Searches for third generation squarks with the ATLAS detector

Martin White

ATLAS Experiment

ICHEP2012 Melbourne

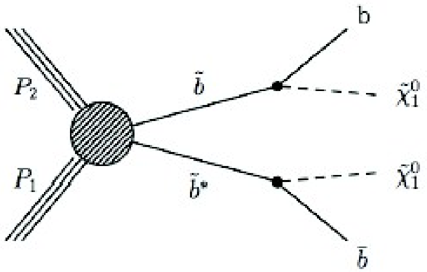
THE UNIVERSITY OF MELBOURNE

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

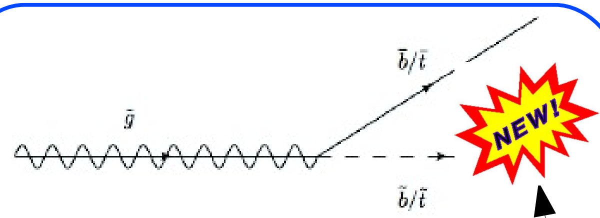
- Supersymmetric particle production was *not* an early LHC discovery

  - if all squarks are similar in mass, this raises limits on the squark masses
  - *a priori*, this is by no means a fair assumption however
  - SUSY with a light third generation is well motivated, but dedicated searches are required

- ATLAS has performed a variety of searches sensitive to third generation squark production



direct sbottom production (2 fb^{-1})

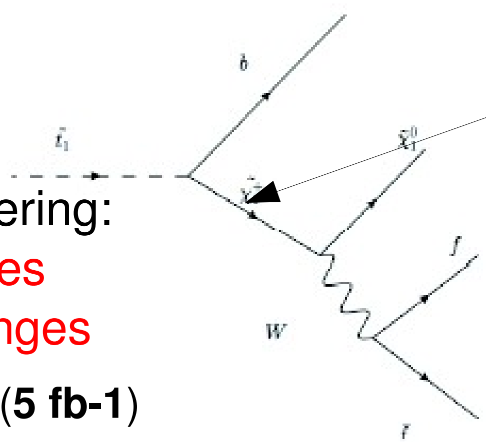


gluino mediated stop/sbottom production (**5 fb**$^{-1}$)

$$\tilde{t}_1 \rightarrow b\tilde{\chi}^+ \text{ or } \tilde{t}_1 \rightarrow t\tilde{\chi}^0_{1(2)}$$
$$\tilde{\chi}^\pm_1 \rightarrow \tilde{\chi}^0_1 f f'$$
$$\tilde{\chi}^0_1 \rightarrow Z\tilde{G}$$

Direct stop pair production In GMSB scenario (2fb^{-1})

- Several searches covering:
  - different final states
  - different mass ranges



direct stop production (**5 fb-1**)

- Main focus of the next 15 minutes

multijet search (5 fb-1) (arxiv:1206.1760)

Same sign dilepton (2 fb-1)(Phys. Rev. Lett. 108, 241802

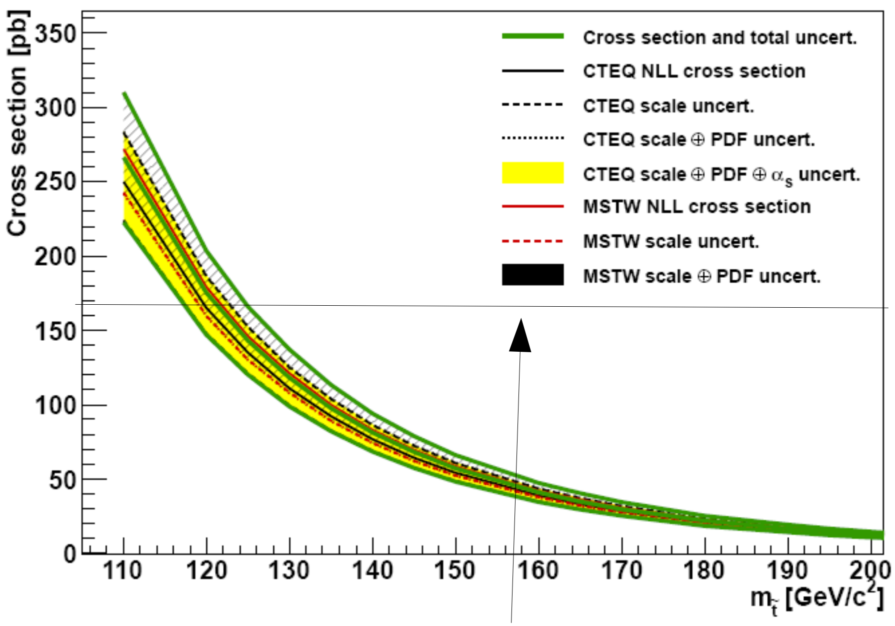
0/1 lepton + 1/2 b (2 fb^{-1}) (Phys. Rev. D 85, 112006)

Direct stop production

- The stop cross section falls rapidly with increasing stop mass

  - dedicated searches must concentrate on reducing the large top background
  - stop pair production cross-section is smaller due to differing spin

- There is a rich variety of decay modes, though the final states are often similar



Top pair production cross section

NEW ATLAS 5 fb^{-1} results (direct stop)

- Stop → b chargino (for m (stop) < 200 GeV)
  - very light stop search (2 leptons)
  - m(stop) ~ m(top) (1 and 2 lepton(s))

- Stop → t neutralino (for m (stop) > 200 GeV)

  - both tops decay hadronically (0 lepton)
  - one top decays leptonically (1 lepton)
  - both tops decay leptonically (2 leptons)

- Let's review the latest ATLAS results in order of increasing stop mass...

Light stop analysis

- Search for stops with m(stop) << m(top) in the dilepton final state

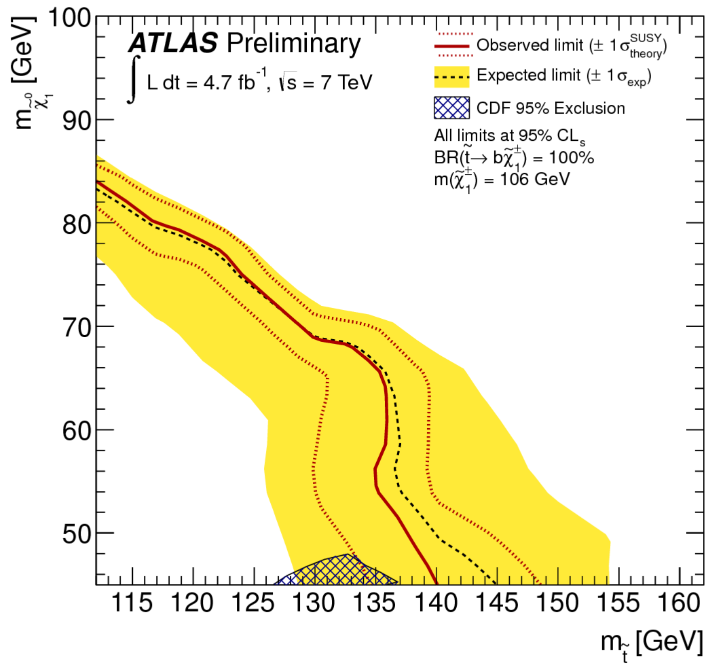
$$m(t) > m(\tilde{t}_1) > m(\tilde{\chi}_1^\pm)$$

$$\tilde{t}_1 \to b\tilde{\chi}_1^\pm$$
$$\tilde{\chi}_1^\pm \to W^{(*)}\tilde{\chi}_1^0$$

- Look for:
  - two low p_T leptons, veto on leptons with high p_T
  - no b jet requirement

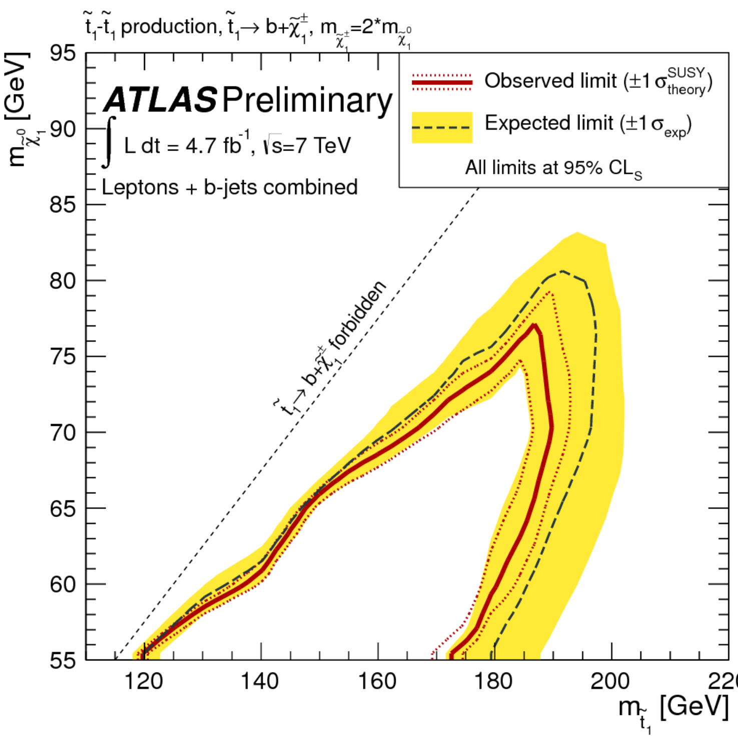
- Background estimation:
  - semi-data-driven estimate using top and Z/γ^* control regions

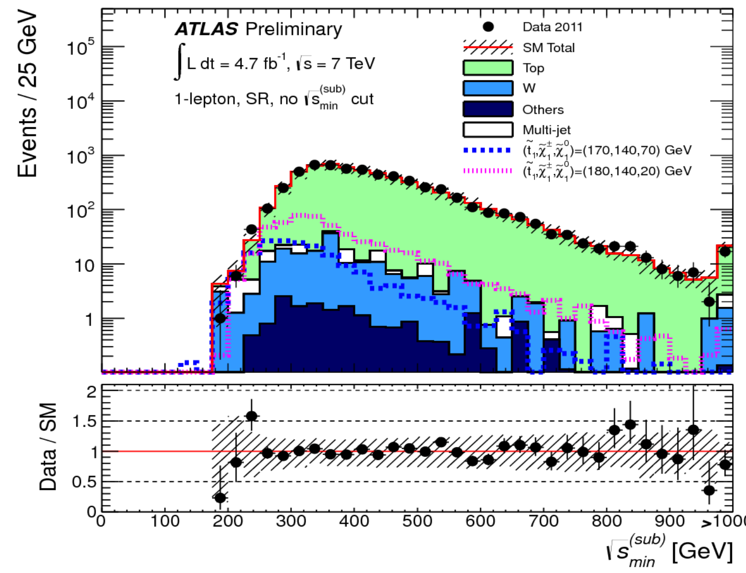
- Dominant systematics: jet energy scale, jet energy resolution, theory errors on top estimate



	ee	$e\mu$	$\mu\mu$	all
Total	$61 \pm 6 \pm 6$	$189 \pm 8 \pm 21$	$190 \pm 19 \pm 31$	$440 \pm 21 \pm 43$
Data	48	188	195	431
σ_{vis} (exp. limit) [fb]	4.9	11.1	16.2	22.0
σ_{vis} (obs. limit) [fb]	3.3	10.9	16.9	21.0

- 1 and 2 lepton analysis looking for stop → b chargino, with m(stop) ~ m(top)
- Use b tagging, place upper cut on a new variable $\sqrt{s}_{min}^{(sub)}$
- Main backgrounds are top, W (1 lepton) and Z (2 lepton)



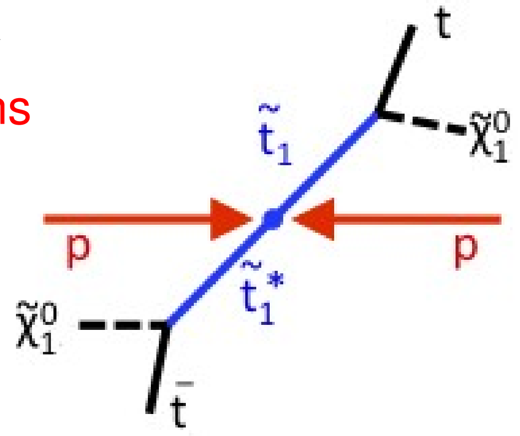


Process	1LSR	2LSR1	2LSR2
Top	$24 \pm 3 \pm 5$	$89 \pm 6 \pm 10$	$36 \pm 2 \pm 5$
W+jets	$6 \pm 1 \pm 2$	n/a	n/a
Z+jets	$0.5 \pm 0.3 \pm 0.3$	$11 \pm 4 \pm 3$	$3 \pm 1 \pm 1$
Fakes	$7 \pm 1 \pm 2$	$12 \pm 5 \pm 11$	$6 \pm 4 \pm 4$
Others	$0.3 \pm 0.1 \pm 0.1$	$2.7 \pm 0.9 \pm 0.7$	$0.9 \pm 0.2 \pm 0.5$
Total SM	$38 \pm 3 \pm 7$	$115 \pm 8 \pm 15$	$46 \pm 4 \pm 7$
Data	50	123	47
$m_{\tilde{t}_1}$ = 170 GeV, $m_{\tilde{\chi}_1^0}$ = 70 GeV	$30 \pm 4 \pm 10$	$70 \pm 7 \pm 9$	$44 \pm 5 \pm 7$
$m_{\tilde{t}_1}$ = 180 GeV, $m_{\tilde{\chi}_1^0}$ = 20 GeV	$18 \pm 3 \pm 5$	$53 \pm 5 \pm 5$	$37 \pm 4 \pm 6$
σ_{vis} (exp.) [fb]	4.2	9.7	5.3
σ_{vis} (obs.) [fb]	6.6	11	5.4

ATLAS-CONF-2012-070

2 lepton search

- Search for stops decaying to top quark, both tops decay leptonically
  - look for either same flavour (SF) or opposite flavour (OF) leptons

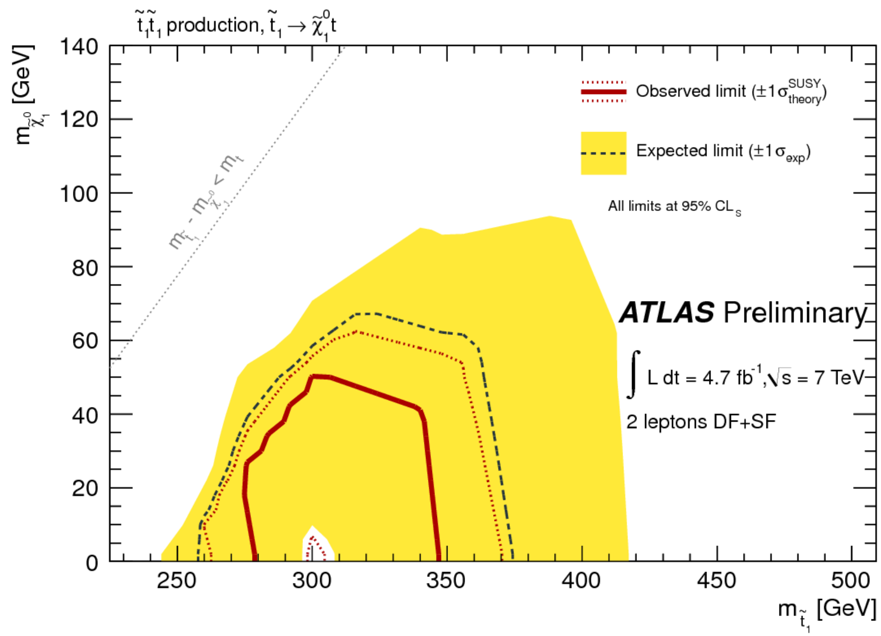


- Dilepton final state, m_{T2} used to suppress background

exactly 2 leptons
≥ 1 jet with p_T > 50 GeV
≥ 2 jets with p_T > 25 GeV
m_{T2} > 120 GeV
for same flavour candidates: 20 GeV < m_{ll} < 71 GeV or m_{ll} > 111 GeV
≥ 1 *b* jet

ATLAS-CONF-2012-071

	SF	DF
$Z/\gamma^\star$+jets	1.2 ± 0.5	-
($Z/\gamma^\star$+jets scale factor)	(1.27)	-
$t\bar{t}$	0.23 ± 0.23	0.4 ± 0.3
($t\bar{t}$ scale factor)	(1.21)	(1.10)
$t\bar{t}W + t\bar{t}Z$	0.11 ± 0.07	0.19 ± 0.12
WW	$0.01^{+0.02}_{-0.01}$	0.19 ± 0.18
$WZ + ZZ$	0.05 ± 0.05	0.03 ± 0.03
Wt	$0.00^{+0.17}_{-0.00}$	$0.10^{+0.18}_{-0.10}$
Fake leptons	$0.00^{+0.14}_{-0.00}$	$0.00^{+0.09}_{-0.00}$
Total SM	1.6 ± 0.6	0.9 ± 0.6
Signal, $m(\tilde{t}_1)$ = 300 GeV, $m(\tilde{\chi}_1^0)$= 50 GeV	2.15	3.73
Signal, m(T) = 450 GeV, $m(A_0)$= 100 GeV	3.10	5.78
Observed	1	2
95% CL limit on $\sigma_{\rm vis}^{\rm obs}$[fb]	0.86	1.08
95% CL limit on $\sigma_{\rm vis}^{\rm exp}$[fb]	0.89	0.79



1 lepton search

- Search for stops decaying to top quark, one top decays leptonically

ATLAS-CONF-2012-073

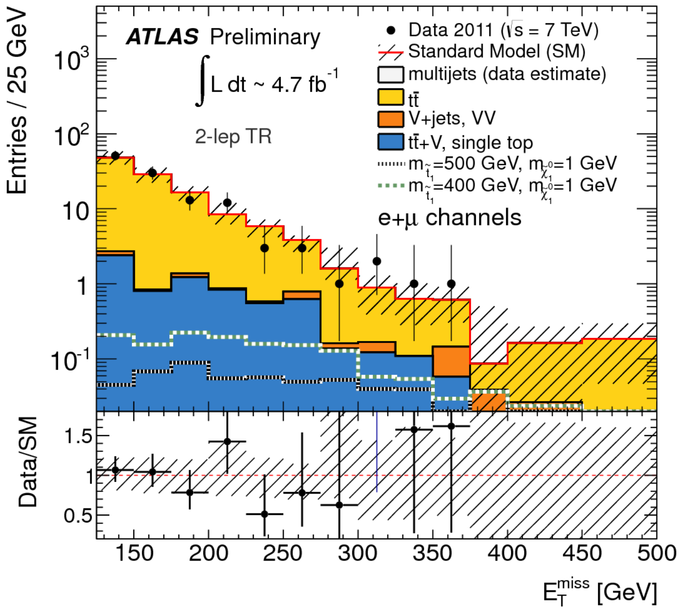
exactly 1 lepton
≥ 4 jets with p_T > 80, 60, 40,25 GeV
≥ 1 b jet
130 GeV < m_{jjj} < 205 GeV
Define 5 different signal regions using further cuts

Requirement	SR A	SR B	SR C	SR D	SR E
E_T^{miss} [GeV] >	150	150	150	225	275
$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] >	7	9	11	11	11
m_T [GeV] >	120	120	120	130	140

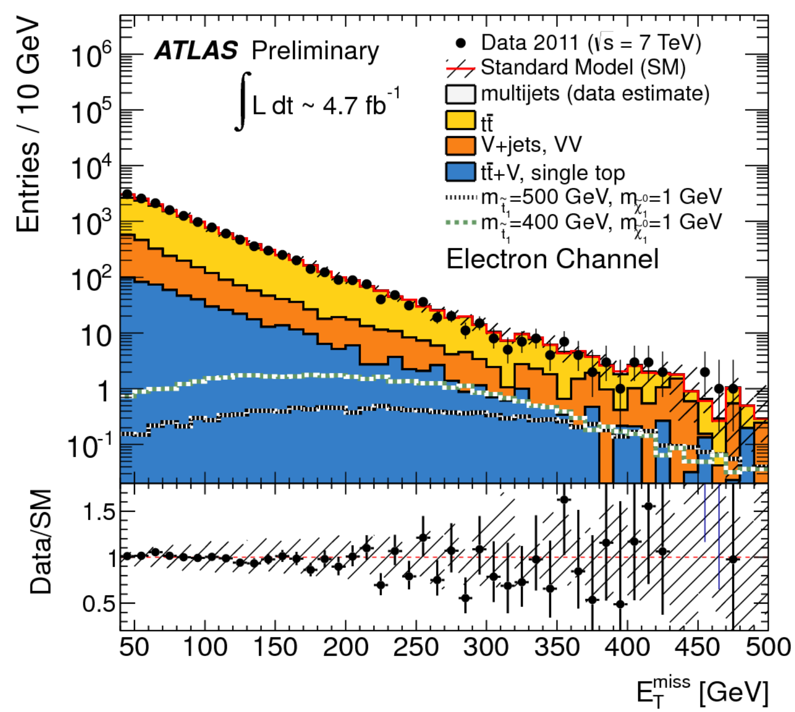
- Main backgrounds estimated using dedicated control regions

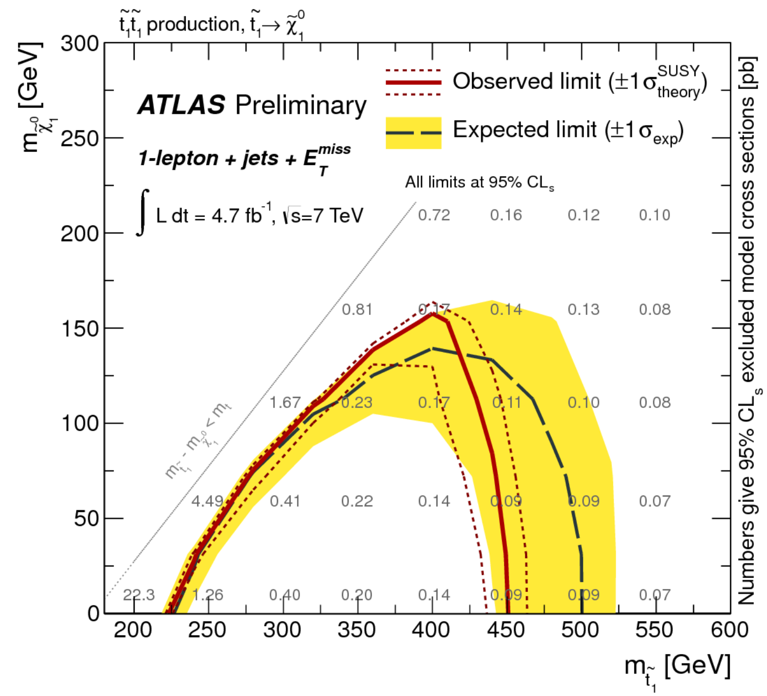
  - single leptonic ttbar, dileptonic ttbar and *W*+jets
  - simultaneous fit performed to all three control regions, plus one signal region at a time

- Main uncertainties are top theory uncertainties, JES, JER and *b*-tagging uncertainties



1 lepton search: Results





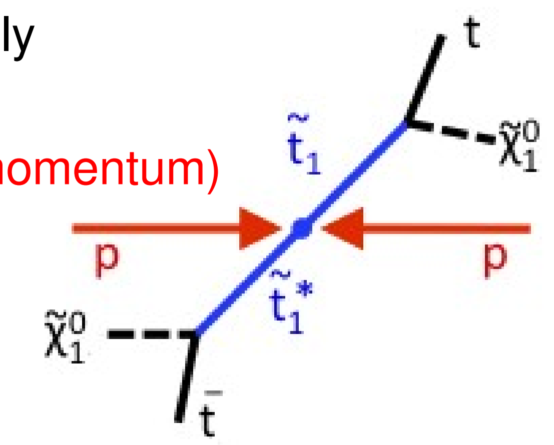
ATLAS-CONF-2012-073

- Exclude a wide range of stop masses

Regions	SR A	SR B	SR C	SR D	SR E	*2-lep TR*	*1-lep TR*	*1-lep WR*
Total background	42 ± 6	31 ± 4	13 ± 2	6.4 ± 1.4	1.8 ± 0.7	118 ± 10	421 ± 20	228 ± 15
Signal benchmark 1 (2)	25.6 (8.8)	23.0 (8.1)	17.5 (6.9)	13.5 (6.2)	7.1 (4.5)	1.7 (0.6)	2.3 (0.6)	0.4 (0.1)
Observed events	38	25	15	8	5	118	421	228
p_0-values	0.5	0.5	0.32	0.24	0.015	-	-	-
Obs. (exp.) $N_{\text{beyond-SM}} <$	15.1 (17.2)	10.1 (13.8)	10.8 (9.2)	8.4 (7.0)	8.2 (4.6)	-	-	-

0 lepton search

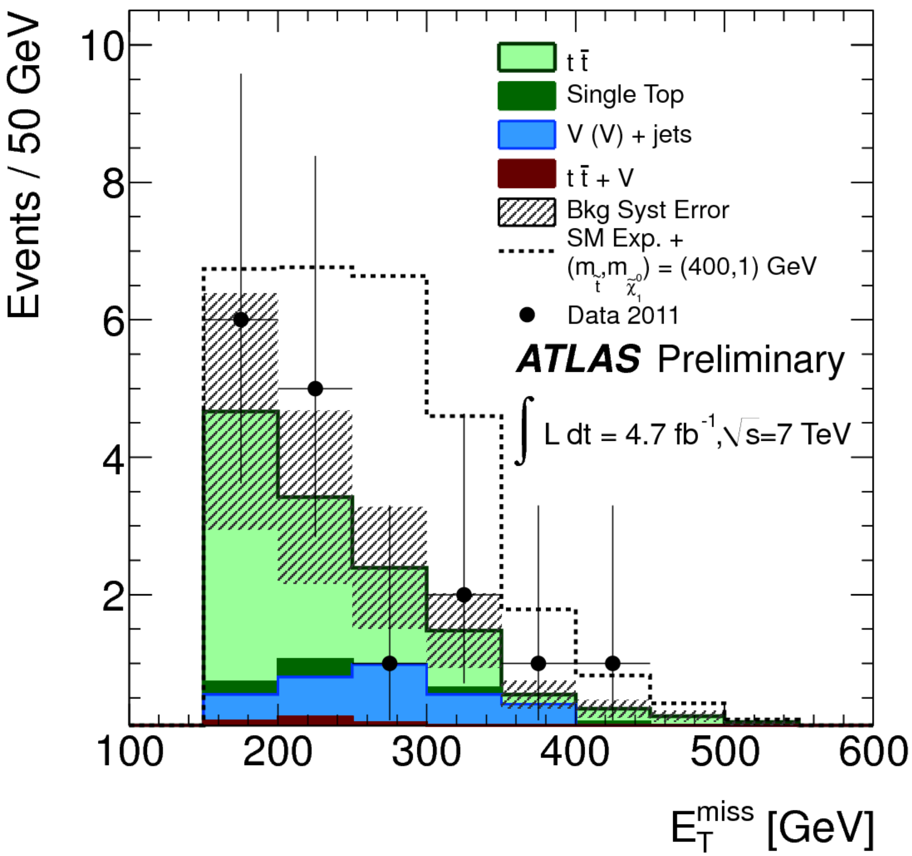
- Search for stops decaying to top quark, both tops decay hadronically
  - expect 6 high p_T jets
  - kinematic reconstruction of both tops is possible (no missing momentum)



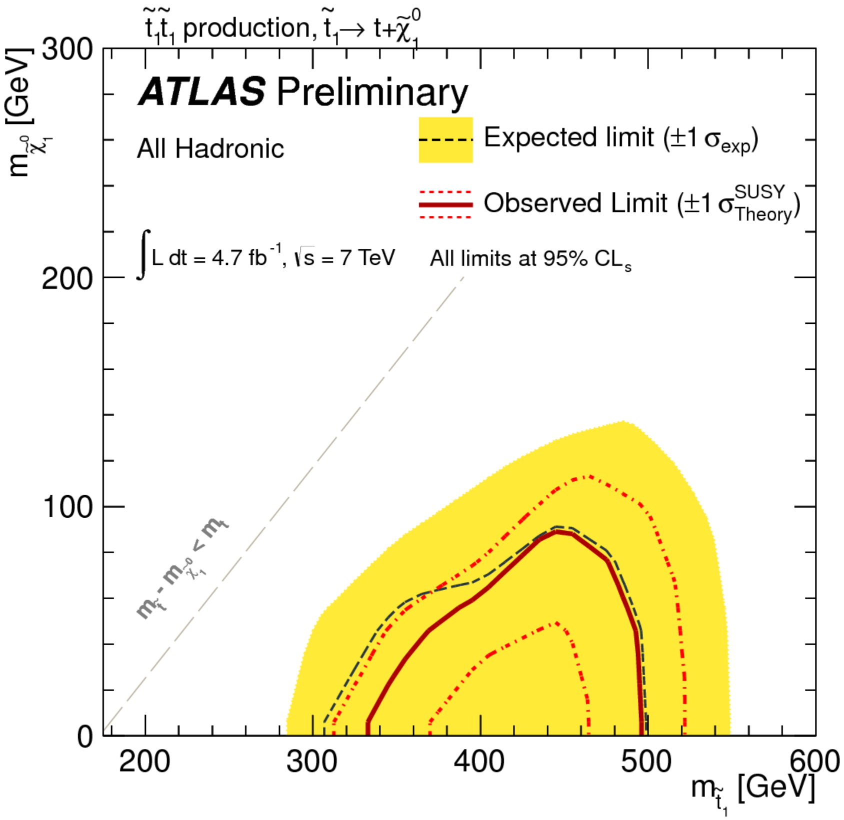
Selection Criteria	
1 tight b-tagged jet OR 2 loose b-tagged jets	
$E_T^{\text{miss,track}} > 30$ GeV and $\left|\Delta\phi\left(E_T^{\text{miss}}, E_T^{\text{miss,track}}\right)\right| < \frac{\pi}{3}$	
$\min\left|\Delta\phi\left(\text{jet}^{0-2}, E_T^{\text{miss}}\right)\right| > 0.2\,\pi$	
$80\text{ GeV} < m_{jjj}^0, m_{jjj}^1 < 270$ GeV	
Veto events with a τ candidate based on $m_T\left(\tau\text{ candidate}, E_T^{\text{miss}}\right)$	
Events with 1 tight b-tagged jet: $\min\left|m_T\left(\text{jet}^{0-3}, E_T^{\text{miss}}\right)\right| > 175$ GeV	
Events with 2 loose b-tagged jets: $m_T\left(b_{\min[\Delta\phi(b,E_T^{\text{miss}})]}, E_T^{\text{miss}}\right) > 175$ GeV	
Signal Region I	Signal Region II
$E_T^{\text{miss}} > 150$ GeV	$E_T^{\text{miss}} > 260$ GeV

ATLAS-CONF-2012-074

- Top background estimated using CR
- SM theory, jet energy scale and jet energy resolution are dominant uncertainties

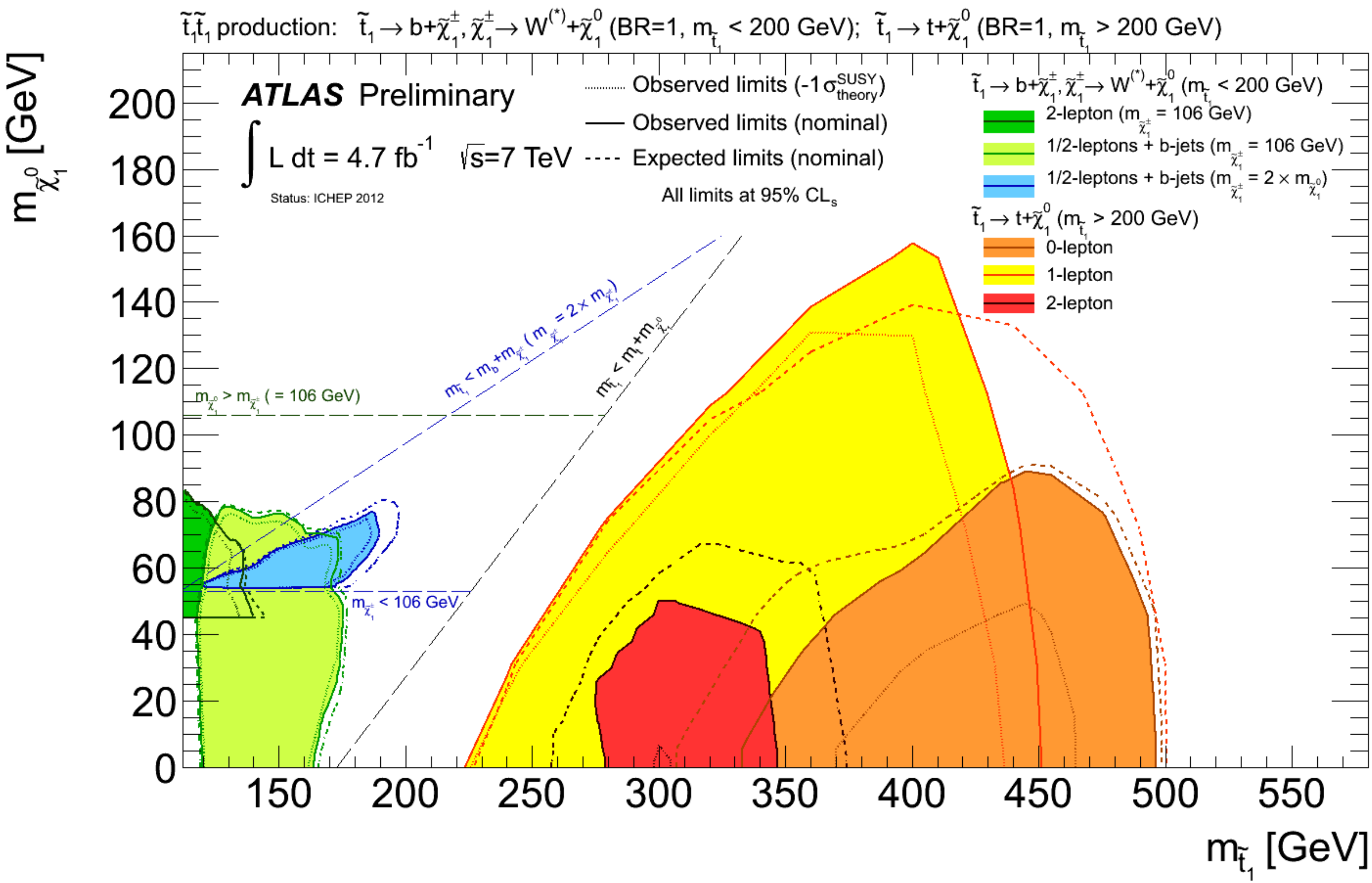


	SRA	SRB
E_T^{miss}	> 150 GeV	> 260 GeV
$t\bar{t}$	9.2 ± 2.7	2.32 ± 0.61
$t\bar{t} + W/Z$	0.8 ± 0.2	0.39 ± 0.12
Single top	0.7 ± 0.4	0.21 ± 0.28
Z+jets	1.3 ± 1.1	0.94 ± 0.75
W+jets	1.2 ± 1.3	0.48 ± 0.42
Multi-jets	0.2 ± 0.2	0.02 ± 0.02
Total SM	13.2 ± 4.9	4.4 ± 1.6
SUSY $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}) = (400, 1)$ GeV	14.8 ± 4.0	8.9 ± 3.1
Data (observed)	16	4



ATLAS-CONF-2012-074

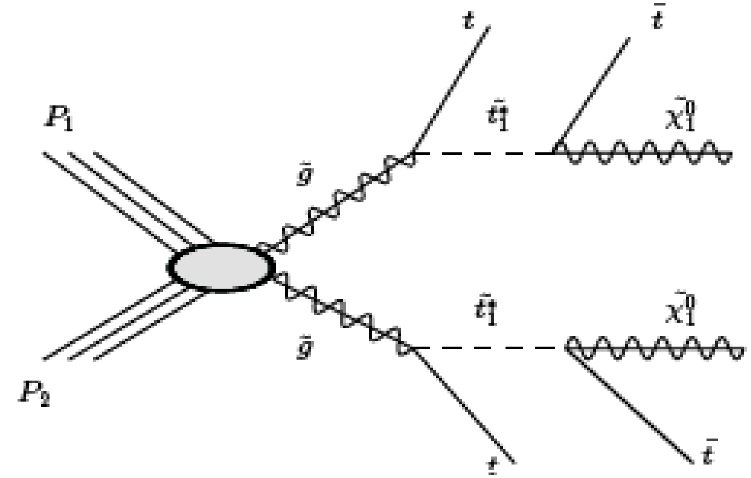
All exclusion limits on one plot



Gluino mediated stop/sbottom production

• Search for gluino mediated stop/sbottom production in the 0 lepton channel with 5 fb^{-1} of ATLAS data

Common criteria: lepton veto, $p_T^{j_1} > 130$ GeV, ≥ 3 b-jets, $E_{\mathrm{T}}^{\mathrm{miss}}/\mathrm{m}_{\mathrm{eff}} > 0.2$, $\Delta\phi_{\mathrm{min}} > 0.4$				
SR	N_J	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\mathrm{m}_{\mathrm{eff}}$	b-tag OP
SR4-L	≥ 4j	>160 GeV	>500 GeV	60%
SR4-M	≥ 4j	>160 GeV	>700 GeV	60%
SR4-T	≥ 4j	>160 GeV	>900 GeV	70%
SR6-L	≥ 6j	>160 GeV	>700 GeV	70%
SR6-T	≥ 6j	>200 GeV	>900 GeV	75%



• Multi-b jet final states enhance the sensitivity

• Various signal regions are optimised for a variety of pMSSM scenarios:

- models with both stop (or sbottom) production and gluino production
- models with the gluino lighter than all squarks, with gluino pair production only

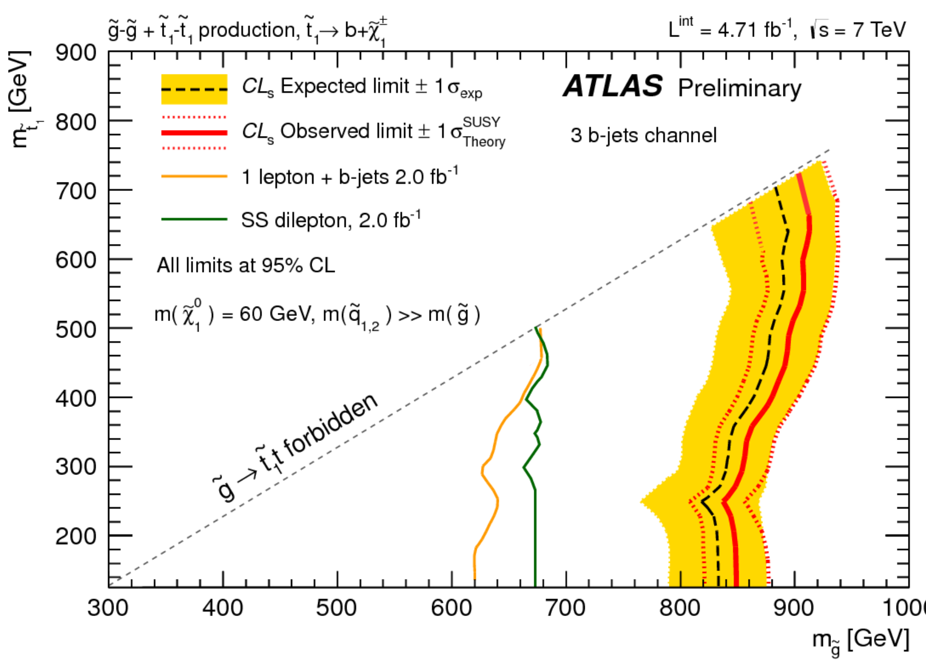
ATLAS-CONF-2012-058

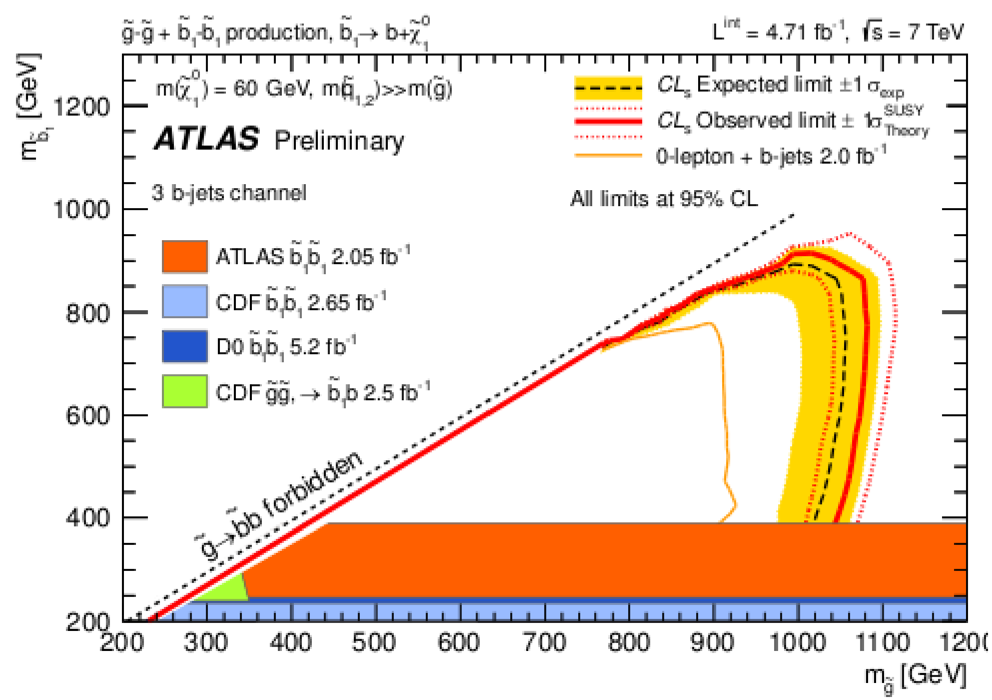
Gluino mediated stop/sbottom production: Results and Interpretation

- No evidence for BSM physics!
- 95% confidence limits are set using the CL_s prescription

ATLAS-CONF-2012-058

SR	$t\bar{t}$+jets (MC)	others	SM	data
SR4-L	33.3 ± 7.9 (32.6 ± 15.4)	11.1 ± 4.9	44.4 ± 10.0	45
SR4-M	16.4 ± 4.1 (16.1 ± 8.4)	6.6 ± 2.9	23.0 ± 5.4	14
SR4-T	9.7 ± 2.1 (11.4 ± 5.4)	3.8 ± 1.6	13.3 ± 2.6	10
SR6-L	10.3 ± 3.3 (10.0 ± 6.2)	2.4 ± 1.4	12.7 ± 3.6	12
SR6-T	8.3 ± 2.4 (7.9 ± 5.3)	1.6 ± 1.1	9.9 ± 2.6	8





Summary

- A variety of analyses targetting third generation squark production have been presented

  - most use 5 fb^{-1} of ATLAS data

- No analysis has shown evidence for BSM physics

  - further work to probe the remaining corners of phase space is ongoing

- Analyses are now turning their attention to the 2012 8 TeV data

  - much more to come!

Backup

Light stop analysis cuts

- Search for stops with m(stop) << m(top) in the dilepton final state

$$m(t) > m(\tilde{t}_1) > m(\tilde{\chi}_1^\pm)$$

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$$

$$\tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0$$

- Assume top decays to a *b* and chargino with BR 100%
- Chargino decays leptonically through off-shell W
- Expect: Soft b jets (not tagged), soft leptons, low missing E_T

- Background estimation:
  - semi-data-driven estimate using top and *Z*/γ* control regions
  - multijet contribution taken from data using a template fitting method

- Dominant systematics: jet energy scale, jet energy resolution, theory errors on top estimate

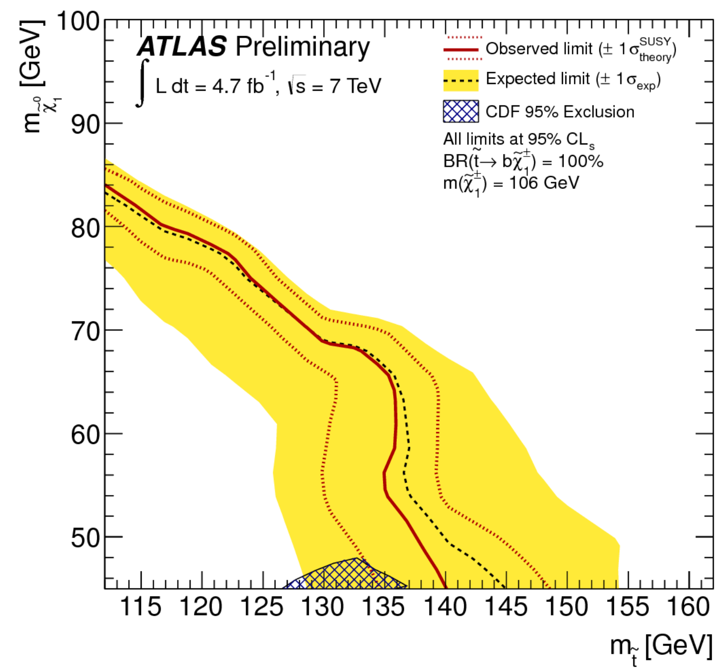
Requirement	ee channel	$e\mu$ channel	$\mu\mu$ channel
Signal Region			
lepton p_T	> 17 GeV	$> 17(12)$ GeV for $e(\mu)$	> 12 GeV
highest lepton p_T	< 30 GeV	< 30 GeV	< 30 GeV
m_{ll}	> 20 GeV and Z veto	> 20 GeV	> 20 GeV and Z veto
jet p_T	≥ 1 jet, $p_T > 25$ GeV	≥ 1 jet, $p_T > 25$ GeV	≥ 1 jet, $p_T > 25$ GeV
E_T^{miss}	> 20 GeV	> 20 GeV	> 20 GeV
$E_T^{miss,sig}$	> 7.5 GeV$^{1/2}$	> 7.5 GeV$^{1/2}$	> 7.5 GeV$^{1/2}$

Light stop search: results and interpretation

	ee	$e\mu$	$\mu\mu$	all
$t\bar{t}$	$44 \pm 4 \pm 6$	$139 \pm 7 \pm 23$	$111 \pm 8 \pm 10$	$293 \pm 12 \pm 34$
Z/γ^*+jets	$5 \pm 1 \pm 2$	$23 \pm 2 \pm 8$	$48 \pm 16 \pm 27$	$76 \pm 16 \pm 27$
Single top	$3 \pm 0.5 \pm 1$	$12 \pm 1 \pm 2$	$12 \pm 1 \pm 2$	$28 \pm 2 \pm 5$
W+jets	$4 \pm 3 \pm 4$	$3 \pm 1 \pm 2$	$15 \pm 9 \pm 3$	$23 \pm 9 \pm 8$
Diboson	$4 \pm 0.4 \pm 0.5$	$9 \pm 0.7 \pm 2$	$10 \pm 0.7 \pm 1$	$22 \pm 1 \pm 3$
QCD multijet	$2.9\,^{+3.2}_{-2.9} \pm 2.2$	$2.0 \pm 1.4 \pm 0.3$	$3.0 \pm 2.8 \pm 0.3$	$8.0 \pm 3.7 \pm 2.3$
Total	$62 \pm 6 \pm 6$	$188 \pm 8 \pm 21$	$199 \pm 21 \pm 31$	$450 \pm 23 \pm 44$
Data	48	188	195	431
σ_{vis} (exp.) [fb]	4.9	11.3	16.9	22.8
σ_{vis} (obs.) [fb]	3.4	11.3	16.3	19.8
p_0	0.89	0.52	0.55	0.64
$m(\tilde{t}, \tilde{\chi}_1^0) = (112, 55)$ GeV	44.1 ± 4.8	137 ± 8	140 ± 8	322 ± 13
$m(\tilde{t}, \tilde{\chi}_1^0) = (160, 55)$ GeV	8.8 ± 1.5	31.4 ± 2.7	36.5 ± 2.9	76.6 ± 4.3

ATLAS-CONF-2012-059

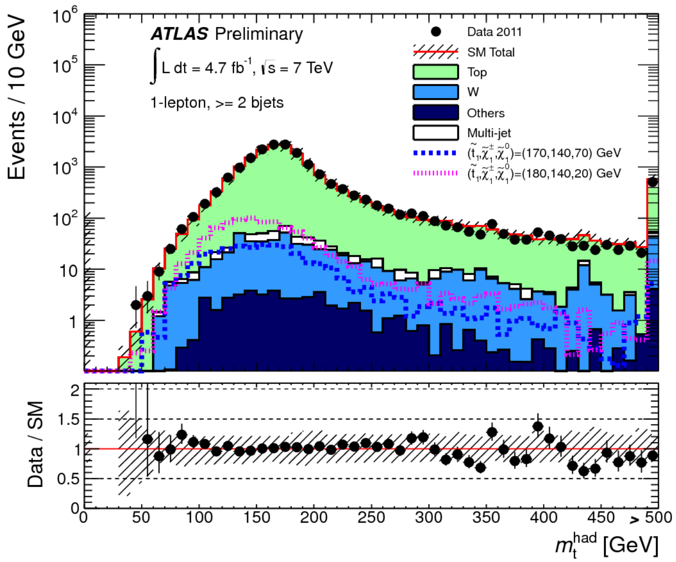
- Observation is consistent with SM background
- 95% confidence limit is set in the stop-neutralino mass plane, assuming a fixed chargino mass (106 GeV), using the CL_s prescription
- The results extend the previous limit set by CDF
- Particularly interesting for MSSM electroweak baryogenesis scenarios...



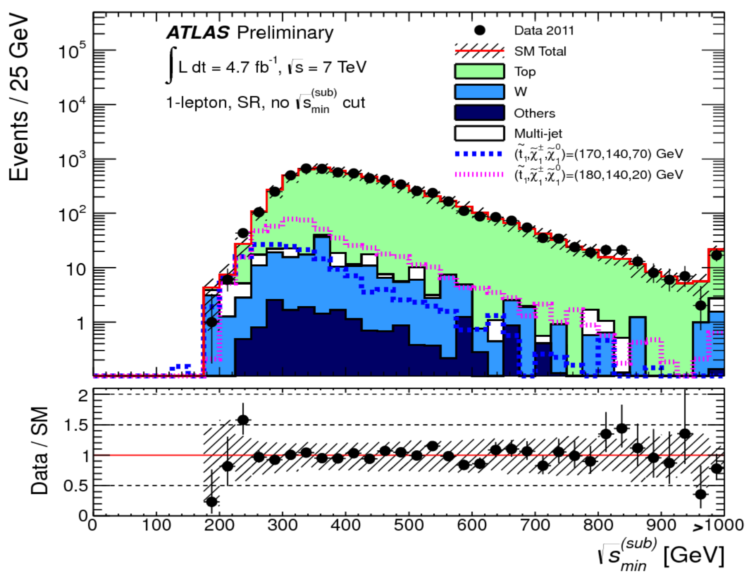
- 1 and 2 lepton analysis looking for stop → b chargino, with m(stop) ~ m(top)
- Use b tagging, and a new variable $\sqrt{s}_{min}^{(sub)}$

ATLAS-CONF-2012-070

- Two variables are used to reduce the top background

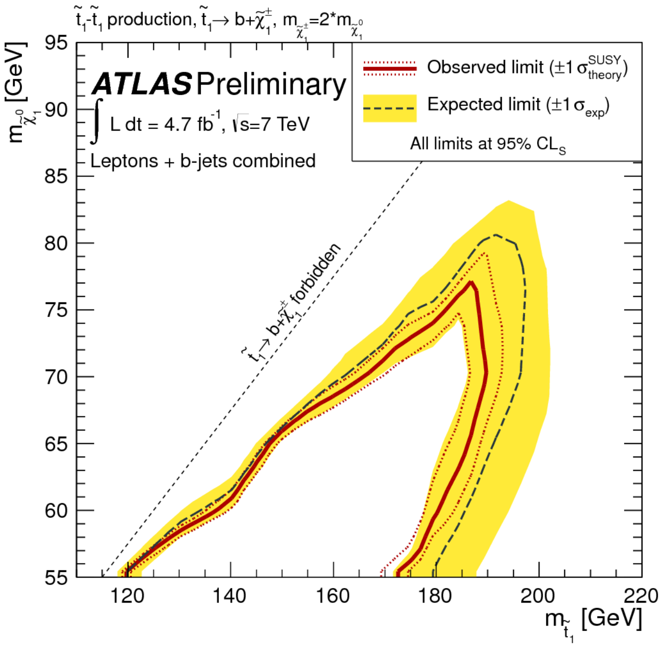


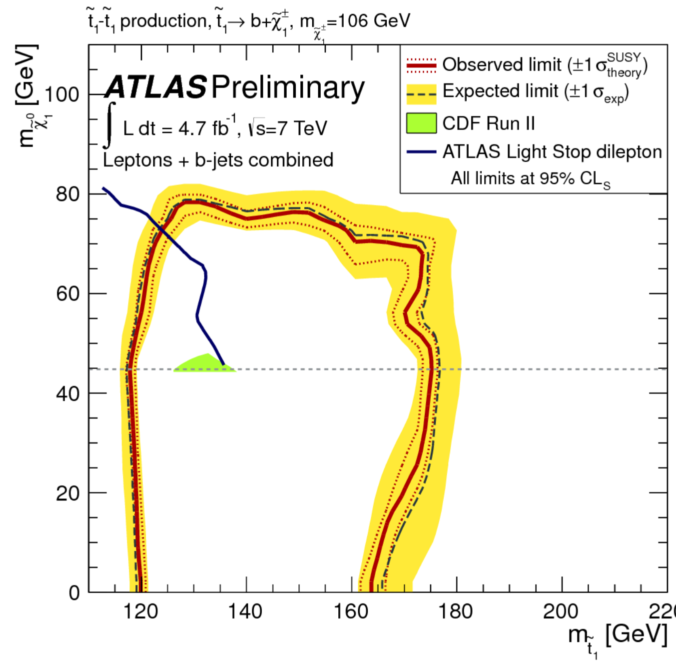
m_t^{had} : Invariant mass of hadronic top decay products
Generally smaller for stop events

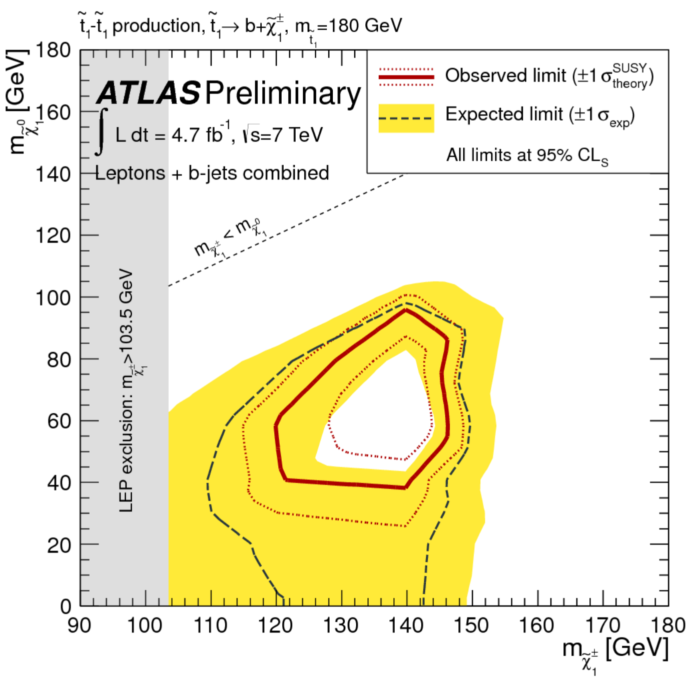


$\sqrt{s}_{min}^{(sub)}$: Minimum mass compatible with "subsystem" of top/stop decay products (see backup)
arXiv:1006.0653

m(stop) ~ m(top): results and interpretation





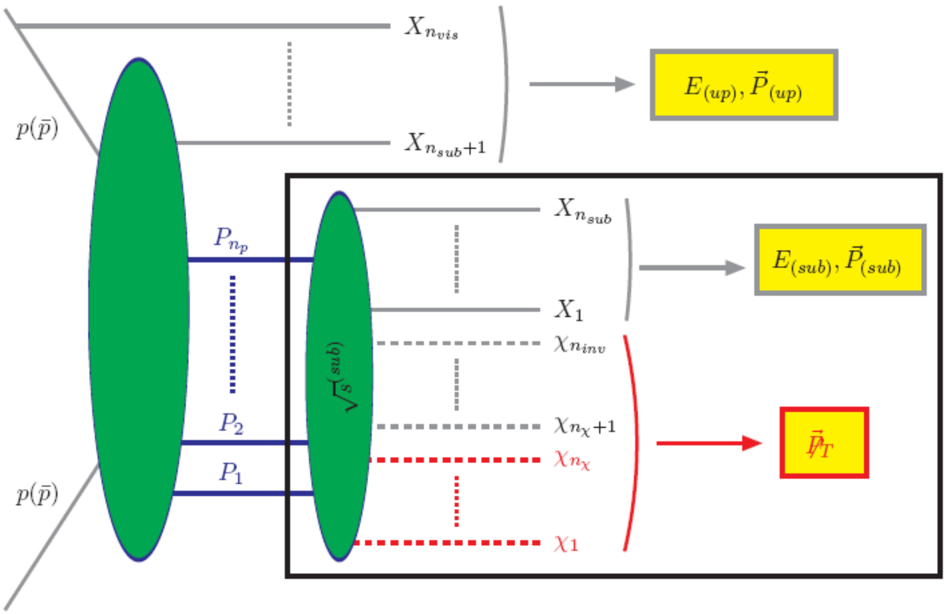


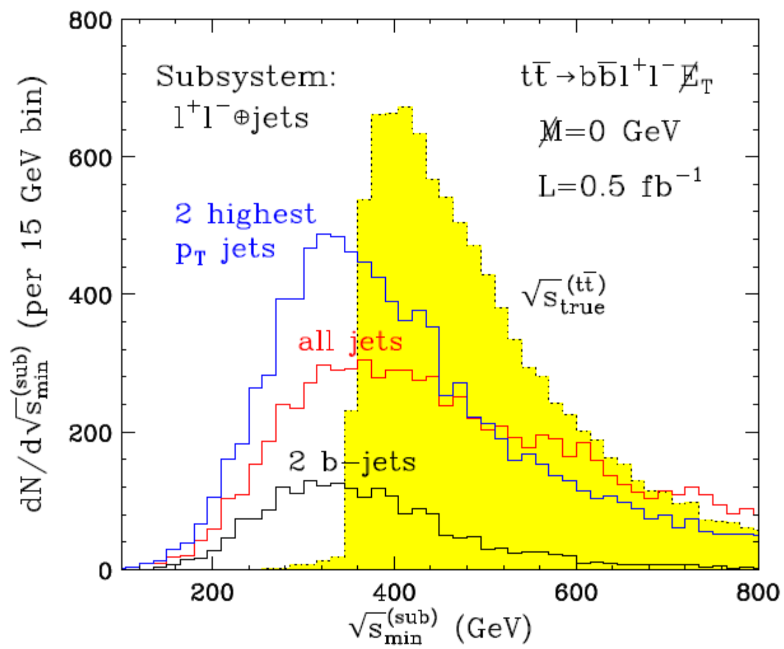
ATLAS-CONF-2012-070

- Observation is consistent with SM background in all channels

- 95% confidence limits are placed on a variety of mass hypotheses using the CL_s prescription

Florida Variable





- Minimum mass compatible with subsystem
  - http://arxiv.org/abs/1006.0653v1
- Subsystem defined from assuming $t\bar{t}$ decay products
  - $\not{M} = 0$ due to neutrinos
  - $\sqrt{s}^{(sub)}_{min}$ expected to peak at $\sim m(t\bar{t}) = 2m(t)$

$$\sqrt{s}^{(sub)}_{min}(\not{M}) = \left\{ \left(\sqrt{M^2_{(sub)} + P^2_{T(sub)}} + \sqrt{\not{M}^2 + \not{P}_T^2} \right)^2 - \left(\vec{P}_{T(sub)} + \vec{\not{P}}_T \right)^2 \right\}^{\frac{1}{2}}$$

m(stop) ~ m(top) selection cuts

Two final states are considered

1 lepton selection

- One signal electron (muon), $p_T > 25$ (20) GeV
- ≥ 4 jets with $p_T > 20$ GeV, two light, two b tagged
- $E_T^{miss} > 40$ GeV
- $m_T(l, E_T^{miss}) > 30$ GeV
- $m_t^{had} < \mu - 0.5\sigma$ (from Gaussian fit to top mass)
- $\sqrt{s}_{min}^{(sub)} < 250$ GeV

Main backgrounds: top, W + jets

2 lepton selection

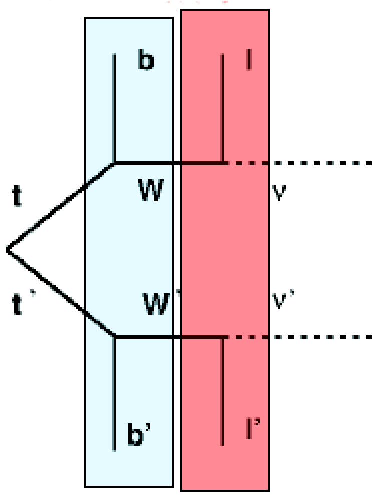
- 2 signal leptons:
  - *ee*: $p_T > 25, 20$ GeV
  - $\mu\mu$: $p_T > 20, 10$ GeV
  - $e\mu$: $p_T(e) > 25$ or $p_T(\mu) > 20$ GeV
- ≥ 2 jets with $p_T > 20$ GeV (≥ 1 b tag in leading two)
- $E_T^{miss} > 40$ GeV
- $30 \text{ GeV} < m_{ll} < 81$ GeV
- Two signal regions with different $\sqrt{s}_{min}^{(sub)}$ cuts:

SR1: $\sqrt{s}_{min}^{(sub)} < 225$ GeV

SR2: $\sqrt{s}_{min}^{(sub)} < 235$ GeV, $m_{lljj} < 140$ GeV

Main backgrounds: top, Z + jets

Main backgrounds are estimated from dedicated control regions in both cases



Top background: the lepton-neutrino transverse mass obeys

$$M_T(l,\nu) = \sqrt{2p_T(l)p_T(\nu)\left[1-\cos(\phi_l - \phi_\nu)\right]} < m(W)$$

obviously, it is true on both sides:

$$\max\left[m_T(l_1,\nu_1), m_T(l_2,\nu_2)\right] < m(W)$$

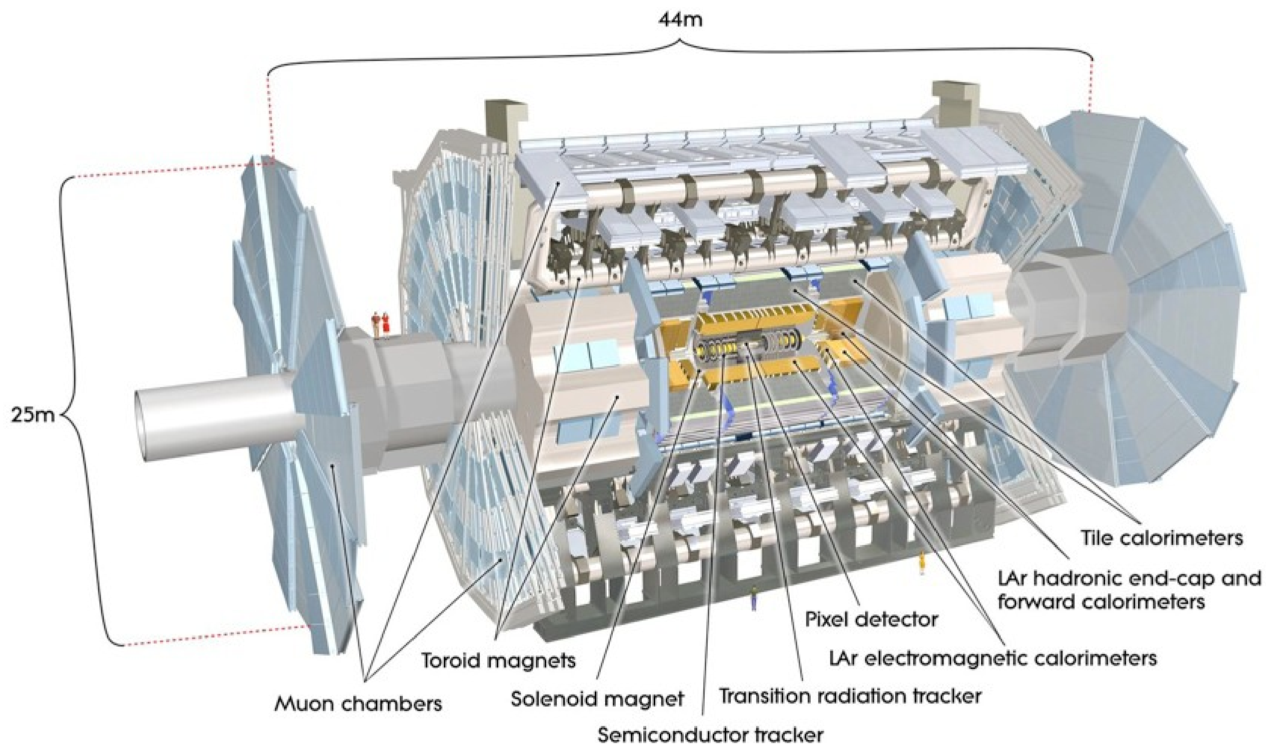
We do not have the direction of the two neutrinos, but we can try out all possibilities and take the minimum:

$$M_{T2}^2(l_1,l_2,p_T^{Miss}) = \min\left\{\max\left[m_T^2(l_1,\nu_1), m_T^2(l_2,\nu_2)\right]\right\}$$

Minimum is over all possible decompositions $\vec{p}_T^{Miss} = \vec{p}_T(\nu_1) + \vec{p}_T(\nu_2)$

it's $M_{T2} < m(W)$ for top pairs, and also for Wt and WW

ATLAS detector



• **Inner tracker:** 2 T magnetic field providing precision tracking of charged particles

• **Calorimeter systems:** Liquid argon or scintillating tiles provide energy measurements

• **Muon spectrometer:** Surrounded by air-core superconducting magnets providing a magnetic field strength varying from 1 to 8 T. The muon spectrometer provides trigger and high precision tracking capabilities.