu$	≥ 1		
N_{jets}	≥ 3		
$p_T(\text{jet}_1)$	> 140 GeV		
$p_T(\text{jet}_2)$	> 100 GeV		
$\Delta\phi(\text{jet}_{1,2}, \vec{p}_T^{\,\text{miss}})$	> 0.5	suppress MultiJets	
$N_{b\text{-jets}}$	≥ 2		
$p_T(b\text{-jet}_1)$	> 100 GeV		
Trigger / E_T^{miss}	E_T^{miss} + b-jet / > 160 GeV	OR	E_T^{miss} / > 200 GeV
Common SR requirements			
N_μ	0		
N_τ	≥ 2		
$\text{OS}(\tau_1, \tau_2)$	yes		
$m(\tau_1, \tau_2)$	[55, 120] GeV	reduce $z \to \tau\tau$ and "non-resonant", ensure $h \to \tau\tau$	
m_{T2}	> 140 GeV	$m_{inv} = 120\ GeV$	
H_T	> 1100 GeV		
	Single-bin SR	Multi-bin SR	
$\Theta_{\min}$	> 0.6	3 bins: < 0.5, [0.5, 1.0], > 1.0	increasing with $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

$$\Theta_{\min} = \min_{i=1,\ldots,4}(\Theta_i)$$

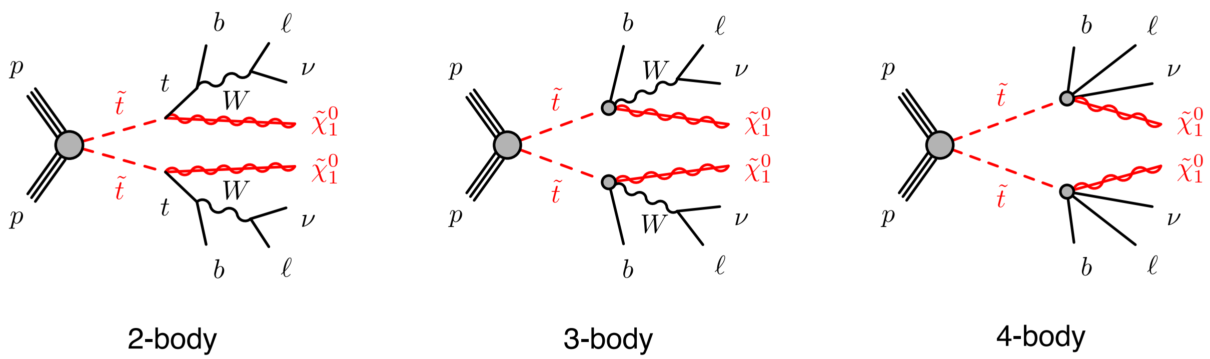








Search $\tilde{t}_1\tilde{t}_1$ with $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ in 2LOS + E_T^{miss} final state:



<table>
<tr><th></th><th colspan="2">$\mathrm{SR}^{2-\mathrm{body}}$</th></tr>
<tr><td>Leptons flavour</td><td>DF</td><td>SF</td></tr>
<tr><td>$p_\mathrm{T}(\ell_1)$ [GeV]</td><td colspan="2">> 25</td></tr>
<tr><td>$p_\mathrm{T}(\ell_2)$ [GeV]</td><td colspan="2">> 20</td></tr>
<tr><td>$m_{\ell\ell}$ [GeV]</td><td colspan="2">> 20</td></tr>
<tr><td>$|m_{\ell\ell} - m_Z|$ [GeV]</td><td>–</td><td>> 20</td></tr>
<tr><td>$n_{b-\mathrm{jets}}$</td><td colspan="2">≥ 1</td></tr>
<tr><td>$\Delta\phi_\mathrm{boost}$ [rad]</td><td colspan="2">< 1.5</td></tr>
<tr><td>$E_\mathrm{T}^\mathrm{miss}$ significance</td><td colspan="2">> 12</td></tr>
<tr><td>$m_\mathrm{T2}^{\ell\ell}$ [GeV]</td><td colspan="2">> 110</td></tr>
</table>

- Multi-bin strategy is applied to maximum the exclusion power:
  - Binned with lepton flavors & m_{T2}^{ll}

<table>
<tr><th></th><th colspan="2">$\mathrm{SR}_W^{3-\mathrm{body}}$</th><th colspan="2">$\mathrm{SR}_t^{3-\mathrm{body}}$</th></tr>
<tr><td>Leptons flavour</td><td>DF</td><td>SF</td><td>DF</td><td>SF</td></tr>
<tr><td>$p_\mathrm{T}(\ell_1)$ [GeV]</td><td colspan="2">> 25</td><td colspan="2">> 25</td></tr>
<tr><td>$p_\mathrm{T}(\ell_2)$ [GeV]</td><td colspan="2">> 20</td><td colspan="2">> 20</td></tr>
<tr><td>$m_{\ell\ell}$ [GeV]</td><td colspan="2">> 20</td><td colspan="2">> 20</td></tr>
<tr><td>$|m_{\ell\ell} - m_Z|$ [GeV]</td><td>–</td><td>> 20</td><td>–</td><td>> 20</td></tr>
<tr><td>$n_{b-\mathrm{jets}}$</td><td colspan="2">$= 0$</td><td colspan="2">≥ 1</td></tr>
<tr><td>$\Delta\phi_\beta^\mathrm{R}$ [rad]</td><td colspan="2">> 2.3</td><td colspan="2">> 2.3</td></tr>
<tr><td>$E_\mathrm{T}^\mathrm{miss}$ significance</td><td colspan="2">> 12</td><td colspan="2">> 12</td></tr>
<tr><td>$1/\gamma_{\mathrm{R}+1}$</td><td colspan="2">> 0.7</td><td colspan="2">> 0.7</td></tr>
<tr><td>R_{p_T}</td><td colspan="2">> 0.78</td><td colspan="2">> 0.70</td></tr>
<tr><td>M_Δ^R [GeV]</td><td colspan="2">> 105</td><td colspan="2">> 120</td></tr>
</table>

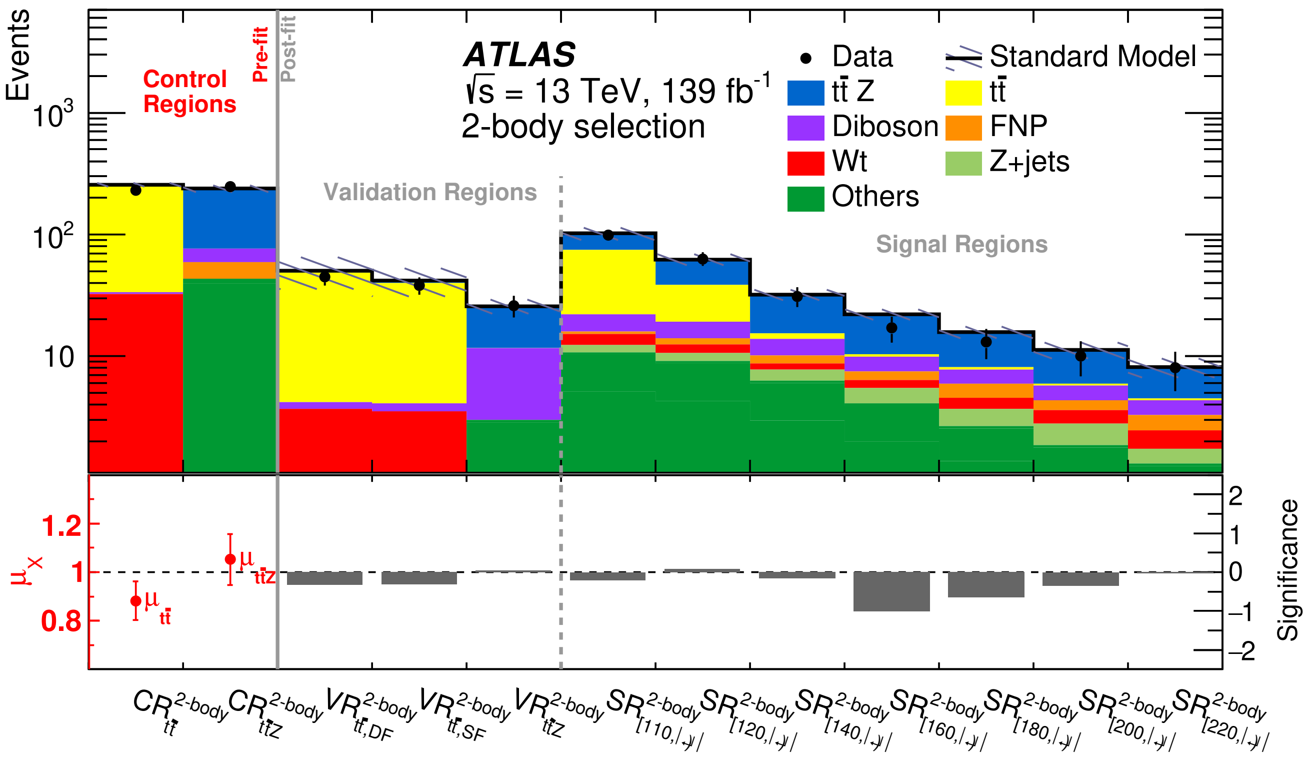
- SR_W^{3-body}: for $\Delta m(\tilde{t}, \tilde{\chi}_1^0) \sim m(W)$ (SR_W^{3-body})
- SR_t^{3-body}: for $\Delta m(\tilde{t}, \tilde{\chi}_1^0) \sim m(t)$ (SR_t^{3-body})
- "super-razor" vars and separated via lepton flavor to maximize sensitivity

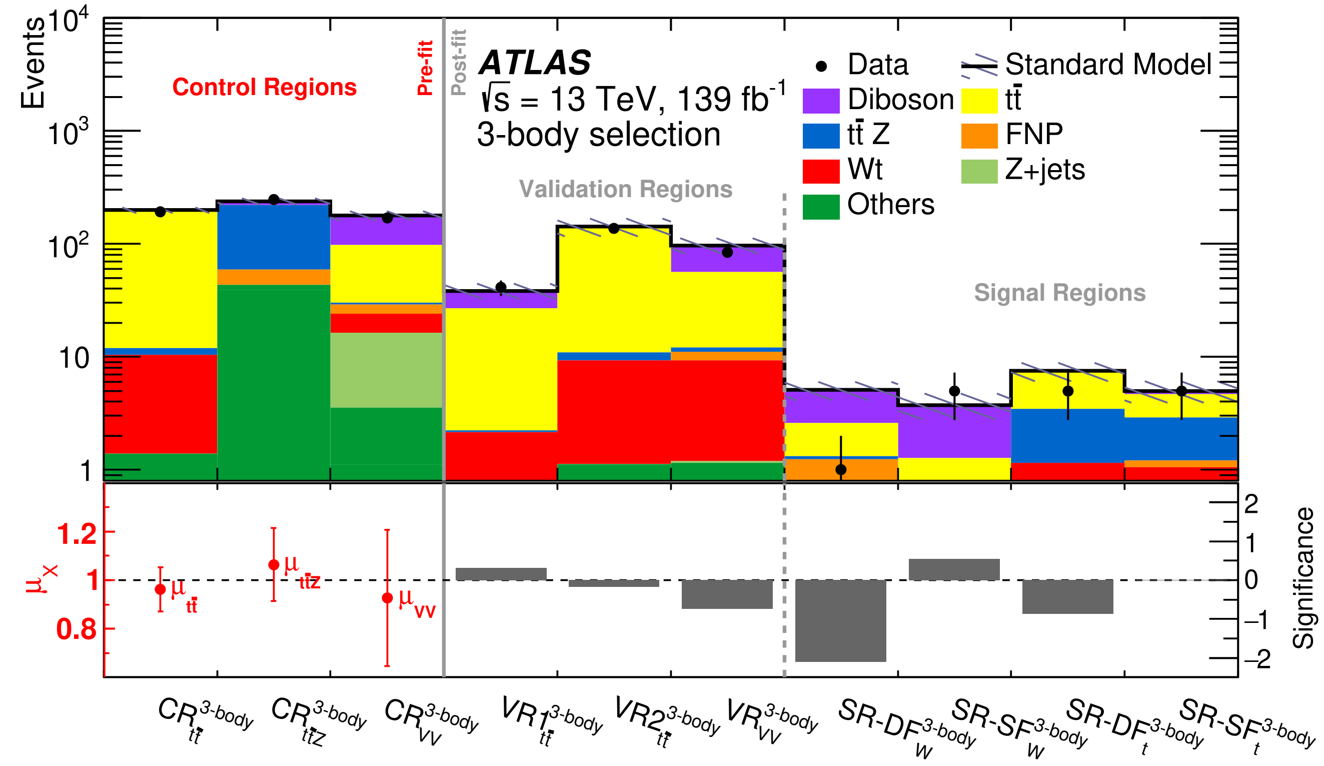
<table>
<tr><th></th><th>$\mathrm{SR}_{\mathrm{Small}\,\Delta m}^{4-\mathrm{body}}$</th><th>$\mathrm{SR}_{\mathrm{Large}\,\Delta m}^{4-\mathrm{body}}$</th></tr>
<tr><td>$p_\mathrm{T}(\ell_1)$ [GeV]</td><td>< 25</td><td>< 100</td></tr>
<tr><td>$p_\mathrm{T}(\ell_2)$ [GeV]</td><td>< 10</td><td>$[10,\ 50]$</td></tr>
<tr><td>$m_{\ell\ell}$ [GeV]</td><td colspan="2">> 10</td></tr>
<tr><td>$p_\mathrm{T}(j_1)$ [GeV]</td><td colspan="2">> 150</td></tr>
<tr><td>$\min \Delta R_{\ell_2, j_i}$</td><td colspan="2">$> 1$</td></tr>
<tr><td>$E_\mathrm{T}^\mathrm{miss}$ significance</td><td colspan="2">> 10</td></tr>
<tr><td>$p_{\mathrm{T,boost}}^{\ell\ell}$ [GeV]</td><td colspan="2">> 280</td></tr>
<tr><td>$E_\mathrm{T}^\mathrm{miss}$ [GeV]</td><td colspan="2">> 400</td></tr>
<tr><td>$R_{2\ell}$</td><td>> 25</td><td>> 13</td></tr>
<tr><td>$R_{2\ell 4j}$</td><td>> 0.44</td><td>> 0.38</td></tr>
</table>

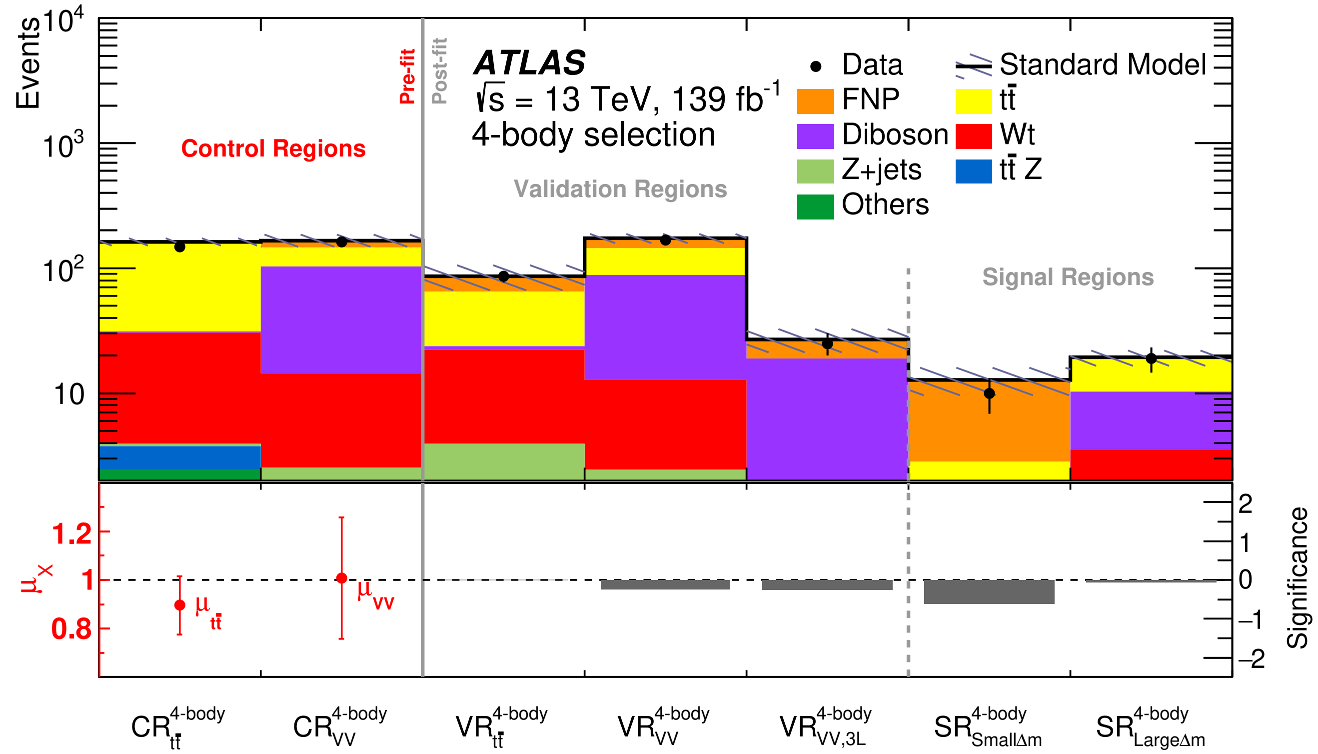
- Boosted ISR Jet signature is used
- Compatible low-pT considered
- Orthogonal SRs for different Δm regions

ATLAS EXPERIMENT

Search $\tilde{t}_1\tilde{t}_1$ with $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ in 2LOS + E_T^{miss} final state:



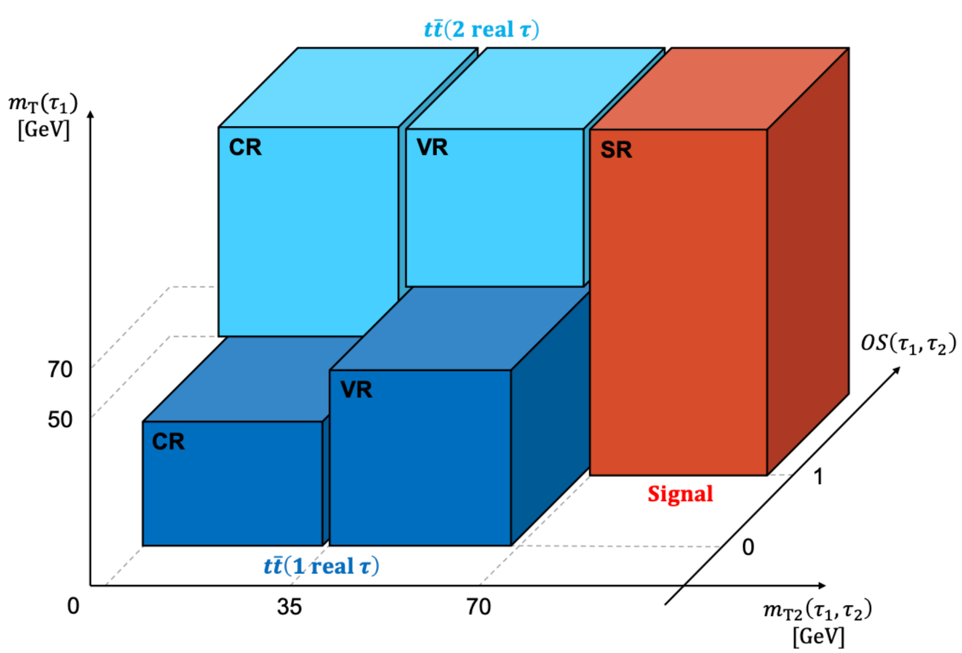


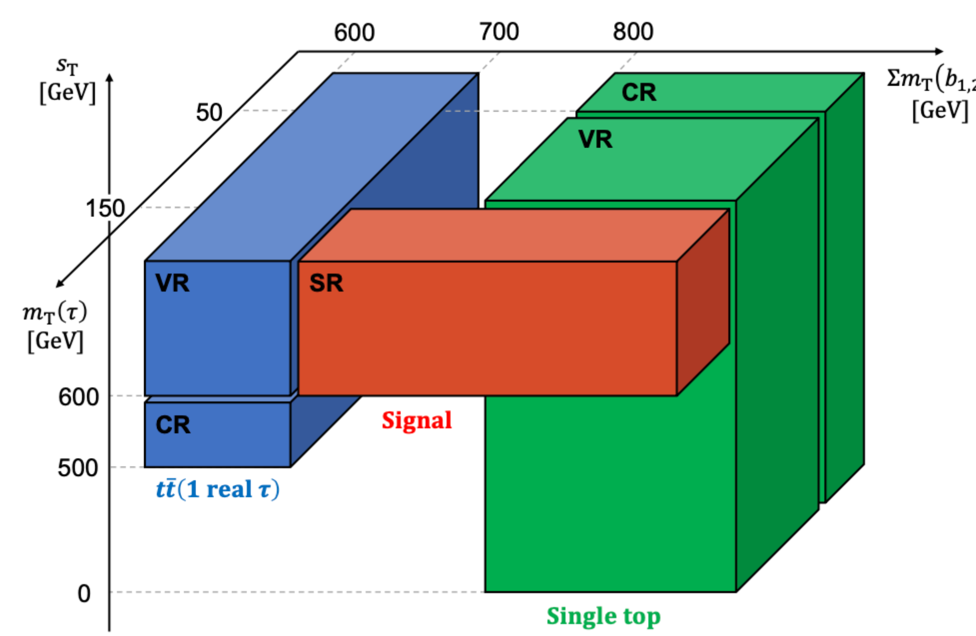


Search $\tilde{t}_1\tilde{t}_1$ with $\tilde{t}_1 \to \tilde{\tau} b \nu, \tilde{\tau} \to \tau \tilde{G}$ in 1-2τ+2Jets/1b+E_T^{miss} final state:

LSP type	Branching ratios for sparticle: stop $t\tilde{\chi}^0_{1,2}$	stop $b\tilde{\chi}^\pm_1$	gluino $tt\tilde{\chi}^0_{1,2}$	gluino $bb\tilde{\chi}^0_{1,2}$	gluino $tb\tilde{\chi}^\mp_1$	Cross-section [fb] for direct production $\tilde{\chi}^\pm_1\tilde{\chi}^0_1$	$\tilde{\chi}^\mp_1\tilde{\chi}^0_2$	$\tilde{\chi}^0_2\tilde{\chi}^0_1$
Bino	100%	0%	100%	0%	0%	0	0	0
Wino	33%	66%	16%	16%	66%	387	0	0
Higgsino	50%	50%	50%	0%	50%	91	91	52

- BKG estimation:
  - Dominant by $t\bar{t}$ and single-Top process:
    - True contributions: 2 real τ and 1 real τ for Di-Tau and Single-Tau channel
    - Fake contributions: 1 real τ and no real τ from single-Top for Di-Tau and Single-Tau channel
    - CRs and VRs for each source separately to correct and validate the estimations
  - Others estimated via MC samples





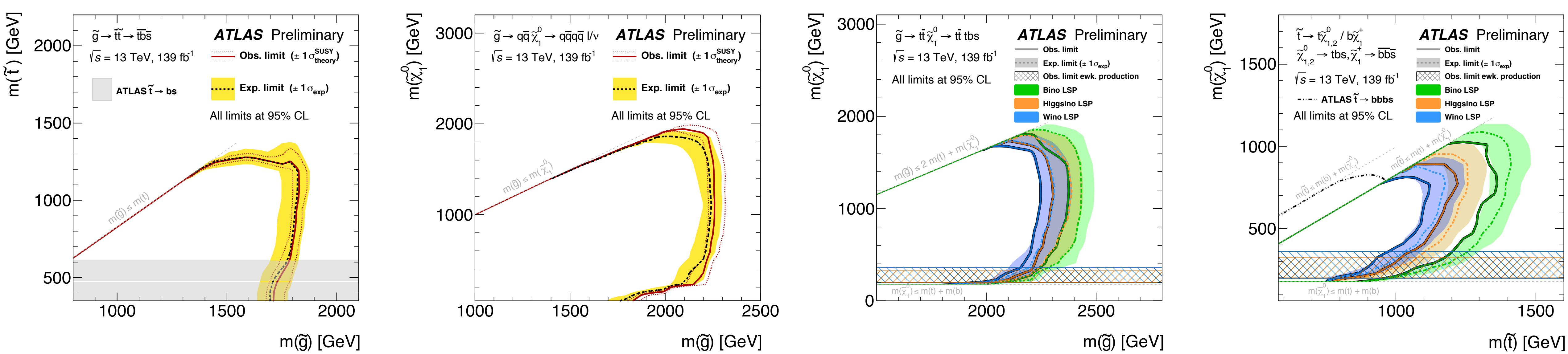
Search $\tilde{g}\tilde{g}$ and $\tilde{t}\tilde{t}$ in RPV with ≥1L+Jets final state:

- Jet multiplicity prediction:

$$r^X(j) \equiv N^X_{j+1}/N^X_j, \text{ with } r^X(j) = c^X_0 + c^X_1/(j + c^X_2) \Rightarrow N^X_j = N^X_4 \cdot \prod_{j'=4}^{j'=j-1} r^X(j')$$

- B-jet multiplicity prediction: $N^X_{j,b} = f^X_{j,b} \cdot N^X_j$ with $\sum_b f^X_{j,b} = 1$ and known N^X_j

$$f_{(j+1),b} = f_{j,b} \cdot x_0 + f_{j,(b-1)} \cdot x_1 + f_{j,(b-2)} \cdot x_2, \text{ with } f_{4,b} \text{ as initial template}$$



ATLAS EXPERIMENT

THE END