Searches for direct pair production of third generation squarks with the ATLAS detector

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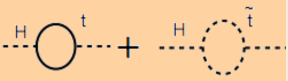
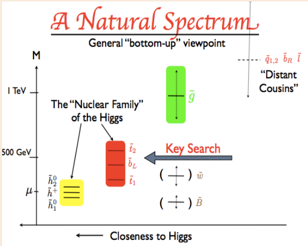
3^{rd} gen. searches and its motivations

SUSY is an elegant theory that aims to explain physics beyond the Standard Model

$\tilde{t}$ is the main contributor to the Higgs' mass regularization

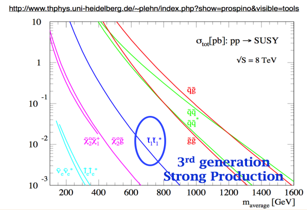


Naturalness motivations + exp. exclusions $\Rightarrow$ relatively light $\tilde{t}, \tilde{b}$, heavy $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$



L. Hall (LBL Workshop, 21-Oct11)

At $\sqrt{s} = 8$ TeV with 21 fb^{-1} of data, ATLAS is getting more and more sensitive to 3rd generations squarks direct production



3^{rd} *generation sparticles*

The focus of this talk are the ATLAS searches for SUSY partners of top and bottom quarks (stop, sbottom) direct production.

sbottom $\tilde{\mathbf{b}}_1$

- $\tilde{b}_1 \rightarrow b\tilde{\chi}^0$
- $\tilde{b}_1 \rightarrow t\tilde{\chi}^\pm$
  $\hookrightarrow W\tilde{\chi}^0$

stop $\tilde{\mathbf{t}}_1$

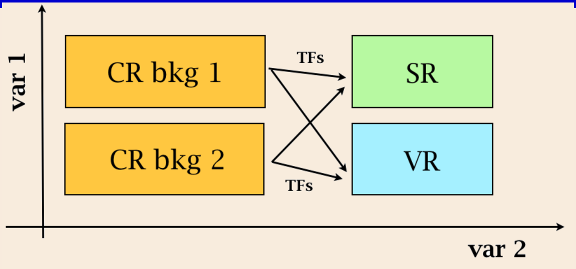
- $\tilde{t}_1 \rightarrow t\tilde{\chi}^0$
- $\tilde{t}_1 \rightarrow b\tilde{\chi}^\pm$
  $\hookrightarrow W\tilde{\chi}^0$

For all analysis: (unless otherwise stated)

- R parity conserving decays
- simplified models:
  - particles' unknown masses are free parameters
  - each decay is assumed with 100% BR

- $\tilde{\chi}^0$ detected as $E_{\mathrm{T}}^{\mathrm{miss}}$
- 0 - 1 - 2 leptons allow access to different final kinematics
- Many parameters ($m_{\tilde{t}}$, $m_{\tilde{b}}$, $\Delta m(\tilde{\chi}^\pm, \tilde{\chi}^0)$, $\Delta m(\tilde{t}/\tilde{b}, \tilde{\chi}^\pm/\tilde{\chi}^0)$, $\tilde{t}$ chirality) determine the kinematics of the final state.

General SUSY search strategy



All analyses are made of few common steps:

1. Definition of a set of Signal Regions (SR)
2. Definition of a set of Control Regions (CR), estimate MC norm from data in CR.
3. Estimation the bkg. norm. CR→SR with *transfer factors* (TF)
4. Validation of the TF in the Validation Region (VR)
5. Unblinding → check whether an excess is observed (p-value calculation)
6. If no excess is found the results are interpreted in terms of limits on selected models.

Selections for 3 SRs

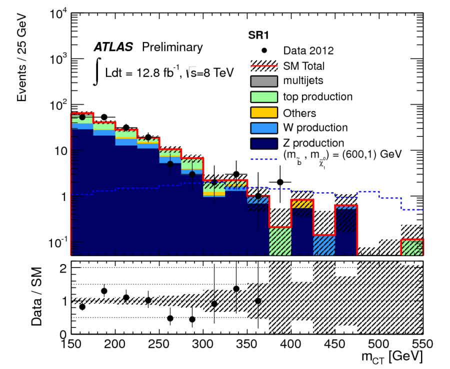
- exactly 2 leading jets b-tagged (high $\Delta m(\tilde{b}, \tilde{\chi}^0)$)
- tightening cuts of con-transverse mass m_{CT}[1]

- hard ISR (anti-tagged) jets + 2 softer b-jets (low Δm)

$2\,b + E_T^{miss}$ signature

$\tilde{b} \rightarrow b\tilde{\chi}^0$

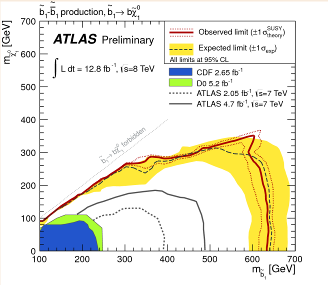
(re-interpreted for $\tilde{t} \rightarrow b\tilde{\chi}^{\pm}$)



Backgrounds		**Strategy**
$Z(\nu\nu)$+HF	$\rightarrow$	2 L ($ee/\mu\mu$)) CR
dileptonic $t\bar{t}$	$\rightarrow$	1/2 L ($e\mu$) CR
W+HF	$\rightarrow$	1 lep CR
Multi-jet	$\rightarrow$	data-driven

[1] $m_{CT}^2(\nu_1, \nu_2) = |E_T(\nu_1) + E_T(\nu_2)|^2 - |\vec{p}_T(\nu_1) - \vec{p}_T(\nu_2)|^2$

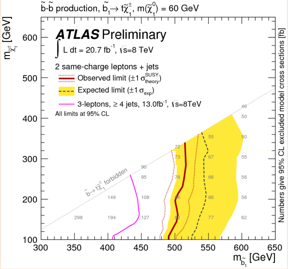
Summary of sbottom searches

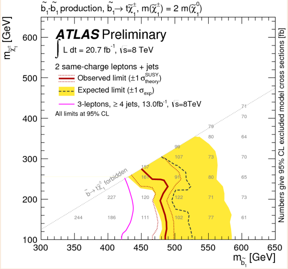


Legend:

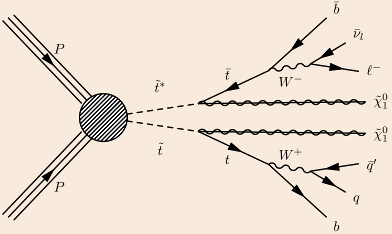
Up: $\tilde{b} \to b\tilde{\chi}^0$
0L bb + $E_{\mathrm{T}}^{\mathrm{miss}}$
(ATLAS-CONF-2012-165)

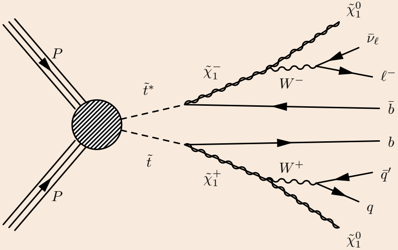
Down: $\tilde{b} \to t\tilde{\chi}^{\pm}$
2 Same Sign lep
(ATLAS-CONF-2013-035)





Looking for stop





- 0 L + $E_{\mathrm{T}}^{\mathrm{miss}}$(focus on $\tilde{t} \to t\chi^0$ [2])
  ATLAS-CONF-2013-024
- 1 L + ($\geqslant$ 4) jets (1/2 bjets) + $E_{\mathrm{T}}^{\mathrm{miss}}$
  ATLAS-CONF-2013-037
- 2 L + $E_{\mathrm{T}}^{\mathrm{miss}}$(focus on $\tilde{t} \to b\chi^{\pm}$)
  ATLAS-CONF-2012-167
- 2L(3L)+b-jets+$E_{\mathrm{T}}^{\mathrm{miss}}$($\tilde{t}_2\tilde{t}_2$ prod. $\tilde{t}_2 \to Z\tilde{t}_1$, $\tilde{t}_1 \to t\tilde{\chi}^0$)
  ATLAS-CONF-2013-025

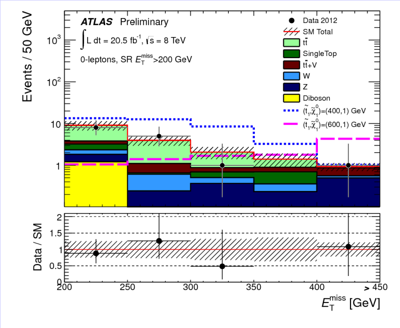
[2] 0 L $\tilde{t} \to b\chi^{\pm}$ results can be found in *ATLAS-CONF-2013-001*

0L $\tilde{t} \to t\chi^0$

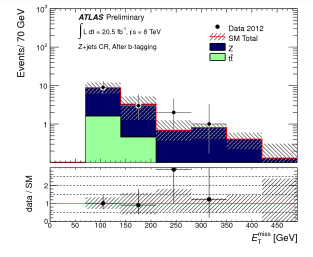
ATLAS-CONF-2013-024 - 21 fb^{-1}

0L Strategy

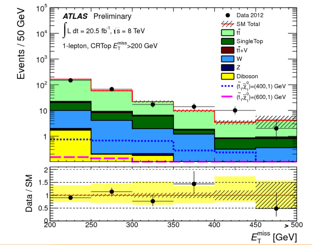
- → 1 CR per main background ($t\bar{t}$, $Z(\nu\nu)$+jets, Multi-jets)
- → reconstruct the top mass, 2-bjets
- → dedicated Multi-jets rejection cuts
- → **Final discrimination: $E_{\mathrm{T}}^{\mathrm{miss}}$**



Z+jet CR



Semi-leptonic $t\bar{t}$ CR (1L)



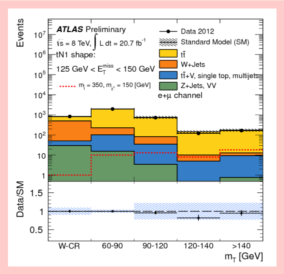
1L $\tilde{t} \to t\chi^0$

ATLAS-CONF-2013-037 - 21 fb^{-1}

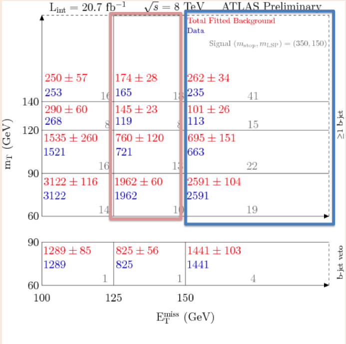
1L Strategy

- → 1 CR per main background ($t\bar{t}$, W+jets)
- → 2 1-bin SRs defined by few discriminating variables: am_{T2} , m^{τ}_{T2}, m_t
- → exploit shape fit for small $\Delta m(\tilde{t}, t)$

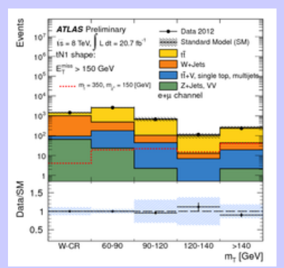
Shape-Fit $125 < E_T^{\mathrm{miss}} < 150$ GeV



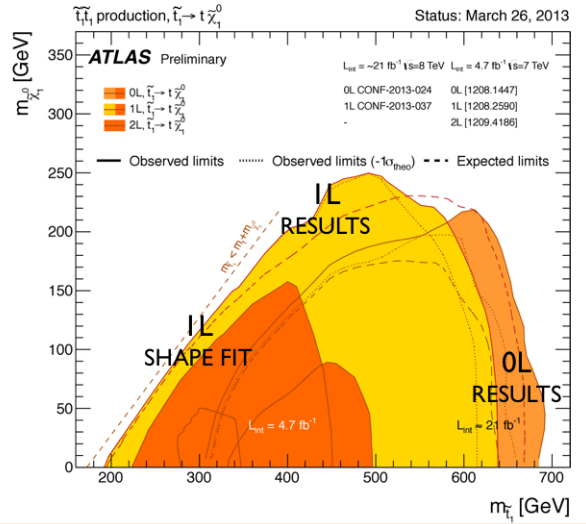
Shape-Fit for $m(\tilde{t}) \gtrsim m_{top}$ region



Shape-Fit $E_T^{\mathrm{miss}} > 150$ GeV



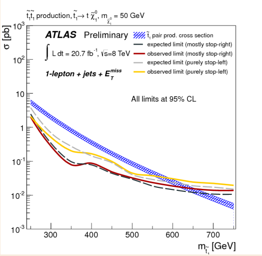
Summary of $\tilde{t} \to t\chi^0$



Assumptions:

- 100% BR
- mostly right-handed stop.

1L results:



Assumption: L-R stops
$m(\chi^0) = 50$ GeV
0L results are not significantly affected.

$\tilde{t} \rightarrow b\tilde{\chi}^{\pm},\ \tilde{\chi}^{\pm} \rightarrow W^{(*)}\tilde{\chi}^{0}$

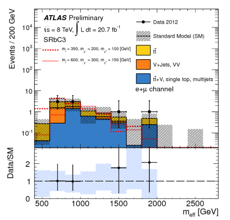
Additional free parameter ($m(\tilde{\chi}^{\pm})$):

Assumption	*Motivation*	*analyses*
$m(\tilde{\chi}^{\pm}) = 2m(\tilde{\chi}^{0})$	gaugino universality	1/2 lep
$m(\tilde{t}) - m(\tilde{\chi}^{\pm}) = 10$ GeV	mass degeneracy	2 lep
$m(\tilde{\chi}^{\pm}) - m(\tilde{\chi}^{0}) = 5/10/20$ GeV	natural scenario (higgsino-like $\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_1^{0}$)	0 lep (2b+$E_{\mathrm{T}}^{\mathrm{miss}}$)
$m(\tilde{\chi}^{\pm}) = 150$ GeV	fixed chargino mass (above LEP limit)	1 lep
$m(\tilde{\chi}^{0}) \sim 0$	massless neutralino	2 lep

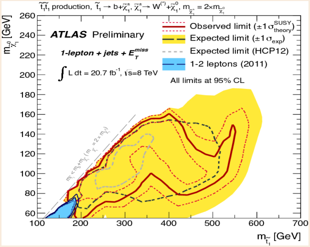
$\tilde{t} \to b\tilde{\chi}^{\pm},\ \tilde{\chi}^{\pm} \to W^{(*)}\tilde{\chi}^0$

1L Strategy

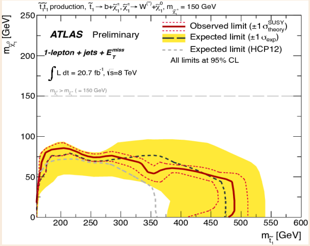
- → top CR / W CR
- → 2 b-jets / tight b-jet p_T
- → $m_{\rm eff}$, aM_{T2} (vs had-τ top)
- → 3 SRs - loose, tight, very tight to address different mass ranges



Interpretation: $m(\tilde{\chi}^{\pm}) = 2m(\tilde{\chi}^0)$



Interpretation: $m(\tilde{\chi}^{\pm}) = 150$ GeV

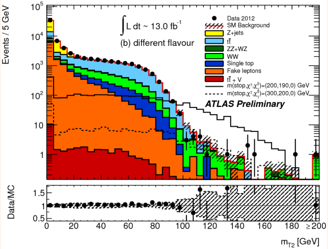


$\tilde{t} \to b\tilde{\chi}^{\pm},\ \tilde{\chi}^{\pm} \to W^{(*)}\tilde{\chi}^{0}$

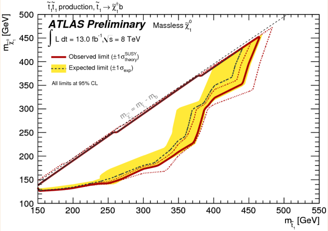
2L Strategy

- $\rightarrow$ 1 CR per $t\bar{t}$, WW and VZ
- $\rightarrow$ $\mathbf{p}_b^{\ell\ell} = \mathbf{p}^{\text{miss}} + \mathbf{p}_T^{\ell 1} + \mathbf{p}_T^{\ell_2}$ (boost of WW or $\tilde{\chi}^{+}\tilde{\chi}^{-}$ system)
- $\rightarrow$ **Final discrimination:** stransverse mass m_{T2}

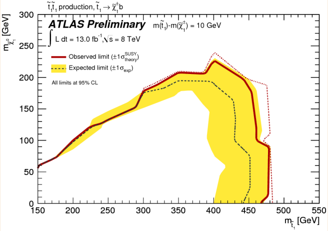
$e\mu$ stransverse mass



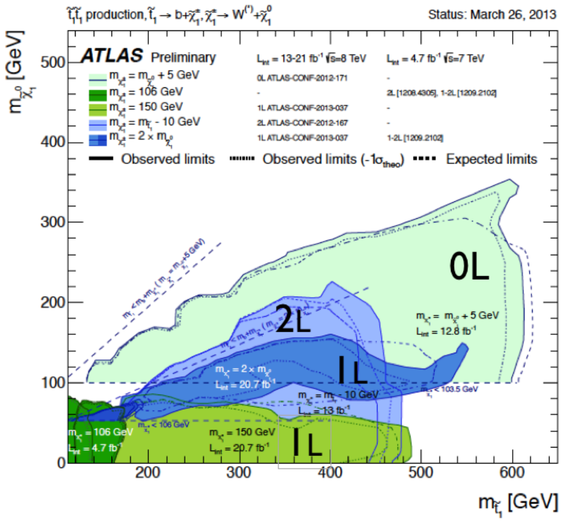
Interpretation: $m(\tilde{\chi}^0) \sim 0$



Interpretation: $m(\tilde{t})$ - $m(\tilde{\chi}^{\pm}) = 10$ GeV

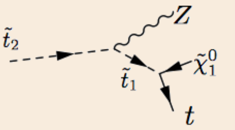


Summary of the $\tilde{t} \to b\tilde{\chi}^{\pm}$, $\tilde{\chi}^{\pm} \to W^{(*)}\tilde{\chi}^{0}$



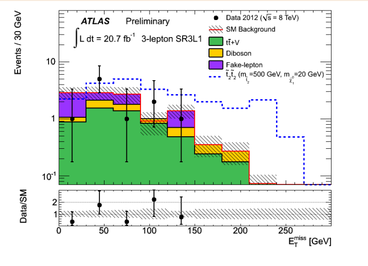
$\tilde{t}_2$ - Final states with Z
ATLAS-CONF-2013-025 - 21 fb^{-1}

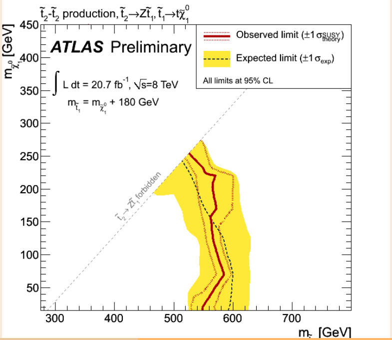
$\tilde{t}_2 \to Z\tilde{t}_1,\ \tilde{t}_1 \to t\tilde{\chi}^0$



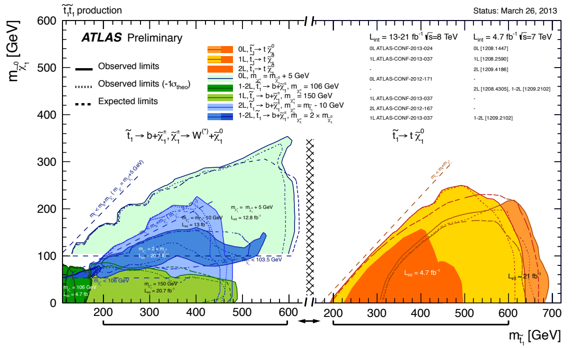
Strategy

- → 2/3 Leptons signatures
- → exploit Z mass and high boost
- → b-tag and high jet multiplicity (3,4,5)





No excess above SM prediction



1. Impressive results have been achieved in spanning the parameter space of 3^{rd} generation squarks direct production.

2. challenging signatures might still hide in these 21 fb^{-1} of data.

3. and if nothing is found, still, we will look forward to LHC running at design $\sqrt{s}$!

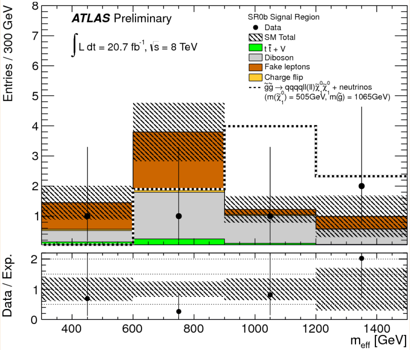
Thank you

BACKUP

Signal Regions based on

- jet and b-jet multiplicity
- m_T lepton - $E_{\mathrm{T}}^{\mathrm{miss}}$
- $E_{\mathrm{T}}^{\mathrm{miss}}$ and effective mass (m_{eff})

Signal region	$N_{\mathrm{b-jets}}$	Signal cuts (discovery case)	Signal cuts (exclusion case)
SR0b	0	$N_{\mathrm{jets}} \geq 3$, $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV	$N_{\mathrm{jets}} \geq 3$, $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, $m_{\mathrm{T}} > 100$ GeV,
		$m_{\mathrm{T}} > 100$ GeV, $m_{\mathrm{eff}} > 400$ GeV	binned shape fit in m_{eff} for $m_{\mathrm{eff}} > 300$ GeV
SR1b	≥ 1	$N_{\mathrm{jets}} \geq 3$, $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV	$N_{\mathrm{jets}} \geq 3$, $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, $m_{\mathrm{T}} > 100$ GeV,
		$m_{\mathrm{T}} > 100$ GeV, $m_{\mathrm{eff}} > 700$ GeV	binned shape fit in m_{eff} for $m_{\mathrm{eff}} > 300$ GeV
SR3b	≥ 3	$N_{\mathrm{jets}} \geq 4$	$N_{\mathrm{jets}} \geq 5$,
		-	$E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV or $m_{\mathrm{T}} < 100$ GeV

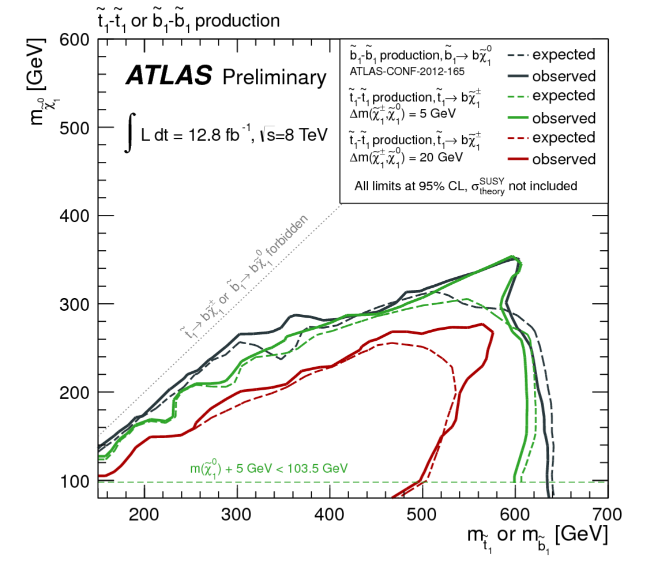


$bb+E_T^{miss}$ SR definition

ATLAS-CONF-2012-165/ATLAS-CONF-2012-001

Description	Signal region			
	SR1	SR2	SR3a	SR3b
Trigger	E_T^{miss} trigger $> 99\%$ efficient for $E_T^{miss} > 150$ GeV			
Event cleaning	Common to all SR			
Lepton veto	No e/μ with $p_T > 10$ GeV			
E_T^{miss}	> 150 GeV	> 200 GeV	> 150 GeV	> 250 GeV
Leading jet $p_T(j_1)$	> 130 GeV, $\|\eta\| < 2.8$	> 60 GeV, $\|\eta\| < 2.8$	> 130 GeV, $\|\eta\| < 2.8$	> 150 GeV, $\|\eta\| < 2.8$
Second jet $p_T(j_2)$	> 50 GeV, $\|\eta\| < 2.8$	> 60 GeV, $\|\eta\| < 2.8$	> 30 GeV, < 110 GeV, $\|\eta\| < 2.8$	
Third jet $p_T(j_3)$	veto event if $p_T(j_3) > 50$ GeV, $\|\eta\| < 2.8$		> 30 GeV, $\|\eta\| < 2.8$	
$\Delta\phi(E_T^{miss}, j_1)$	-		> 2.5	
jet b-tagging ($\|\eta\| < 2.5$)	j_1 and j_2 tagged		j_1 anti-tagged, j_2 and j_3 tagged	
$\Delta\phi_{min}(n)$	> 0.4 ($n = 2$)		> 0.4 ($n = 3$)	
$E_T^{miss}/m_{eff}(j_1, j_2, j_3)$	> 0.25			
m_{CT}	$> 150, 200, 250, 300$ GeV	> 100 GeV	-	
$H_{T,x}$	-	< 50 GeV, $x = 2$	< 50 GeV, $x = 3$	

$bb+E_T^{miss}$ SR definition
ATLAS-CONF-2012-001



0L $\tilde{t} \to t\chi^0$

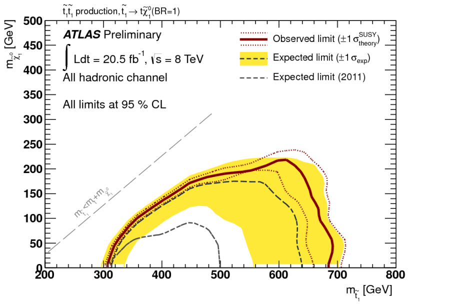
ATLAS-CONF-2013-024 - 21 fb^{-1}

	Signal	**$t\bar{t}$ CR**	**Z+jets CR**	**Multijet CR**
Trigger	E_T^{miss}	single electron (muon)	two electron (muon)	E_T^{miss}
N_{lep}	0	1	2	0
p_T^{ℓ}	< 10 (10)	> 35 (35)	> 20 (20)	< 10 (10)
$p_T^{\ell_2}$	—	< 10 (10)	> 20 (10)	—
$m_{\ell\ell}$	—	—	81 to 101	—
N_{jet}	≥ 6	≥ 6	≥ 6	≥ 6
p_T^{jet}	$> 80,80,35,...35$	$> 80,80,35,...35$	$> 80,80,35,...35$	$> 80,80,35,...35$
$N_{b\text{-jet}}$	≥ 2	≥ 2	≥ 2	≥ 2
m_{jjj}	80 to 270	0 to 600	80 to 270	—
E_T^{miss}	$> 200, 300, 350$	$> 200, 300, 350$	> 70	> 160
$E_T^{miss,track}$	> 30	> 30	> 30	> 30
$\Delta\phi(E_T^{miss}, E_T^{miss,track})$	$< \pi/3$	$< \pi/3$	$< \pi/3$	$> \pi/3$
$m_T(\ell, E_T^{miss})$	—	40 to 120	—	—
$\Delta\phi(\text{jet}, E_T^{miss})$	$> \pi/5$	$> \pi/10$	$> \pi/5$	$< \pi/5$
$m_T(b\text{-jet}, E_T^{miss})$	> 175	—	> 175	> 175
Tau veto	yes	no	yes	no

0L $\tilde{t} \to t\chi^0$
ATLAS-CONF-2013-024 - 21 fb^{-1}

Main Systematics:

Uncertainty	SR1	SR2	SR3
Total	18%	33%	45%
Background sample sizes	10%	17%	21%
Jet energy scale and res	10%	10%	25%
$t\bar{t}$ theory	10%	19%	22%
Z+jets theory	4%	8%	8%
$t\bar{t} + W/Z$ theory	5%	8%	10%



$\Rightarrow$ No excess seen, limits are extended.

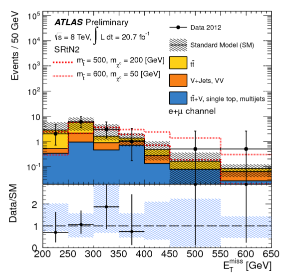
Limits on visible xsec, number of signal events and p-value

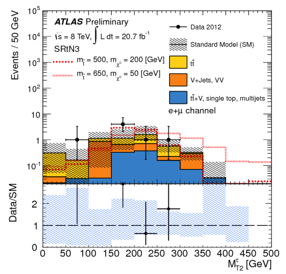
Signal region	$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$[fb]	S^{95}_{obs}	S^{95}_{exp}	CL_B
SR1	0.49	10.0	$10.6^{+5.5}_{-1.7}$	0.39
SR2	0.17	3.6	$5.3^{+3.2}_{-1.7}$	0.20
SR3	0.19	3.9	$4.5^{+1.9}_{-0.7}$	0.27

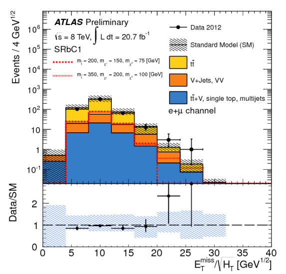
Requirement	SRtN1_shape	SRtN2	SRtN3	SRbC1	SRbC2	SRbC3
$\Delta\varphi(\mathrm{jet}_1, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) >$	0.8	-	0.8	0.8	0.8	0.8
$\Delta\varphi(\mathrm{jet}_2, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) >$	0.8	0.8	0.8	0.8	0.8	0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV] >	$100^{(\star)}$	200	275	150	160	160
$E_{\mathrm{T}}^{\mathrm{miss}} / \sqrt{H_{\mathrm{T}}}$ [GeV$^{1/2}$] >	5	13	11	7	8	8
m_{T} [GeV] >	$60^{(\star)}$	140	200	120	120	120
$\mathrm{m}_{\mathrm{eff}}$ [GeV] >	-	-	-	-	550	700
am_{T2} [GeV] >	-	170	175	-	175	200
m_{T2}^{τ} [GeV] >	-	-	80	-	-	-
m_{jjj}	Yes	Yes	Yes	-	-	-
$N^{\mathrm{iso-trk}} = 0$	-	-	-	Yes	Yes	Yes
Number of b-jets ≥	1	1	1	1	2	2
p_{T} (leading b-jet) [GeV] >	25	25	25	25	100	120
p_{T} (second b-jet) [GeV] >	-	-	-	-	50	90

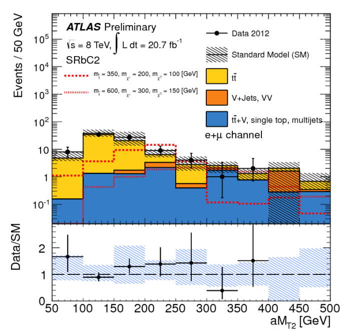
1L stop analysis

ATLAS-CONF-2013-037 - 21 fb^{-1}





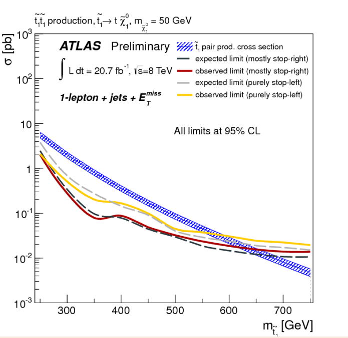




$\tilde{t} \to t\chi^0$: *different assumptions*

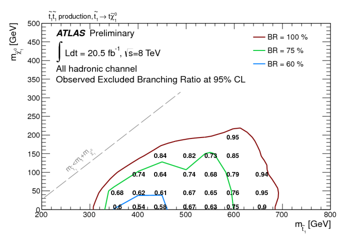
Chirality:

cross section limit for left or right-handed stop



Assumption: $m(\chi^0) = 50$ GeV

1L results. 0L are not significantly affected.



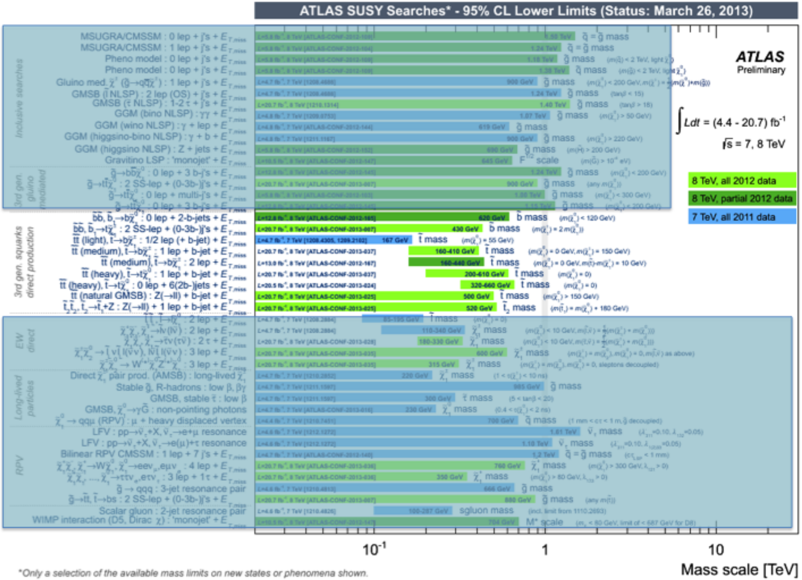
Branching Ratio:

vary the stop BR in $t\chi^0$

0L results

Assumption: other decay modes are

Outlook and perspectives



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Stop - Final states with Z
ATLAS-CONF-2013-025

No excess above SM prediction

$\tilde{t}_2\tilde{t}_2$ prod. $\tilde{t}_2 \to Z\tilde{t}_1$, $\tilde{t}_1 \to t\tilde{\chi}^0$

	SR2L1A	SR2L1B	SR2L2	SR3L1	SR3L2
N^{lepton}	2			≥ 3	
$\lvert m_{\ell\ell} - m_Z \rvert$	< 5 GeV	< 10 GeV	< 5 GeV	< 10 GeV	
$N^{b\text{-jets}}$	≥ 1			≥ 1	
N^{jets}	3, 4		≥ 5	≥ 5	
$p_T(\text{jet}_1)$	> 30 GeV			> 50 GeV	> 40 GeV
$p_T(\text{jet}_N)$	> 30 GeV			> 30 GeV	> 40 GeV
E_T^{miss}	> 160 GeV	> 200 GeV	> 160 GeV	> 60 GeV	
$p_T(\ell\ell)$	> 80 GeV	> 160 GeV	> 80 GeV	-	> 75 GeV
$\Delta\phi^{\ell\ell}$	< 1.5 rad			-	
$p_T(\ell_1)$	> 25 GeV			> 40 GeV	> 60 GeV