Search for new physics in events with large b-jet multiplicity using the ATLAS detector at the LHC

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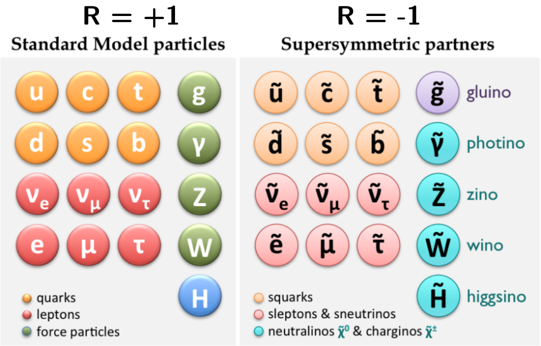
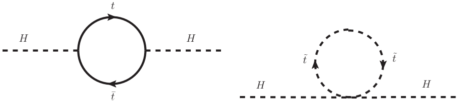
Supersymmetry (SUSY) Model

- SUSY relates space-time and internal symmetries
  - Unifies the elementary constituents (fermions) with the interactions they undergo (bosons)
  - Solves conceptual problems of the Standard Model (SM)



- *Light* top squark → solution to hierarchy problem



$$\Delta m_H^2 = -\frac{6y_t^2}{16\pi^2}\Lambda^2 + \frac{6y_t^2}{16\pi^2}\Lambda^2 - \frac{3y_t^2}{4\pi^2}m_{\tilde{t}}^2 \ln(\Lambda/m_{\tilde{t}}) + \dots$$

Superpotential of MSSM

- The superpotential of MSSM can be separated into two parts:

$$W_{MSSM} = \bar{\tilde{u}}\mathbf{y}_u\tilde{Q}H_u - \bar{\tilde{d}}\mathbf{y}_d\tilde{Q}H_d - \bar{\tilde{e}}\mathbf{y}_e\tilde{L}H_d + \mu H_u H_d,$$
$$W_{\not{R}_p} = \frac{1}{2}\lambda^{ijk}L_iL_j\bar{e}_k + \lambda^{'ijk}L_iQ_j\bar{d}_k + \mu^{'i}L_iH_u + \frac{1}{2}\lambda^{''ijk}\bar{u}_i\bar{d}_j\bar{d}_k$$

- New symmetry R-parity: $\boxed{\mathsf{R} = (-1)^{3(\mathsf{B}-\mathsf{L})+2\mathsf{S}}}$

B: Baryonic number
L: Leptonic number
S: Spin number

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$$\cancel{W_{\not{R}_p} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^{i} L_i H_u + \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k}$$

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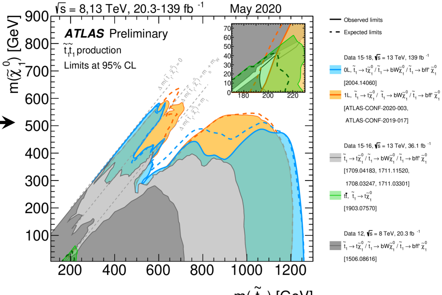
R-parity conserving (RPC) model

- Conserve B and L
- Sparticles produced in pairs
- Stable LSP behaves like a neutrino → escape detection
- Large missing transverse energy (MET)

Top squark heavily constrained up to 1.2 TeV



[ATL-PHYS-PUB-2020-013]

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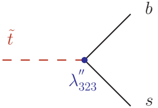
R-parity violating (RPV) model

- Violate B or L
- Single sparticle production is possible
- LSP not necessary stable $\rightarrow$ possibility for new signals
- MET not necessarily large

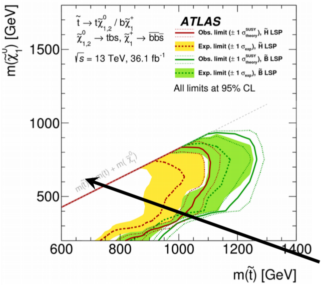
- Many constraints on SUSY searches disappear
- Top squark decays via $\boldsymbol{\lambda''_{332}}$ favored by MFV



Search for RPV decay of top squarks pair in events with multi-b-jets

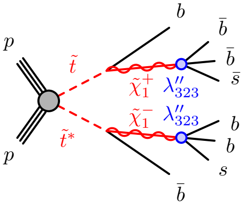
For natural SUSY, a triplet of higgsino-like states are LSP $(\tilde{\chi}_2^0, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$

Higgsino LSP



[arxiv:1704.08493]

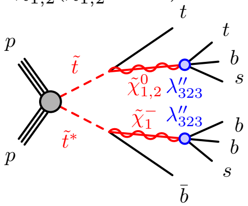
$\tilde{t} \to b\chi_1^+ (\chi_1^+ \to \bar{b}\bar{b}\bar{s})$



Saturate BR in $m_{\tilde{t}} - m_{\tilde{\chi}^+} < m_t$

$\tilde{t} \to b\chi_1^+ (\chi_1^+ \to \bar{b}\bar{b}\bar{s})$ BR = 0.5

$\tilde{t} \to t\chi_{1,2}^0 (\chi_{1,2}^0 \to tbs)$ BR = 0.5



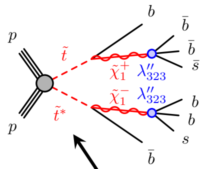
Dominant in $m_{\tilde{t}} - m_{\tilde{\chi}^+} > m_t$

No leptonic final states can be used for this scenario

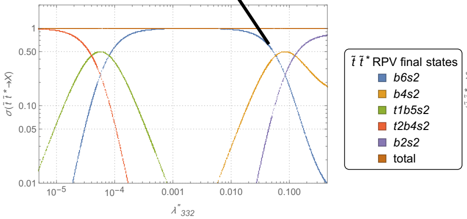
Search for signal in events with high b-tagged jet multiplicity

Top-squark pair production in natural RPV SUSY

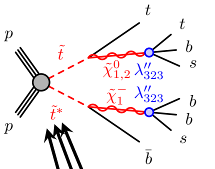
$$m_{\tilde{t}} - m_{\tilde{\chi}^0_{1,2},\tilde{\chi}^\pm_1} < m_\mathrm{t}$$



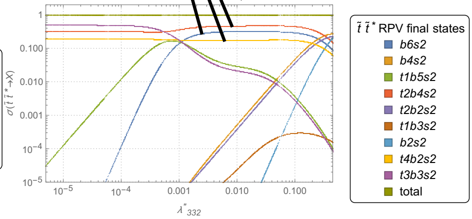
$m_{\tilde{t}} = 600$ GeV, $m_{\tilde{\chi}^0_{1,2},\tilde{\chi}^\pm_1} = 550$ GeV



$$m_{\tilde{t}} - m_{\tilde{\chi}^0_{1,2},\tilde{\chi}^\pm_1} > m_\mathrm{t}$$



$m_{\tilde{t}} = 600$ GeV, $m_{\tilde{\chi}^0_{1,2},\tilde{\chi}^\pm_1} = 250$ GeV



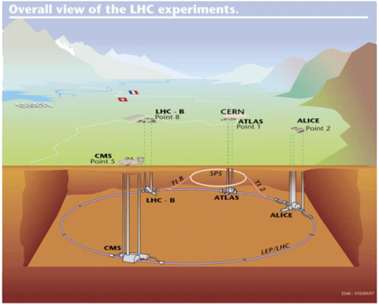
- Analysis can be sensitive to values of $\boldsymbol{\lambda''_{332}}$

  Sara Diglio, Lorenzo Feligioni, Gilbert Moultaka. *Stashing the stops in multijet events at the LHC*. Phys. Rev., D 96(5)

- For $\boldsymbol{\lambda''_{332}} \to 0$ the produced top squark tends to be long-lived

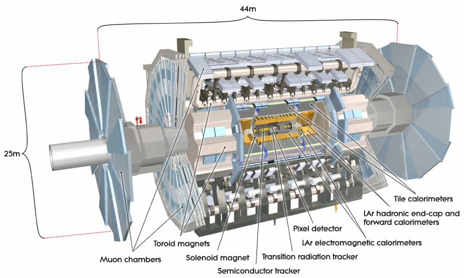
The LHC and ATLAS detector

Large Hadron collider (LHC)



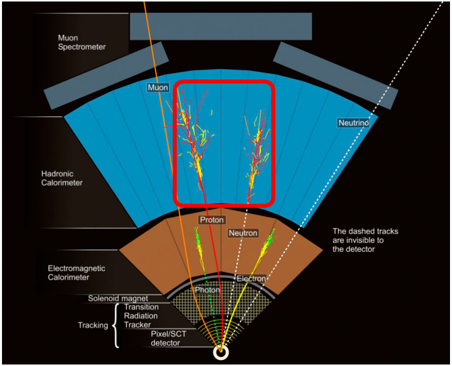
- Proton-proton (pp) collisions at four interaction points
  - 2010-2012: $\sqrt{s} = 7, 8$ TeV
  - 2015-2018: $\sqrt{s} = 13$ TeV (Run 2)
- Very high instantaneous luminosity
  - 70 pp interactions per bunch-crossing

A Toroidal LHC ApparatuS (ATLAS)



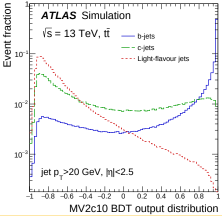
- Multi-purpose detector:
  - Higgs boson physics
  - SM precision measurements
  - New physics searches
- Large pp collisions dataset in Run 2 ~ 140 fb^{-1}

Overview of particles passage through ATLAS detector

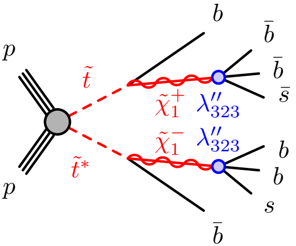


- **Electrons**: Energy deposition in calorimeter and charged track in ID
- **Photons**: Energy deposition in calorimeter, no track in ID
- **Muons**: Combined track in ID and MS
- **MET**: negative vectorial sum of selected physics objects and the soft term
- **Jets**: Energy deposition in calorimeters and charged tracks in ID
- **b-jets**: jets containing ≥ 1 b-hadrons

$\rightarrow$ ATLAS uses a Multivariate b-tagging algorithm to separate b-jet from light and c-jet

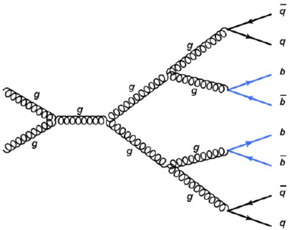


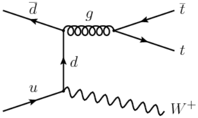
Signal and background diagrams



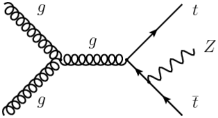
$\sigma_{pp\to\tilde{t}\bar{\tilde{t}}} = 0.0017 \sim 2.1$ pb

Multijet: data-driven ($\mathbf{TRF_{MJ}}$)

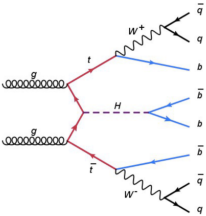




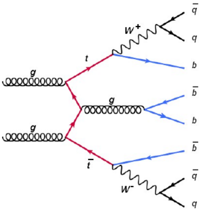
$\sigma_{t\bar{t}W} = 1.12$ pb



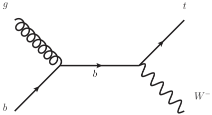
$\sigma_{t\bar{t}Z} = 0.16$ pb



$\sigma_{t\bar{t}H} = 0.5$ pb



$\sigma_{t\bar{t}+\text{jets}} = 730$ pb



$\sigma_{Wt} = 76$ pb

Multijet background esatimation: $\mathrm{TRF_{MJ}}$ method

- $\mathbf{TRF_{MJ}}$ based on the **probability of tagging jet in QCD events**
  - Starting from events with the number of b-tagged jets $N_b \geq 2$, one can predict the number of multijet events in high jet multiplicities

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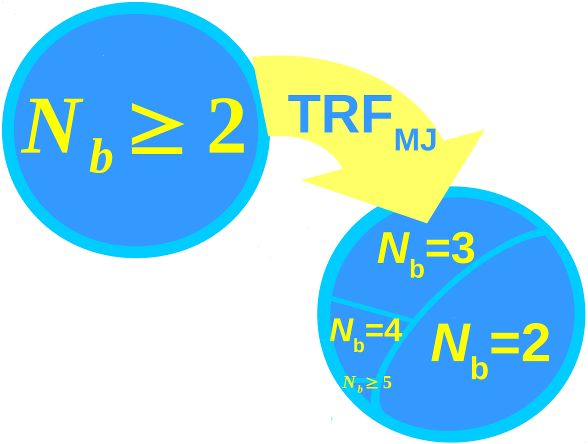
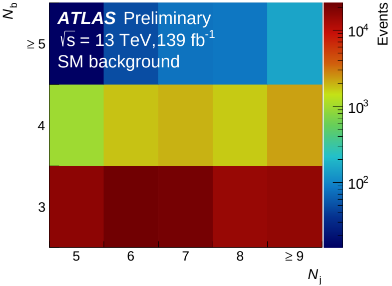
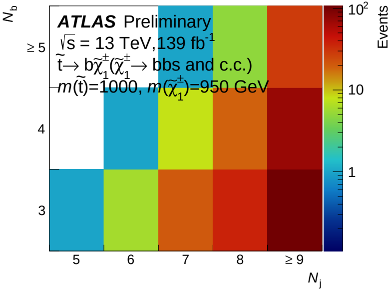


Events pre-selection

- $\geq$4 jets with $p_T > 120$ (140) GeV
- additional jets must have $p_\mathrm{T} > 25$ GeV, $|\eta| < 2.5$
- $\geq$ 2 b-tagged jets
- Events containing leptons are discarded
- Strategy: Counting events in different jet and b-tagged jet multiplicity regions
    - **SM background** is accumulated in **low** b-**tag** multiplicity
    - **Signal** is accumulated in **high jet** multiplicity





Analysis strategy

Analysis Regions		N_b: 3	4	≥ 5
N_j	6		$\longleftarrow$ $\mathrm{SR}_{\mathrm{stop}}$ $\longrightarrow$	$\longleftarrow$ $\mathrm{SR}_{\mathrm{stop}}$ $\longrightarrow$
		$\leftarrow$ VR-MJ $\rightarrow$	$\leftarrow$ VR-MJ $\rightarrow$	
	7		$\longleftarrow$ $\mathrm{SR}_{\mathrm{stop}}$ $\longrightarrow$	$\longleftarrow$ $\mathrm{SR}_{\mathrm{stop}}$ $\longrightarrow$
		$\leftarrow$ VR-MJ $\rightarrow$	$\leftarrow$ VR-MJ $\rightarrow$	
	8		$\longleftarrow$ $\mathrm{SR}_{\mathrm{stop}}$ $\longrightarrow$	$\longleftarrow$ $\mathrm{SR}_{\mathrm{stop,discovery}}$ $\longrightarrow$
		$\leftarrow$ VR-MJ $\rightarrow$	$\leftarrow$ VR-MJ $\rightarrow$	
	≥ 9		$\longleftarrow$ $\mathrm{SR}_{\mathrm{stop}}$ $\longrightarrow$	$\longleftarrow$ $\mathrm{SR}_{\mathrm{stop,discovery}}$ $\longrightarrow$
		$\leftarrow$ VR-MJ $\rightarrow$	$\leftarrow$ VR-MJ $\rightarrow$	

- N_j: number of jets, N_b: number of b-tagged jets

Analysis strategy: validation regions

Analysis Regions		N_b 3	4	≥ 5
N_j	6		⟵ $\mathrm{SR_{stop}}$ ⟶	⟵ $\mathrm{SR_{stop}}$ ⟶
		⟵ VR-MJ ⟶	⟵ VR-MJ ⟶	
	7		⟵ $\mathrm{SR_{stop}}$ ⟶	$\mathrm{SR_{stop}}$ ⟶
		⟵ VR-MJ ⟶	⟵ VR-MJ ⟶	
	8		⟵ $\mathrm{SR_{stop}}$ ⟶	$\mathrm{SR_{stop,discovery}}$ ⟶
		⟵ VR-MJ ⟶	⟵ VR-MJ ⟶	
	≥9		⟵ $\mathrm{SR_{stop}}$ ⟶	$\mathrm{SR_{stop,discovery}}$ ⟶
		⟵ VR-MJ ⟶	⟵ VR-MJ ⟶	

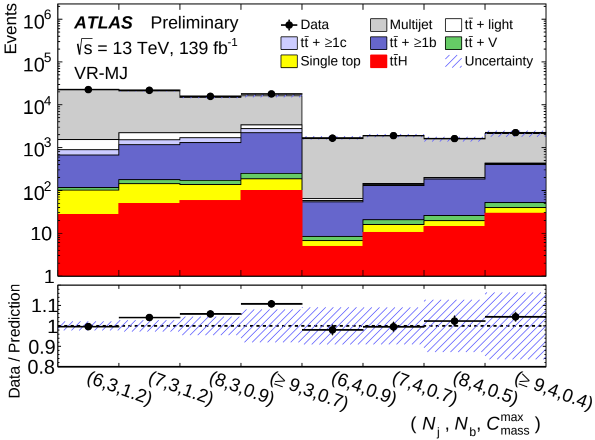
$\mathrm{TRF_{MJ}}$

validation regions

- N_j: number of jets, N_b: number of b-tagged jets
- Validation regions (VR-MJ) based on C_{mass} (H_T/M_{jets}) cut

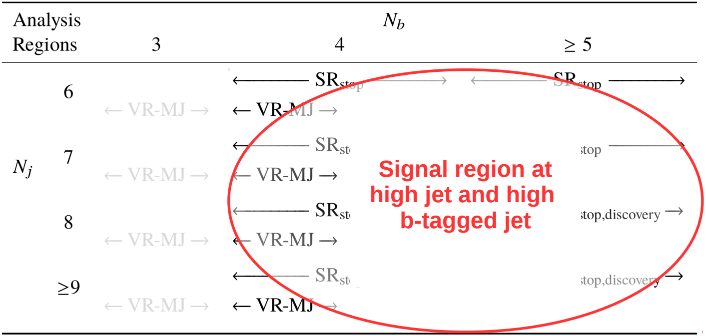
Validation of $\mathrm{TRF_{MJ}}$ method in VR-MJ in data

- Number of predicted multijet events with $N_j \geq 6$ and $N_b = 3$ or $N_b \geq 4$



- $C^{\text{max}}_{\text{mass}}$: region dependent upper cut on C_{mass}
- Systematic uncertainties are represented by the blue hatched area

Analysis strategy: model-dependent test

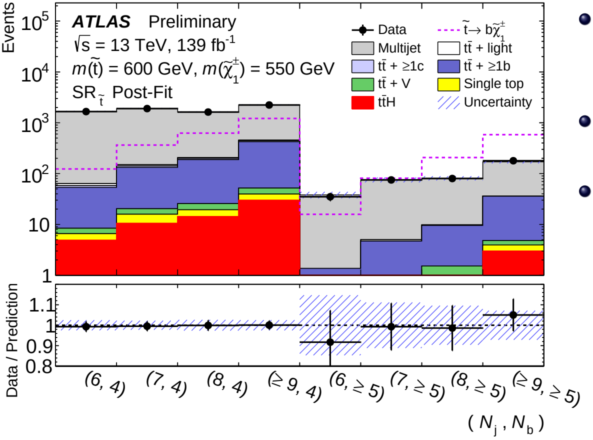


- N_j: number of jets, N_b: number of b-tagged jets
- Signal regions: $N_j \geq 6$ and $N_b \geq 4$

Statistical analysis

- Profile-likelihood fit is performed on 8 SRs

$$\mathcal{L}(N^{\text{data}}|\mu,\boldsymbol{\theta}) = \prod_{i\in bins} \mathcal{P}(N_i^{data}|\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))\Gamma(\theta_i^{\text{stat}}) \prod_{k\in\text{systematics}} \mathcal{N}(\theta_{ki}^{\text{sys}})$$



- $\mu = \frac{\sigma_{\text{obs}}}{\sigma_{\text{MSSM}}}$: signal strength parameter
- $\boldsymbol{\theta}$: nuisance parameters
- Systematic uncertainties are represented by the blue hatched area

← **Background-only fit**

Analysis strategy: model-independent test

Analysis Regions		N_b 3	4	≥ 5
N_j	6	← VR-MJ →	← SR$_{\text{stop}}$ → / ← VR-MJ →	← SR$_{\text{stop}}$ →
	7	← VR-MJ →		← SR$_{\text{stop}}$ →
	8	← VR-MJ →		← SR$_{\text{stop,discovery}}$ →
	≥9	← VR-MJ →		← SR$_{\text{stop,discovery}}$ →

Discovery regions

- N_j: number of jets, N_b: number of b-tagged jets
- Discovery regions: ($N_j \geq 8$, $N_b \geq 5$) and ($N_j \geq 9$, $N_b \geq 5$)

Model-independent results

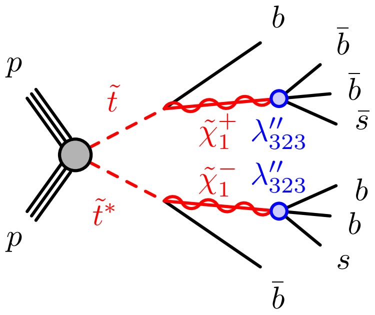
- Fitted background yields in $(N_j \geq 8,\ N_b \geq 5)$ and $(N_j \geq 9,\ N_b \geq 5)$ signal regions

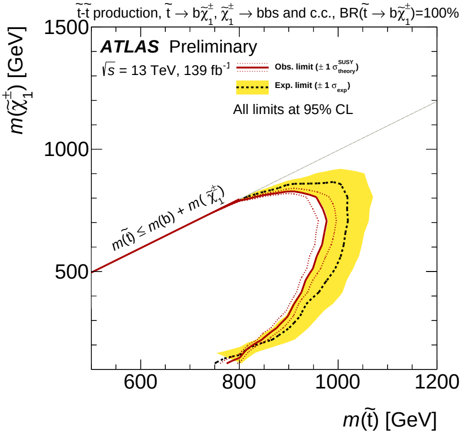
	(N_j, N_b)	
Process	≥8,≥5	≥9,≥5
Multijet	200 ± 40	123 ± 20
$t\bar{t} + \geq 1c$	0.6 ± 0.6	0.29 ± 0.33
$t\bar{t} + \geq 1b$	26 ± 20	20 ± 15
$t\bar{t} + W$	0.11 ± 0.05	0.09 ± 0.04
$t\bar{t} + Z$	1.4 ± 0.7	0.8 ± 0.7
Wt channel	0.9 ± 0.8	0.9 ± 1.2
$t\bar{t}H$	3.7 ± 1.6	2.9 ± 1.4
Total background	230 ± 40	147 ± 20
Data	259	179

- No significant excess observed
- Model-independent limits on the contribution of new phenomena to the signal-region yields are calculated in terms of the total observed cross section

Signal region	σ^{95}_{obs} [fb]	N^{95}_{obs}	N^{95}_{exp}	p_0 (Z)
$N_{\text{jets}} \geq 8,\ N_{\text{b}} \geq 5$	0.76	105	85^{+30}_{-24}	0.24 (0.7)
$N_{\text{jets}} \geq 9,\ N_{\text{b}} \geq 5$	0.54	75	52^{+20}_{-15}	0.11 (1.2)

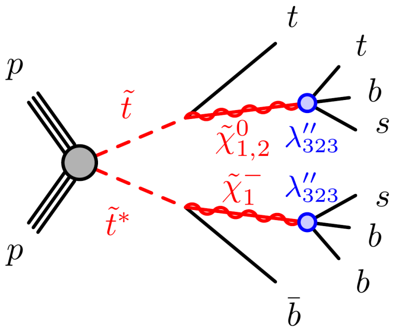
Exclusion limits on signal strength $\mu_{\tilde{t}\tilde{t}^*}$ with BR($\tilde{t} \to b\chi^+(\chi^+ \to bbs)) = 1$

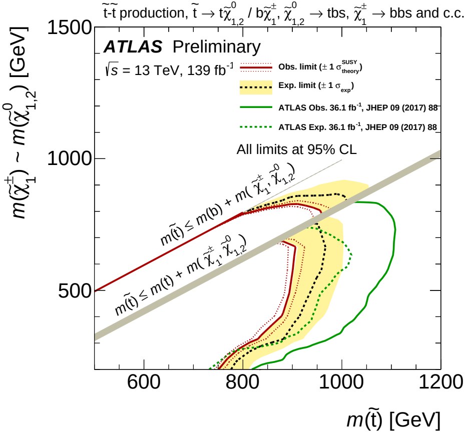




- Observed (expected) sensitivity up to 950 GeV (1 TeV)

Exclusion limits on signal strength $\mu_{\tilde{t}\tilde{t}^*}$ for $\tilde{H}$ LSP scenario

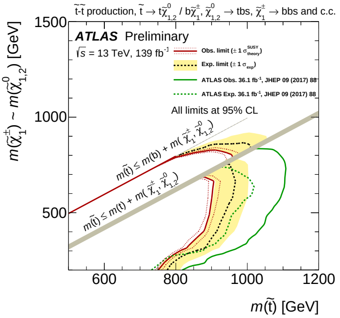




- Observed (expected) sensitivity up to 950 GeV (1 TeV)

Conclusions

- SUSY is an elegant way to relate fermions and bosons and solving many SM shortcomings
  - Light top squark $\rightarrow$ solution to the hierarchy problem
- Extensive program to explore uncovered phase space for RPV models
  - $pp \rightarrow \tilde{t}\tilde{t}^* \rightarrow bbbs\bar{b}\bar{b}\bar{b}\bar{s}$ have been a blind spot for natural SUSY
- Search for RPV decay of top squarks pair production in 139 fb^{-1} of ATLAS data:
  - Strategy based on a profile likelihood based fit in different N_j and N_b
  - Multijet background estimated using TRF$_{\text{MJ}}$ method. Validated in data and MC
  - No significant excess is observed
    - Model-independent observed limit on BSM cross-section is 0.54 fb in (≥9j,≥5b)
    - Observed (Expected) 95% CL exclusion limit is set for top squark mass up to 0.95 TeV (1 TeV)



- More information in ATLAS-CONF-2020-016

THANK YOU FOR YOUR ATTENTION