Searches for strong production of supersymmetric particles

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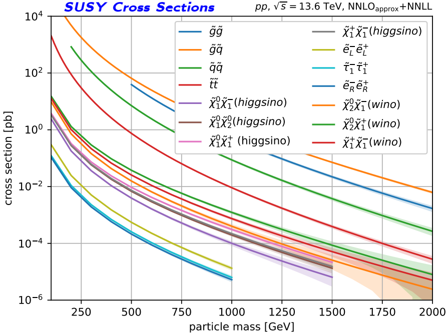
35th Rencontres de Blois - October, 23rd 2024

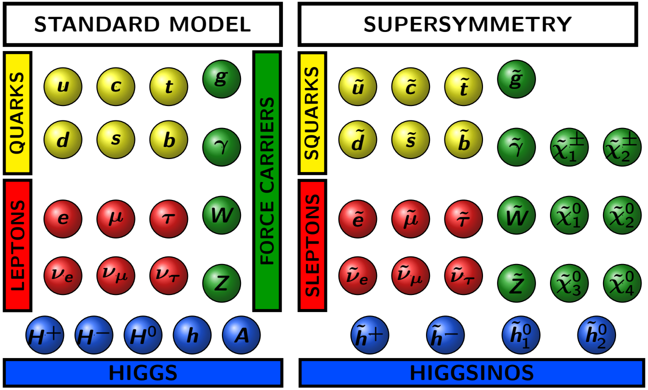
Supersymmetry (SUSY)



- Broad search program at the LHC
- *Simplified Models* for optimisation:
  - 100% Branching Ratios (BR)
  - A few particle masses as free parameters
- Electroweak searches in *Ben's talk*
- Long-lived searches in *Ian Alejandro's talk*

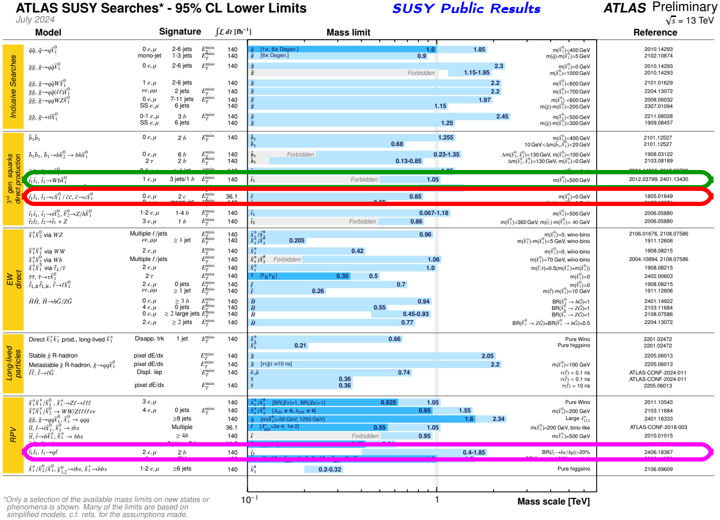
Possible solution for Standard Model shortcomings:

- Dark Matter (DM)
- Fine-tuning of the Higgs mass
- Unification of the forces (gravity)



ATLAS Latest Results

- **CERN-EP-2024-136**
  R-Parity Violating
  $\tilde{t}_1 \to b\ell$
- **JHEP 03 (2024) 139**
  Search for new phenomena with top-quark pairs and large missing transverse momentum
- **JHEP 07 (2024) 250**
  $\tilde{t}_1 \to (t/c) + \tilde{\chi}_1^0$ NEW!
- **CERN-EP-2024-218**
  Search for supersymmetry in final states with missing transverse momentum and c-tagged jets at 139 fb^{-1}



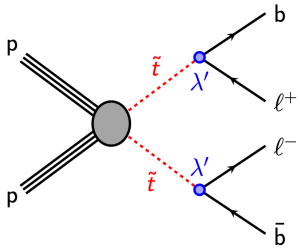
RPV $\tilde{t} \to b\ell$: Introduction

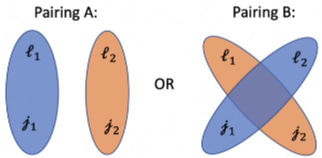
CERN-EP-2024-136

- B-L Model motivated by *theory*
- *Previous analysis* done on partial Run 2 dataset
- Identical branching ratios $\mathcal{B}(\tilde{t} \to \ell b) = 1/3$
- Final state: 2 oppositely charged leptons + 2 b-jets
- Search for resonances in combined *b-jet + lepton* ($b\ell$) invariant mass distribution (m^0_{bl})
- $b\ell$ leading and sub-leading mass pairs, with smallest asymmetry

$$m^{asym}_{b\ell} = \frac{m^0_{bl} - m^1_{bl}}{m^0_{bl} + m^1_{bl}} > 0$$

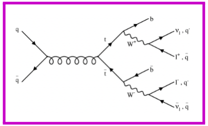
- Multi-bin fit over m^0_{bl}, optimized with variable bin widths



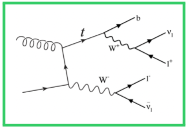


RPV $\tilde{t} \to b\ell$: Background Estimation

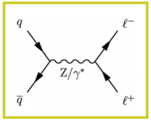
CERN-EP-2024-136



$t\bar{t}$

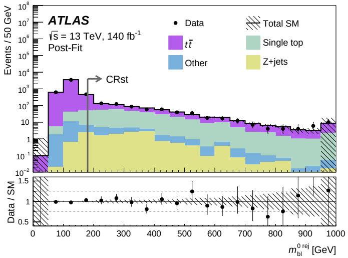


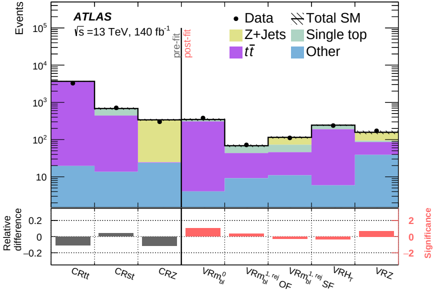
Single top



$Z + jets$

- Top backgrounds: 2ℓ from $W + \geq 1$ b-jets
- 2 Control Regions (CR) with mis-paired $(b\ell)$
- CRZ: leptons from Z, jets from ISR/FSR





Good agreement in the 5 Validation Regions (VR)

RPV $\tilde{t} \to b\ell$: Results

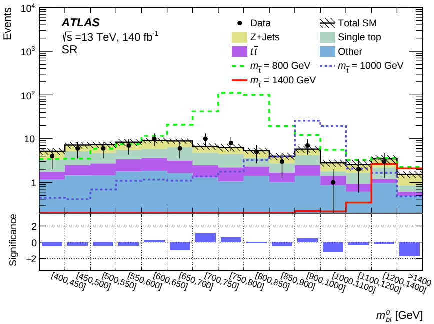
CERN-EP-2024-136

Two exclusion fits for each stop mass and lepton BR combination, after reweighting events accordingly:

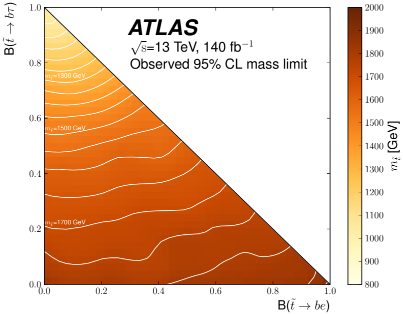
- 15 SRs, flavor-agnostic configuration
- 45 SRs, three lepton flavor channels (ee, $e\mu$, $\mu\mu$)

} *SRs binned in m_{bl}^{0}*

- Results with the strictest expected limits are used



No excess found in both configurations



Improved early Run 2 limits on $m_{\tilde{t}}$

$\sim$ 0.80/1.8/1.9 TeV for $b\tau/b\mu/be$ 100% BRs

Stop to top and E_T^{miss} - 1L: Introduction

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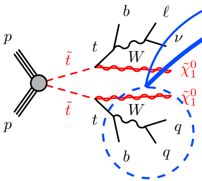

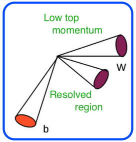

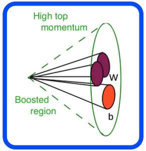

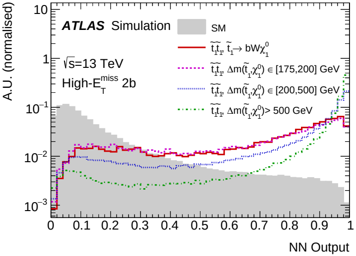

2 ($\tilde{t}_1\tilde{t}_1$ and DM) event-based NN classifiers trained to define CRs/VRs/SRs

Resolved High-MET

- $200 < p_T^{top} < 600$ GeV
- No large-R jets
- NN approach for 2-3 small-R jet combinations with exactly 1 b-jet
- 70% tagging efficiency
- Additional region split in $= 1$ and ≥ 2 b-jet

Boosted

- $p_T^{top} > 600$ GeV
- ≥ 1 large-R jets
- Multivariate classifier using jet substructure
- 80% tagging efficiency
- 6 extra regions: $[0, 1]$ large-R t-jet, $[1, \geq 2]$ b-jets and (in/out)side the large-R jet

Stop to top and E_T^{miss} - 1L: Background Estimation

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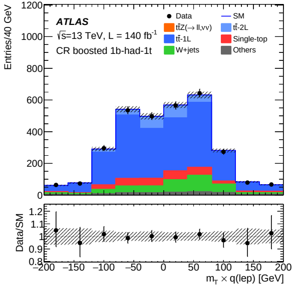
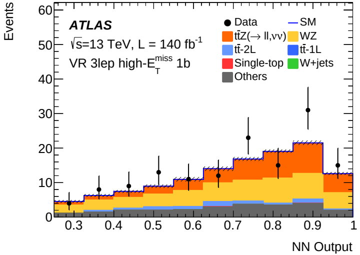
Dominant sources (SFs): $t\bar{t}$ (split in $t\bar{t}$-1L and $t\bar{t}$-2L), Single-top, W+jets





- CRs binned in $m_T \times q(lep)$: simultaneous determination of $t\bar{t}$ and W+jets backgrounds
- Background with only one $W \to \ell\nu$ have an endpoint at m_W, but $t\bar{t}$-2L
- Lepton charge to discriminate between $t\bar{t}$-1L and W+jets

- $t\bar{t}Z(\to \nu\bar{\nu})$ has low cross-section, but signal-like signature
- Background not fitted
- Validated in 3 VRs with 2 SFOS leptons at Z-peak, added to $\boldsymbol{p}_T^{miss}$ to mimic ν in SRs

Stop to top and E_T^{miss} - 1L: Results

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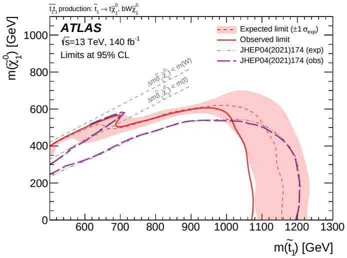

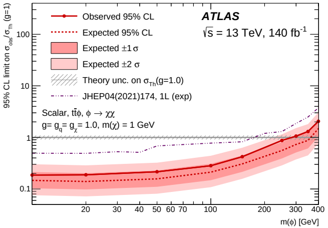

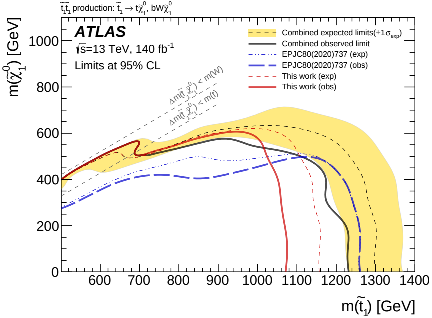

- No excess in SRs → 95% CL exclusion limits
- Combination with *stop 0L* results
- Combined exclusion up to ∼ 1.25 TeV for nearly massless $\tilde{\chi}_1^0$

Combination with *previous 1L* results, both DM and $\tilde{t}_1\tilde{t}_1$, improving exclusion in the **compressed region**

$\tilde{t}_1 \to (t/c) + \tilde{\chi}^0_1$: Introduction

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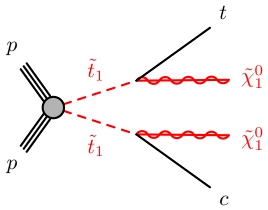
- First LHC results targeting t/c final states without leptons
- Motivated by *Non-Minimal Flavor Violation* extension of MSSM
- Final state signature: hadronically decaying top, charm quark and missing transverse energy

c-tagging recipes not well-established!

- Based on the well-known *DL1r algorithm*
- 3 output probabilities $p_{i=b,c,\ell}$ combined together with optimised parameters for c-jets
- ***DL1r*** and ***DL1r$_c$*** algorithms ran in sequence, with b-tag precedence avoiding high b-mistag rates



$$DL1r^{77\%} = \ln\left(\frac{p_b}{f_c p_c + (1 - f_c)p_\ell}\right) \longrightarrow DL1r_c^{20\%} = \ln\left(\frac{p_c}{f_b p_b + (1 - f_b)p_\ell}\right)$$

$\tilde{t}_1 \to (t/c) + \tilde{\chi}_1^0$: Selection

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Boosted

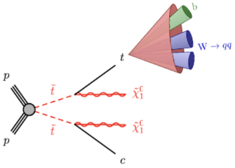
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \gg m_t$

Intermediate

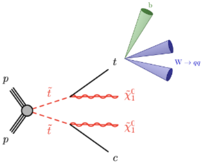
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m_t$

Resolved

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \simeq m_t$



- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet



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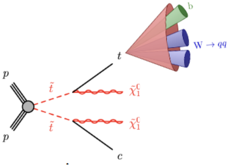
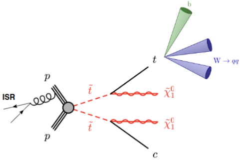


- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet



- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet

$\tilde{t}_1 \to (t/c) + \tilde{\chi}_1^0$: Selection

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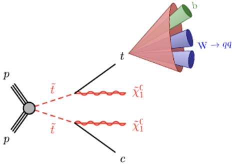
Boosted

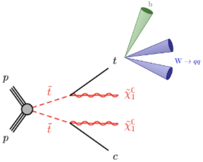
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \gg m_t$



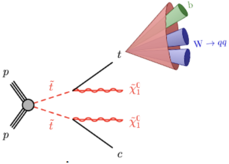
- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- Leading c- or b-jet

Intermediate

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m_t$



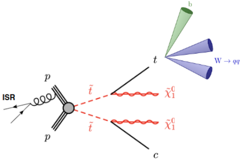
- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- Leading c- or b-jet



- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- Leading c- or b-jet

Resolved

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \simeq m_t$



- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- **ISR**, no c- or b-jet

$\tilde{t}_1 \rightarrow (t/c) + \tilde{\chi}_1^0$: Selection

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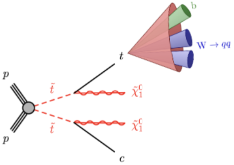
Boosted

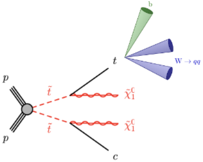
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \gg m_t$



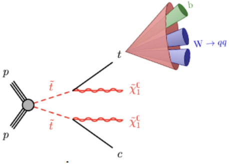
- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- Leading c- or b-jet
- $N^{DNN}_{top,R=1.0} \geq 1$

Intermediate

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m_t$



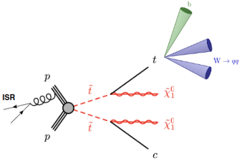
- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- Leading c- or b-jet
- $N^{DNN}_{top,R=1.0} = 0$



- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- Leading c- or b-jet
- $N^{DNN}_{top,R=1.0} \geq 1$

Resolved

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \simeq m_t$



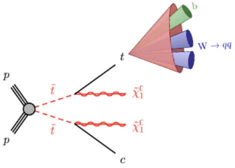
- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- **ISR**, no c- or b-jet

$\tilde{t}_1 \to (t/c) + \tilde{\chi}_1^0$: Selection

JHEP 07 (2024) 250

Boosted

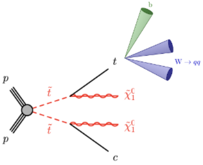
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \gg m_t$



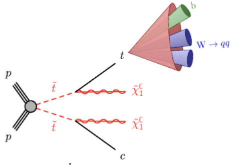
- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- Leading c- or b-jet
- $N^{DNN}_{top,R=1.0} \geq 1$
- $m_{T2} \geq 450$ GeV

Intermediate

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m_t$



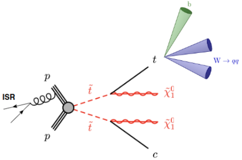
- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- Leading c- or b-jet
- $N^{DNN}_{top,R=1.0} = 0$



- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- Leading c- or b-jet
- $N^{DNN}_{top,R=1.0} \geq 1$
- $m_{T2} \in [200, 450]$ GeV

Resolved

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \simeq m_t$



- E_T^{miss} trigger + 0L
- ≥ 1 b-jet, ≥ 1 c-jet
- **ISR**, no c- or b-jet

$\tilde{t}_1 \rightarrow (t/c) + \tilde{\chi}_1^0$: Analysis Strategy

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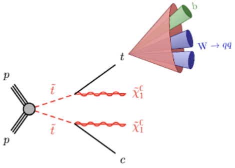
Boosted

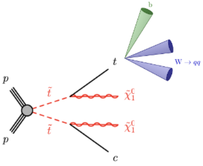
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \gg m_t$



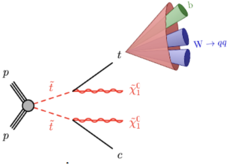
- Binned in $m_{T2}(j^b_{R=1.0}, c)$
- High m_{T2} and object-based E_T^{miss}

Intermediate

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m_t$



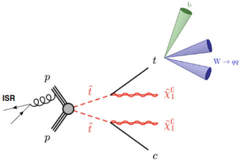
- Binned in $m_T(j, E_T^{miss})_{close}$
- Resolved topology



- Binned in $m_T(j, E_T^{miss})_{close}$
- Boosted topology, orthogonality thanks to reversed m_{T2} cut

Resolved

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \simeq m_t$



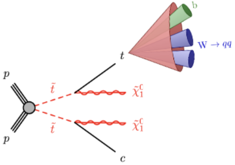
- Binned in m_{eff} and $m_T(j, E_T^{miss})_{close}$
- Multi-class NN to discriminate signal from $t\bar{t}$ and V+jets events

$\tilde{t}_1 \to (t/c) + \tilde{\chi}_1^0$: Background Estimation

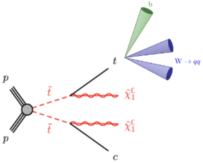
JHEP 07 (2024) 250

Boosted

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \gg m_t$



- Z+jets: 2L selection. Added to E_T^{miss}, mimicking $Z \to \nu\nu$



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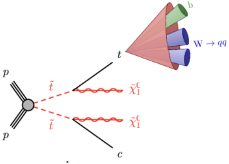
Intermediate

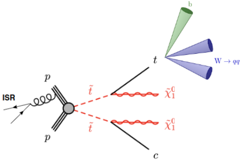
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m_t$



- Z+jets: 2L selection. Added to E_T^{miss}, mimicking $Z \to \nu\nu$

Resolved

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \simeq m_t$



- Z+jets: 2L selection. Added to E_T^{miss}, mimicking $Z \to \nu\nu$

$\tilde{t}_1 \rightarrow (t/c) + \tilde{\chi}_1^0$: Background Estimation

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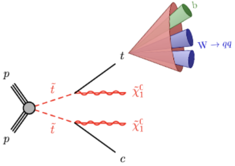
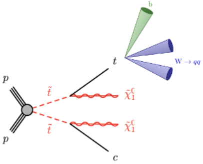
Boosted

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \gg m_t$



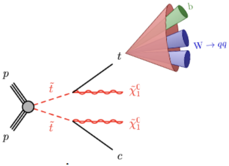


- Z+jets: 2L selection. Added to E_T^{miss}, mimicking $Z \rightarrow \nu\nu$
- Single-top: 1L selection

- Z+jets: 2L selection. Added to E_T^{miss}, mimicking $Z \rightarrow \nu\nu$

Intermediate

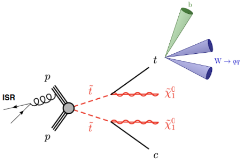
$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m_t$



- Z+jets: 2L selection. Added to E_T^{miss}, mimicking $Z \rightarrow \nu\nu$
- Single-top: 1L selection

Resolved

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \simeq m_t$



- Z+jets: 2L selection. Added to E_T^{miss}, mimicking $Z \rightarrow \nu\nu$
- $t\bar{t}$, W+jets: 1L selection. Treat lepton as jet (τ)

$\tilde{t}_1 \to (t/c) + \tilde{\chi}_1^0$: Results

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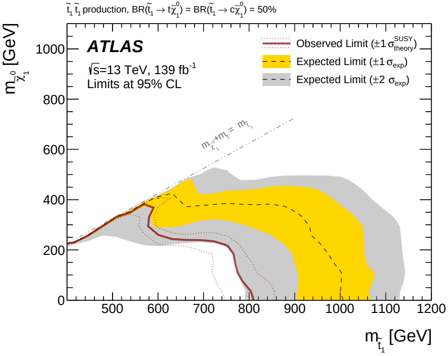
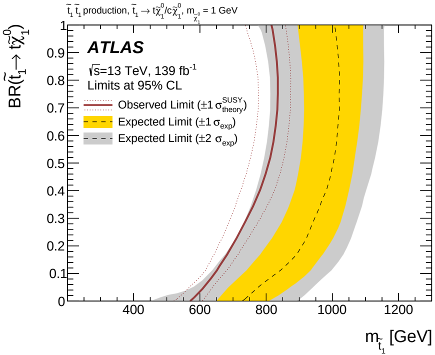
No significant excess in SRs: setting first LHC exclusion limits in this final state!





- Results for $\mathcal{B}(\tilde{t}_1 \to (t/c)\tilde{\chi}_1^0) = 50\%$
- $m(\tilde{t}_1) \lesssim 800$ GeV excluded for high mass
- $m(\tilde{t}_1) \lesssim 600$ GeV excluded for compressed spectra

- Scan in $\mathcal{B}(\tilde{t}_1 \to t\tilde{\chi}_1^0)$ at fixed $m(\tilde{\chi}_1^0) = 1$ GeV

SUSY search with E_T^{miss} and c-jets: Introduction

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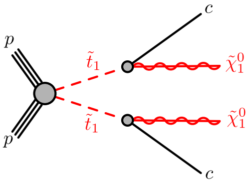

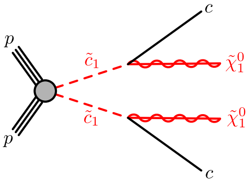

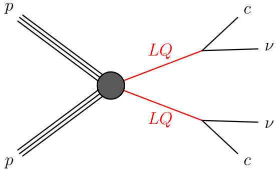

- *Minimal Flavor Violation*: when $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_W$, $\mathcal{B}(\tilde{t}_1 \to c\tilde{\chi}_1^0)$ can dominate
- Scalar LQ decaying to c quarks and e/μ
- Vector LQ decaying to $c + \tau$, with minimal or YM coupling
- No LHC limits on the LQ model

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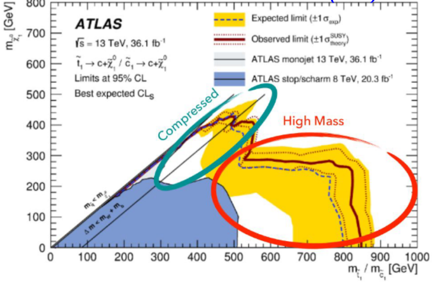
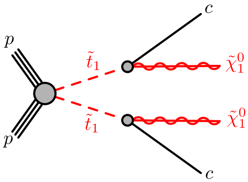
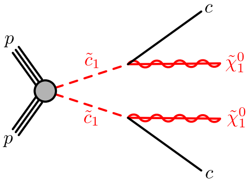
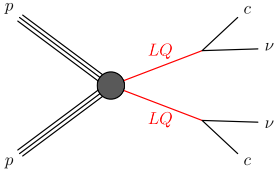


SUSY search with E_T^{miss} and c-jets: Introduction

CERN-EP-2024-218







- $DL1r$ to veto b-jets and tune $DL1r_c$ for 20% c-tag efficiency
- Object-based E_T^{miss} selection focusing on **High Mass** signal models
- *Recursive Jigsaw Reconstruction* selection, using ISR jet, for **Compressed** signal models
- **Orthogonality**: c-tagging of the leading jet

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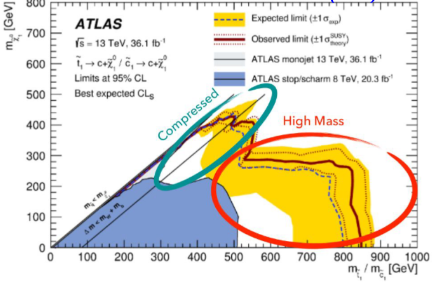

SUSY search with E_T^{miss} and c-jets: Background Estimation

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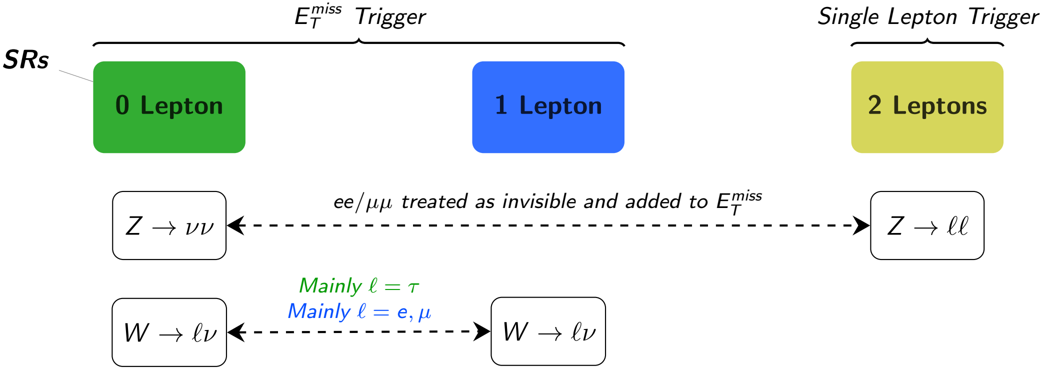

SUSY search with E_T^{miss} and c-jets: Results

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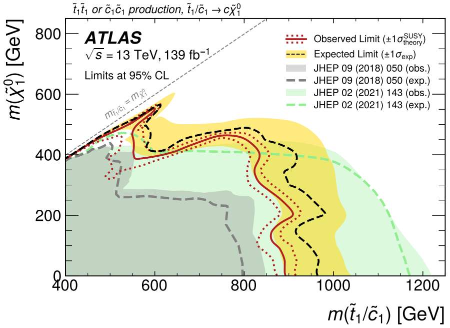

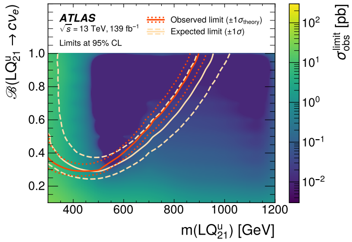

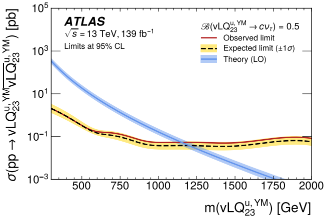

- No significant excesses observed over the expected SM backgrounds
- $m(t_1/c_1) \lesssim 900$ GeV for nearly massless $\tilde{\chi}_1^0$
- ~ 100 GeV more than previous effort
- Better results at compressed spectra wrt *single squark production search* w/o c-tagging

Scalar (Vector) LQ masses excluded up to ~ 0.900 (1.15) TeV

Conclusion

- 4 recent results using full Run 2 dataset have been presented:
  - Strong production of top squarks motivated by RPV/RPC SUSY
  - ML-based approaches being largely used for several tasks, i.e. object reconstruction, identification, S/B discrimination
  - New signature being explored using II generation squarks
- No significant excess over SM backgrounds. Several exclusion limits in place:
  - Top squarks pair production cross-section
  - Top squarks branching ratios
  - Interpretations in DM and LQ models

Many full Run 2 results already public and Run 3 analyses

Backup

RPV $\tilde{t} \to b\ell$: Upper Limits

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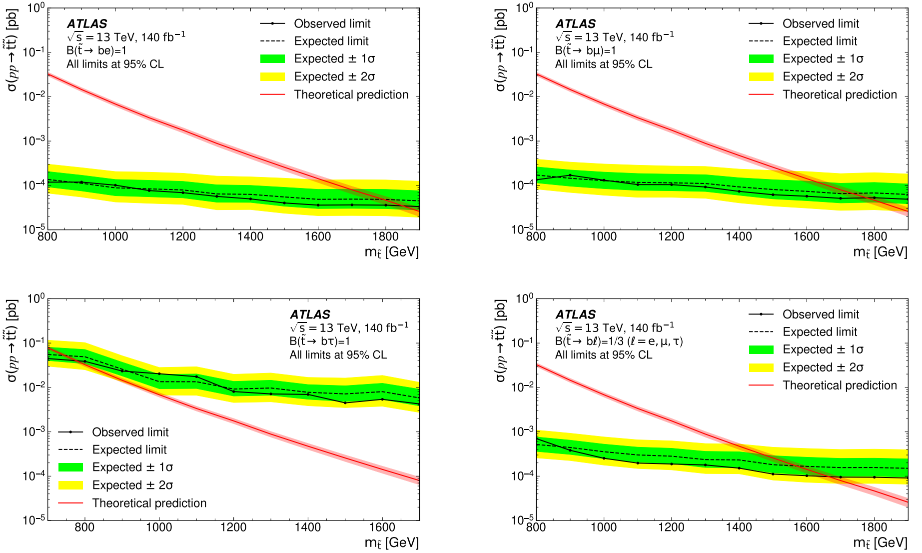

Stop to top and E_T^{miss} - 1L: DM Combination

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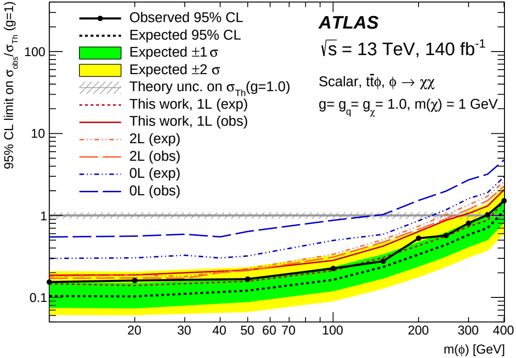

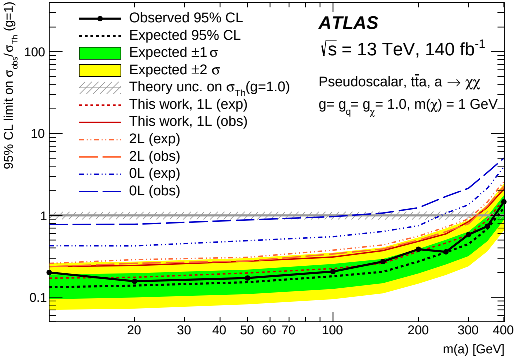

$\tilde{t}_1 \rightarrow (t/c) + \tilde{\chi}_1^0$: SRs

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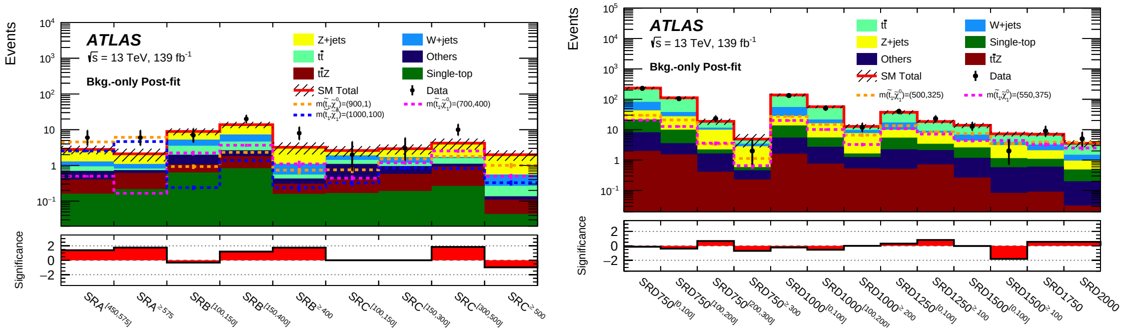

SUSY search with E_T^{miss} and c-jets: VRs/SRs

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