Search for phenomena beyond the Standard Model in events with large b-jet multiplicity using the ATLAS detector at the LHC

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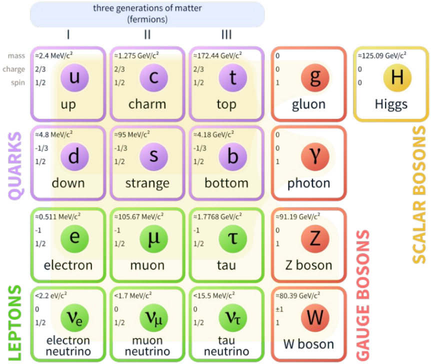
Contents

Standard Model (SM) of Particle Physics

- Quantum field theory under gauge symmetry group:
  - $SU(3)_C \times SU(2)_L \times U(1)_Y$

- Describes elementary particles and their interactions (strong and electroweak)
- Fundamental particles:
  - Fermions: quarks and leptons
  - Vector boson: gluons, Z and $W^{\pm}$ bosons, photon
  - Scalar boson: Higgs boson
    - generate **mass** for fundamental particles
- Experimentally established with high precision



- Mass spectrum of SM particles ranging from O(eV) to ∼173 GeV (t-quark)

Standard Model (SM) of Particle Physics

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- Describes elementary particles and their interactions (strong and electroweak)
- Fundamental particles:
  - Fermions: quarks and leptons
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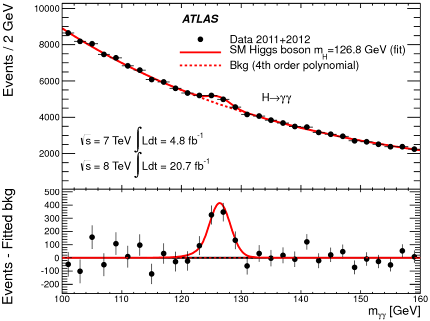
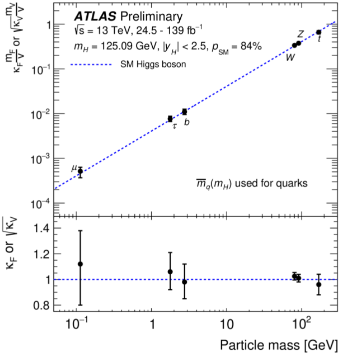
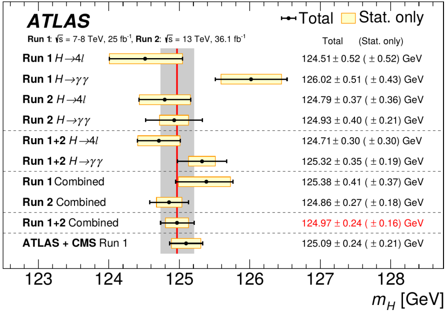
  - Scalar boson: Higgs boson
    - generate **mass** for fundamental particles
- In 2012, the last piece of the particles in SM picture, the Higgs boson, has been discovered by the LHC



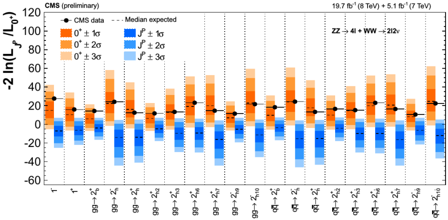
[arXiv:1207.7214]

The Higgs boson measurements

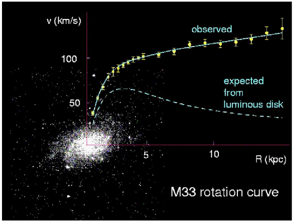




- Higgs coupling to 3rd generation of fermions and vector bosons are measured
  - $y_f = \sqrt{2}\frac{m_f}{v}$ and $g_V \sim 2\frac{m_V^2}{v}$
- Mass measurement Run 1+2:
  - $m_H = 124.97 \pm 0.24$ GeV
- Compatible with SM spin-0 and even parity prediction



Standard Model shortcomings



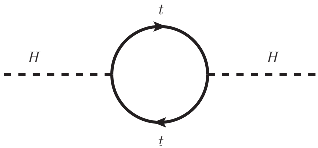
[arXiv:astro-ph/9909252]

[Matter-antimatter asymmetry]

- Regardless of the SM successes, some unsolved questions still remain:
  - Why is Higgs boson so light (so-called "naturalness" problem)?
  - What is the dark matter ($\sim 25\%$ total mass-energy of the universe)?
  - What is the origin of neutrino masses?
  - What is the origin of matter-antimatter asymmetry in our universe?
  - Is there unification of the forces?
- Many extensions of the SM have been developed to answer those questions

Top quark as a probe for new physics

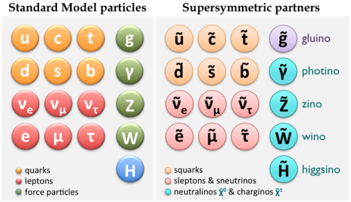
- Top quark play an important role in any BSM theory

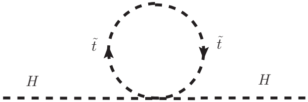


$$\Delta m_H^2 = -\frac{|y_t|^2}{8\pi^2}\Lambda^2 + ...$$

- Destabilizes the Higgs mass (so-called "naturalness" problem)
- Solved by BSM models which have top-partner: Supersymmetry, Composite Higgs models.

- Supersymmetry (SUSY):





$$\Delta m_H^2 = \frac{y_t^2}{8\pi^2}\Lambda^2 + ...$$

- Naturally stabilizes Higgs masss
- SUSY is a broken symmetry → natural SUSY $m_{\tilde{t}} \leq$ O(1) TeV

Superpotential of Minimal Supersymmetric Standard Model (MSSM)

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

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

- 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

Superpotential of MSSM

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$$\sout{W_{\not{R}_p} = \frac{1}{2}\lambda^{ijk}L_iL_j\bar{e}_k + \lambda'^{ijk}L_iQ_j\bar{d}_k + \mu'^{i}L_iH_u + \frac{1}{2}\lambda''^{ijk}\bar{u}_i\bar{d}_j\bar{d}_k}$$

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

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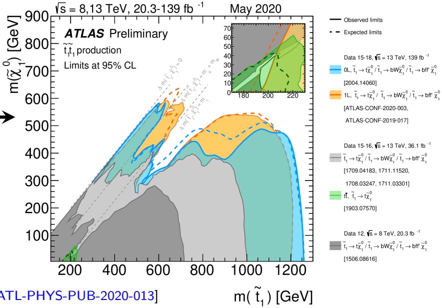
R-parity conserving (RPC) model

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

→



[ATL-PHYS-PUB-2020-013]

$m_{\tilde{t}}$ heavily constrained up to 1.2 TeV

Superpotential of MSSM

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

$$W_{MSSM} = \bar{\tilde{u}}\mathbf{y}_u\tilde{Q}H_u - \bar{\tilde{d}}\mathbf{y}_d\tilde{Q}H_d - \bar{\tilde{e}}\mathbf{y}_e\tilde{L}H_d + \mu H_u H_d,$$

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

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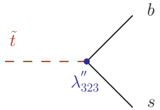
R-parity violating (RPV) model

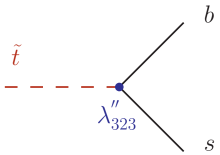
- Violate B or L
- Single sparticle production is possible
- LSP not necessary stable → possibility for new signals
- MET not necessarily large

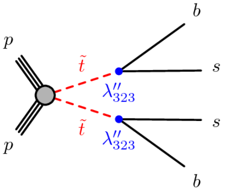
→

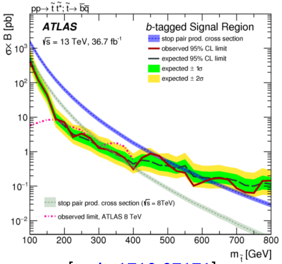
- Many constraints on SUSY searches disappear
- Top squark decays via $\boldsymbol{\lambda}''_{\mathbf{323}}$ favored by MFV



Top-squark RPV phenomenology and searches in ATLAS

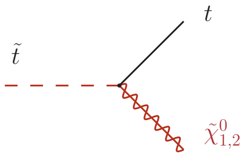


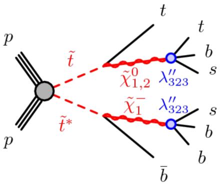


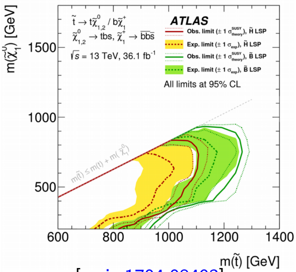


[arxiv:1710.07171]

- Top-squark is LSP







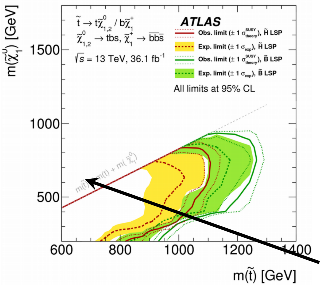
[arxiv:1704.08493]

- Higgsino $(\tilde{\chi}^0_2, \tilde{\chi}^\pm_1, \tilde{\chi}^0_1)$ is LSP
  - $m_{\tilde{t}} - m_{\chi^0,\chi^\pm} > m_t$

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

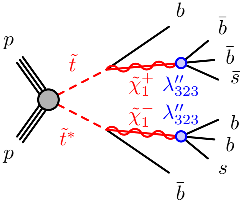
For natural SUSY, a triplet of higgsino-like states are LSP $(\tilde{\chi}^0_2, \tilde{\chi}^\pm_1, \tilde{\chi}^0_1)$

Higgsino LSP



[arxiv:1704.08493]

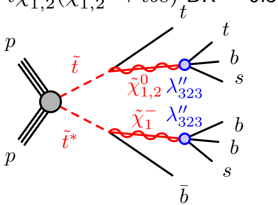
$\tilde{t} \to b\chi^+_1 (\chi^+_1 \to \bar{b}\bar{b}\bar{s})$



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

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

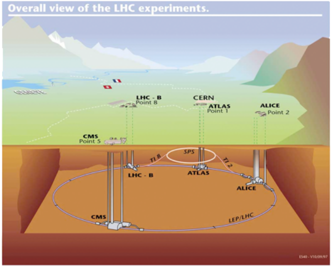


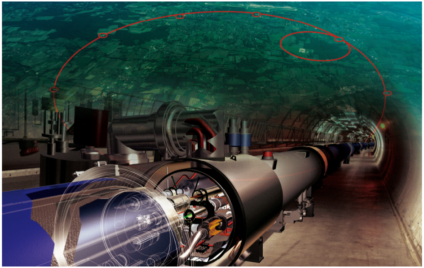
Dominant in $m_{\tilde{t}} - m_{\tilde{\chi}^+} > m_t$

No leptonic final states can be used for this scenario

Search for signal in events with high b-jet multiplicity

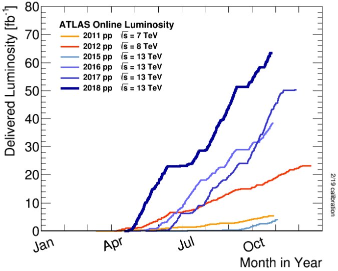
The Large Hadron Collider (LHC) at CERN





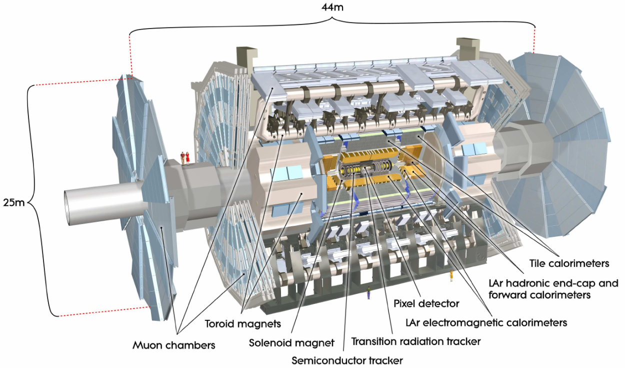
- Circular collider of protons/ions
- Proton-proton (pp) collisions:
  - 2010-2012: $\sqrt{s} = 7, 8$ TeV (Run 1)
  - 2015-2018: $\sqrt{s} = 13$ TeV (Run 2)
- Long shutdown in 2019 – 2020
  - Prepare for high luminosity increase
  - 2021-2023: $\sqrt{s} = 13/14$ TeV (Run 3)

ATLAS Luminosity Public



The Large Hadron Collider (LHC) at CERN

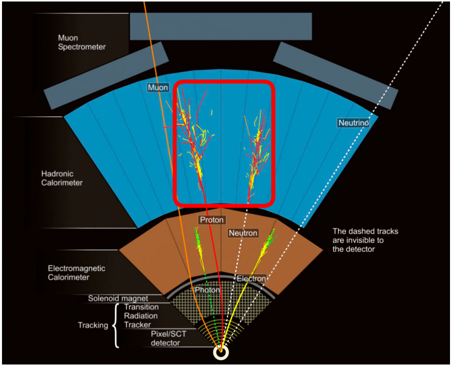
The ATLAS detector



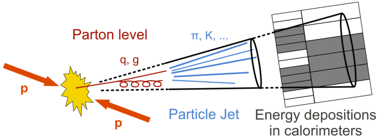
- Multi-purpose detector:
  - Higgs boson physics
  - SM precision measurements
  - New physics searches
- 3 sub-components:
  - Inner detector (ID)
  - Calorimeters
  - Muon Spectrometer (MS)
- Large pp collisions dataset in Run 2, $L \sim 140$ fb^{-1}

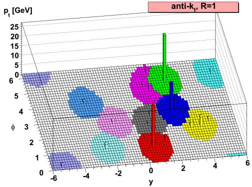
Overview of particles passage through ATLAS detector

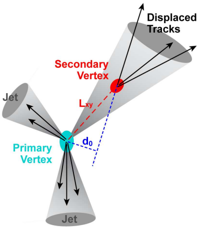
- **Electrons**: Energy deposition in calorimeter and charged track in ID
- **Photons**: Energy deposition in calorimeter, no track in ID
- **Muons**: Combined track in ID and MS
- **Jets**: Energy deposition in calorimeters and charged tracks in ID
- **MET**: negative vectorial sum of selected physics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

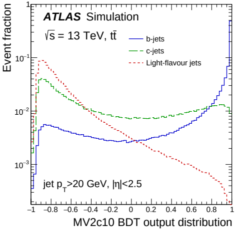


Jet reconstruction and b-jet identification



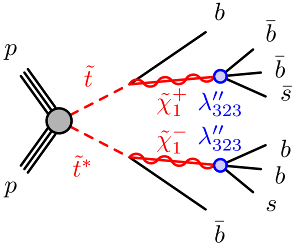




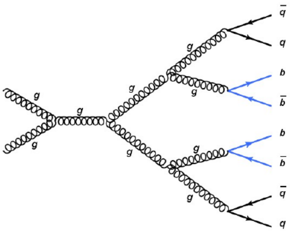


- Jet reconstruction:
  - Quarks/ gluons → fragmentation and hadronization → collimated spray of particles, a jet
  - Jets reconstructed by anti-k_t algorithm
- b-jet identification
  - b-hadrons travel few hundreds μm before decay.
  - Impact parameter track resolution of $\sim 10\ \mu$m
  - Reconstructs the Secondary Vertex (SV) to identify b-jet
  - **Multivariate b-tagging algorithm** separates b-jet from light and c-jet

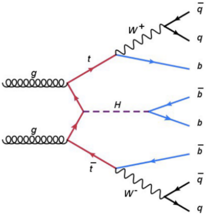
Signal and background processes



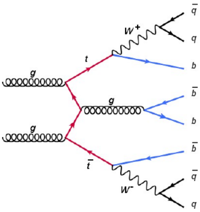
$\sigma_{pp\to\tilde{t}\bar{\tilde{t}}} = 0.0017 \sim 2.1$ pb



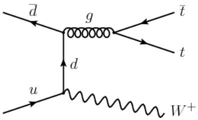
$\sigma_{\text{multijet}} \sim O(1)$ mb



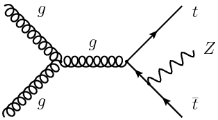
$\sigma_{t\bar{t}H} = 0.5$ pb



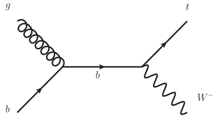
$\sigma_{t\bar{t}+\text{jets}} = 730$ pb



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

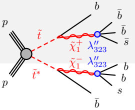


$\sigma_{t\bar{t}Z} = 0.16$ pb

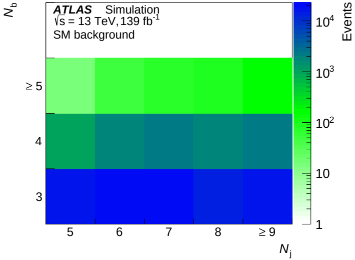


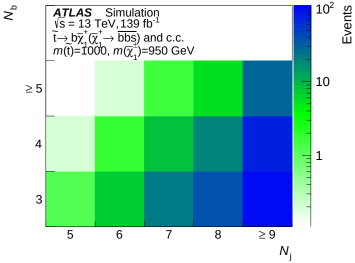
$\sigma_{Wt} = 76$ pb

RPV top squark production: Analysis strategy



- $\geq$4 hadronic 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 vetoed
- **Strategy**: Counting events in different jet and b-tagged jet multiplicity regions
- Top-quark backgrounds simulated by NLO MC generators
- Most dominant **multijet** background estimated by data-driven ($\mathrm{TRF_{MJ}}$) method





Event categorization

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

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

Validation regions for $\mathrm{TRF}_{\mathrm{MJ}}$ method

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

$\mathrm{TRF}_{\mathrm{MJ}}$ **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

Signal region definition

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

Signal region at high jet and high b-tagged jet

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

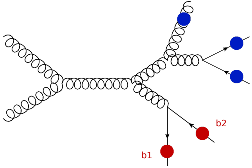
Model-independent test setup

Analysis Regions		N_b: 3	4	≥ 5
	6	← VR-MJ →	←— SR_{stop} —→ ← VR-MJ →	←— SR_{stop} —→
N_j	7	← VR-MJ →		←— SR_{stop} —→
	8	← VR-MJ →	**Discovery regions**	←— $SR_{stop,discovery}$ —→
	≥9	← VR-MJ →		←— $SR_{stop,discovery}$ —→

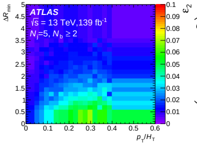
- N_j: number of jets, N_b: number of b-tagged jets
- Discovery regions: ($N_j \geq 8$, $N_b \geq 5$) and ($N_j \geq 9$, $N_b \geq 5$)

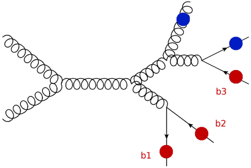
Tag-Rate-Function multijet: $\mathrm{TRF}_{\mathrm{MJ}}$ data-driven method

- $\mathrm{TRF}_{\mathrm{MJ}}$ predicts the b-tagged jet spectrum of multijet events:
  - Based on the probability of b-tagging a jet in events with **2** ($\boldsymbol{\varepsilon}_2$) and **3** ($\boldsymbol{\varepsilon}_3$) b-tagged jets estimated in 5 jets events
  - After removing **2** (**3**) jets with highest b-tagging weight, $\boldsymbol{\varepsilon}_2$ ($\boldsymbol{\varepsilon}_3$) derived as a function of:
    - $p_{\mathrm{T}}/H_{\mathrm{T}}$ and minimum angular distance between the jet and the removed b-tagged jets

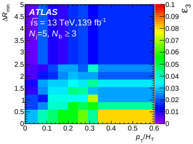


$\boldsymbol{\varepsilon}_2$





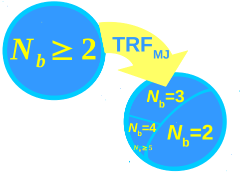
$\boldsymbol{\varepsilon}_3$



Starting from a sample with $N(\geq 2b)$:

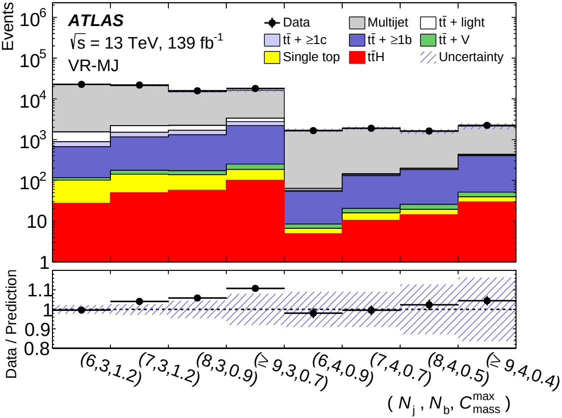
$N(2b) = \sum_i P^{2b}(i)$, where $P^{2b}(i) = \prod_{j \neq b_1, b_2}^{N_i} (1 - \varepsilon_2(j))$

for $N(3b), N(4b), N(\geq 5b)$ $\boldsymbol{\varepsilon}_2$ and $\boldsymbol{\varepsilon}_3$ used in combination



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

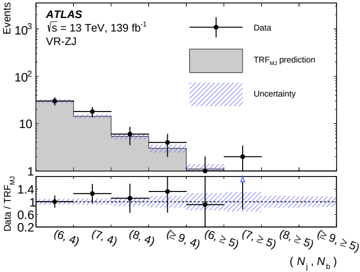
- Number of predicted multijet events with $N_j \geq 6$ and $N_b = 3$ or $N_b = 4$



- $C_{\text{mass}}^{\text{max}}$: region dependent upper cut on C_{mass}
  - Signal contamination less than 5%
- Systematic uncertainties are represented by the blue hatched area

Validation of $\mathrm{TRF_{MJ}}$ method in Z + jets events

- VR-ZJ event selection:
  - Single isolated lepton trigger (e, μ)
  - 2 opposite-sign same flavor leptons $p_{\mathrm{T}} > 27$ GeV
  - $m_{l^{\pm}l^{\mp}} > 60$ GeV
  - ≥ 5 jets with $p_{\mathrm{T}} > 25$ GeV
  - ≥ 2 b-tagged jets
- $\mathrm{TRF_{MJ}}$ is derived and applied to estimate the spectrum of number of b-tagged jets in VR-ZJ
  - Overall agreement within uncertainties
- $\mathrm{TRF_{MJ}}$ systematic uncertainties derived in MC dijet events
  - Max between residual non-closure and statistical uncertainty in each N_j, N_b

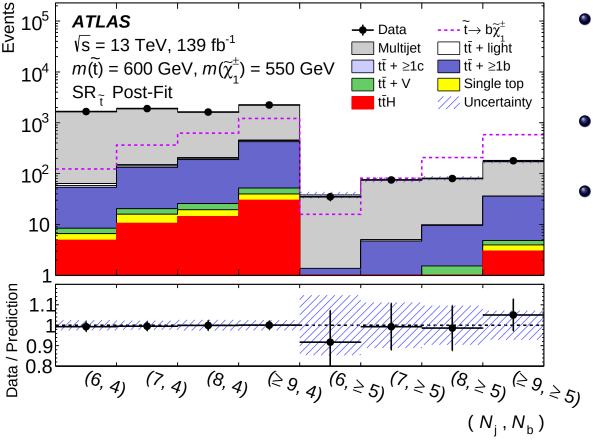


$\mathrm{TRF_{MJ}}$ uncertainty		N_{b}: 4	N_{b}: ≥5
N_{j}	6	9%	27%
	7	9%	30%
	8	13%	18%
	≥9	16%	14%

Statistical model

- Profile-likelihood fit is performed on 8 SRs

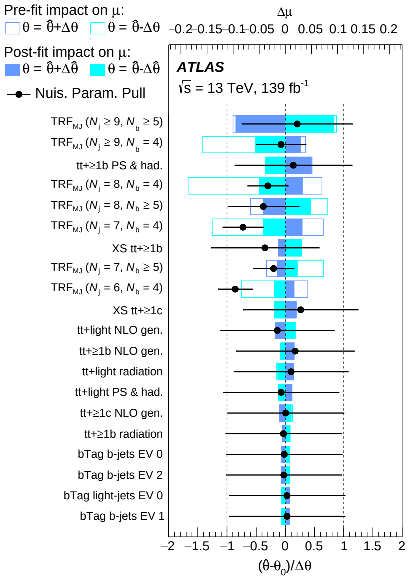
$$\mathcal{L}(N^{\text{data}}|\mu,\boldsymbol{\theta}) = \prod_{i\in bins} \mathcal{P}(N_i^{data}|\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))\Gamma(\theta_i^{\text{stat}}) \prod_{k\in\text{systematics}} \mathcal{N}(\theta_{ki}^{\text{sys}})$$



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

← **Background-only fit**

Impact of systematics on μ



- $\mathrm{TRF}_{\mathrm{MJ}}$ normalization uncertainty: non-closure as found in MC dijet events
- $t\bar{t}$+jets modeling uncertainties: parton shower (PS), generator (Gen) and initial and final-state radiation (ISR, FSR)
- 50% uncertainties on cross-section of $t\bar{t}+\geq 1b$ and $t\bar{t}+\geq 1c$ backgrounds
- Jets experimental uncertainties: jet energy scale (JES), jet energy resolution (JER), jet vertex tagging (JVT)
- b-tagging uncertainties

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

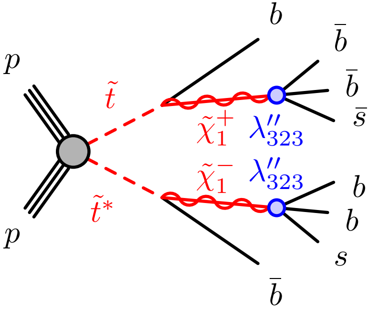
Process	$N_\mathrm{j} \geq 8$, $N_\mathrm{b} \geq 5$	$N_\mathrm{j} \geq 9$, $N_\mathrm{b} \geq 5$
Multijet	200 ± 40	123 ± 20
$t\bar{t} + \geq 1c$	0.6 ± 0.6	0.29 ± 0.33
$t\bar{t} + \geq 1b$	26 ± 20	20 ± 15
$t\bar{t} + W$	0.11 ± 0.05	0.09 ± 0.04
$t\bar{t} + Z$	1.4 ± 0.7	0.8 ± 0.7
Wt	0.9 ± 0.8	0.9 ± 1.2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

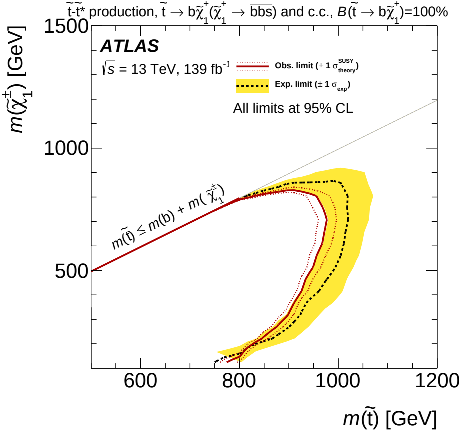
- No significant excess observed

- Model-independent limits are set on the contribution of new phenomena to the signal-region yields.

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

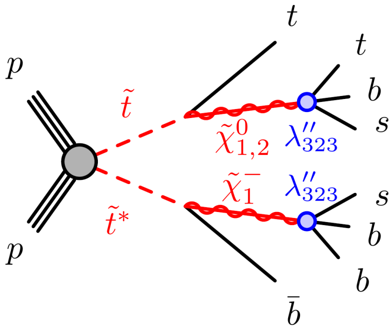
Exclusion limits with BR($\tilde{t} \to b\chi^+(\chi^+ \to bbs)) = 1$

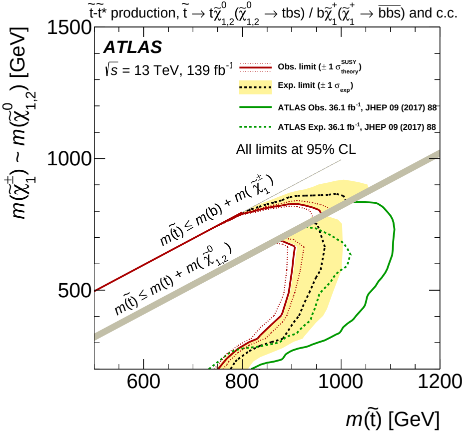




- For the signal model considered, set exclusion limits on $m_{\tilde{t}}$ up to 950 GeV

Exclusion limits for $\tilde{H}$ LSP scenario

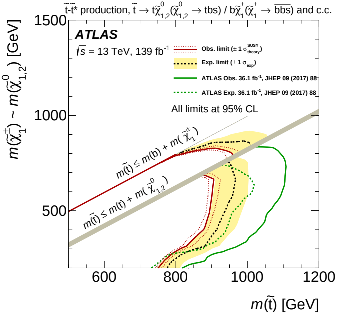




- For the signal model considered, set exclusion limits on $m_{\tilde{t}}$ up to 950 GeV

Conclusions

- SUSY is an elegant way to relate fermions and bosons and solving many SM shortcomings
  - Light top squark $\rightarrow$ solution to the naturalness 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 ($\geq$9j,$\geq$5b)
    - Observed (Expected) 95% CL exclusion limit is set for top squark mass up to 0.95 TeV (1 TeV)



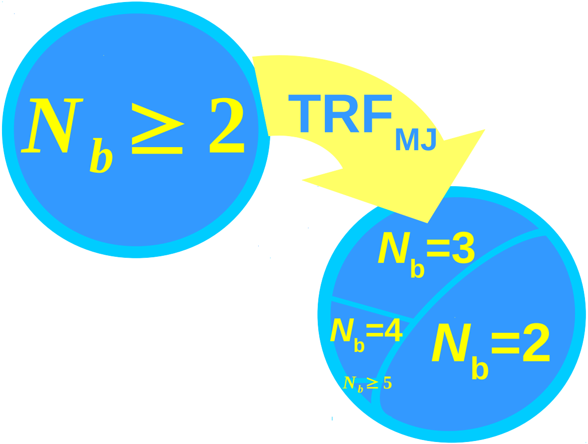
- More information in 2010.01015

THANK YOU FOR YOUR ATTENTION

BACK UP

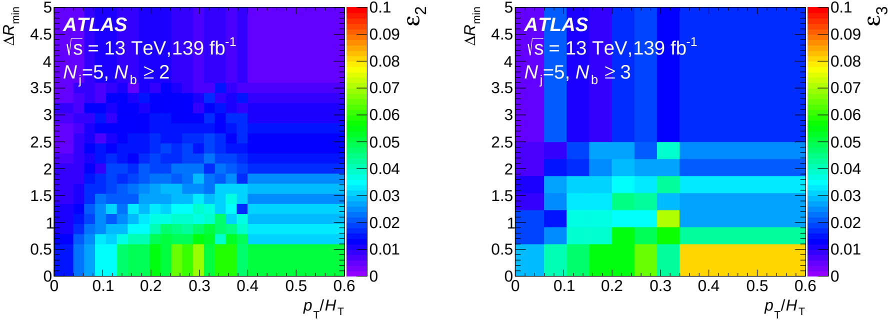
Multijet background esatimation: $\mathrm{TRF}_{\mathrm{MJ}}$ method

- $\mathrm{TRF}_{\mathrm{MJ}}$ based on the **probability of b-tagging a jet in multijet events**
  - Starting from events with the number of b-tagged jets $N_b \geq 2$, one can predict the b-tagged jet spectrum of multijet events at high jet multiplicity

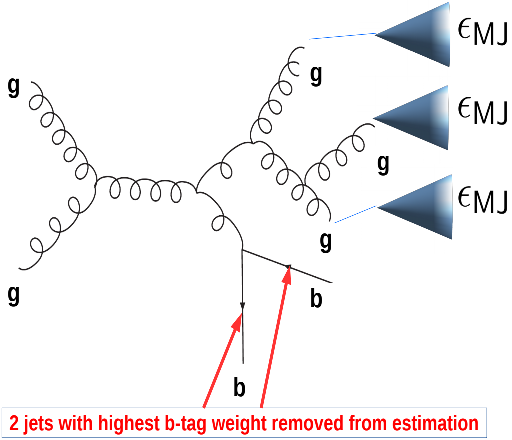


Deriving b-tagging probability ε_2 and ε_3 in data

- ε_2 and ε_3 are derived in 5 jets events
  - Low signal contamination and close to search regions
  - MC backgrounds are subtracted from data when estimating ε_2 and ε_3
- Parametrization with respect to:
  - $p_\mathrm{T}/H_\mathrm{T}$
  - ΔR_{min}: minimum ΔR between jet and highest b-tagging weight jets



$\mathrm{TRF_{MJ}}$: Predicting b-tagging spectrum



- Take as example events with (5 jets, $\geq$2 b-tags)
  - Remove 2 jets with highest b-tagging weight
- b-tagged probability of a jet i-th: $\varepsilon_{\mathsf{MJ}}(i)$
- Probability to have 3 $b$tag : $P_3 = \prod_{i=1}^{3} \varepsilon_{\mathsf{MJ}}(i)$
- Probability to have 0 $b$tag : $P_0 = \prod_{i=1}^{3} (1 - \varepsilon_{\mathsf{MJ}}(i))$
- Probability to have 1 $b$tag : $P_1 = \sum_{j=1}^{3} \left(\varepsilon_j \prod_{i \neq j} (1 - \varepsilon_i) \right)$
- Permutation is considered for P_2