Searches for Direct Stop Production in ATLAS

Implications of LHC results for TeV-scale physics
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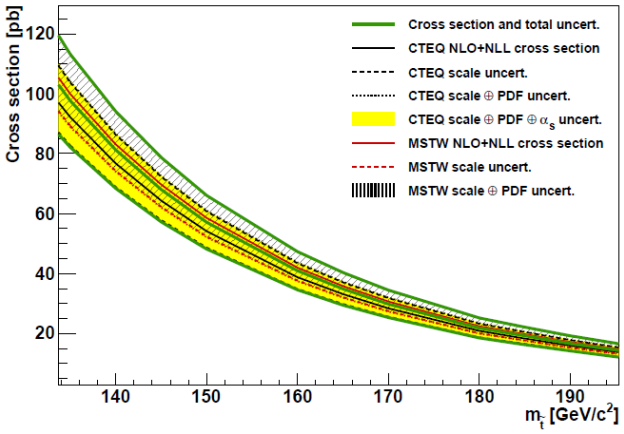
(on behalf of ATLAS Collaboration)

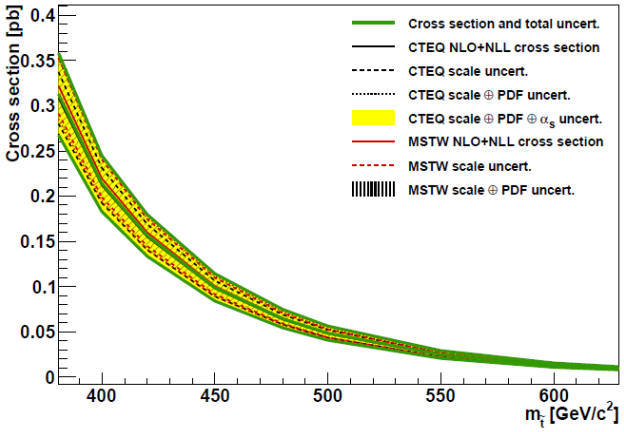
Introduction

- Even if other squarks are heavy, stop can be light because of large Yukawa coupling.
  - Light stop is favored from naturalness arguments.
- In ATLAS, the following direct stop pair production searches are performed using $\sqrt{s}$=7 TeV collision data recorded in 2011.

Channel	Statistics	paper/CONF note
stop in GMSB, higgsino: 2-lepton	2.05 fb^{-1}	arXiv:1204.6736 accepted by PLB
$\tilde{t}_1 \rightarrow$ b+chargino (light stop):2-lepton	4.7 fb^{-1}	ATLAS-CONF-2012-059
$\tilde{t}_1 \rightarrow$ b+chargino:1,2-lepton	4.7 fb^{-1}	ATLAS-CONF-2012-070
$\tilde{t}_1 \rightarrow$ t+LSP: 0-lepton	4.7 fb^{-1}	ATLAS-CONF-2012-074
$\tilde{t}_1 \rightarrow$ t+LSP: 1-lepton	4.7 fb^{-1}	ATLAS-CONF-2012-073
$\tilde{t}_1 \rightarrow$ t+LSP: 2-lepton	4.7 fb^{-1}	ATLAS-CONF-2012-071

Stop Pair Production

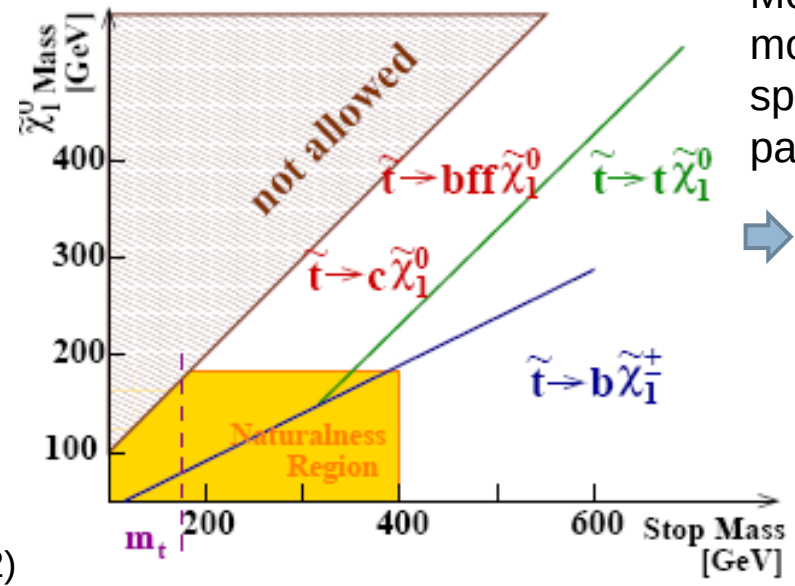




stop pair production cross-section as a function of stop mass (arXiv:1206.2892)

- Stop pair production signal tend to be similar to top pair production.
- While the cross-section rapidly decreases with the increase of the mass.

⇒ Dedicated analysis is necessary optimized for each topology for higher sensitivity.



Moreover, stop decay modes depend on mass spectrum of other susy particles.

⇒ We made certain assumptions on mass spectrum in each analysis.

stop decay modes in $m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$ plane in case of $m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0)$

Background Estimation

- QCD multijet
  - 0-lepton channel: smearing technique with jet resultion function
  - 1,2-lepton channel: matrix method (“loose” → “tight” with efficiencies taken from measurement)
- Non-QCD major backgrounds
  - ex) $$(N_{t\bar{t}})_{\mathrm{SR}} = \left((N_{\mathrm{data}})_{\mathrm{CR}} - (N_{\mathrm{non}\text{–}t\bar{t},\mathrm{MC}})_{\mathrm{CR}}\right)\frac{(N_{t\bar{t},\mathrm{MC}})_{\mathrm{SR}}}{(N_{t\bar{t},\mathrm{MC}})_{\mathrm{CR}}}$$

    SR: signal region CR: control region
- Other minor backgrounds
  - Monte Carlo only estimation

stop in GMSB, light Higgsino

- In GMSB ($m(\tilde{G}) < 1$ keV), with light higgsino model ($\tilde{\chi}_1^0 \approx \tilde{H}^0$), specific decay modes are possible from stop pair production.
  - It is favored from "naturalness" of Higgs boson mass. [M. Asano et al., JHEP 12, 019 (2010)]

Event selection
- exactly 2 opposite sign lepton (e^+e^- or $\mu^+\mu^-$)
- 86 GeV < m_{ll} < 96 GeV
- jet p_T > 60, 50 GeV
- at least 1 *b*-tagged jet
- E_T^{miss} > 50 (80) GeV

$$\tilde{t}_1 \to b + \tilde{\chi}_1^+, \tilde{\chi}_1^+ \to \tilde{\chi}_1^0 + f + f'$$

$$\tilde{\chi}_1^0 \to Z / h + \tilde{G}$$

too soft to be detected

capture $Z \to ll$ process

stop in GMSB, light Higgsino

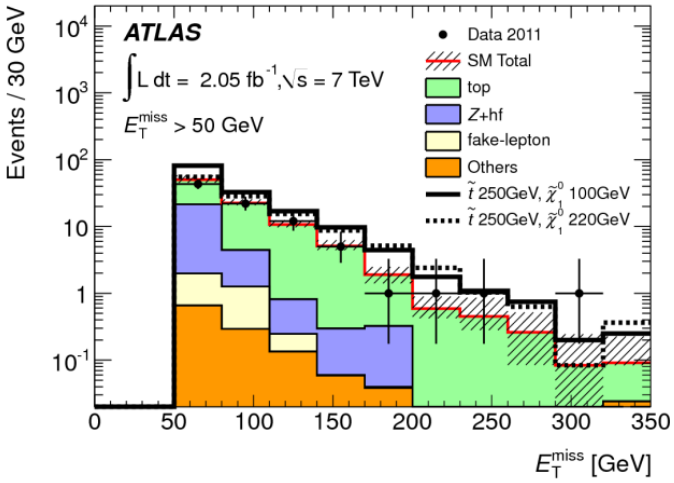
E_T^{miss}	50 GeV	80 GeV
Data	86	43
SM	92±19	40.7 ± 6.0
top	64.3±7.7	34.8 ± 5.0
Z+hf	24±16	4.2±3.2
fake lepton	2.4 ± 0.9	1.1 ± 0.6
Others	1.2 ± 1.2	0.6 ± 0.6

95% C.L. upper limits: observed (expected)		
events	37.2 (40.6)	19.8 (17.8)
visible σ [fb]	18.2 (19.8)	9.7 (8.7)

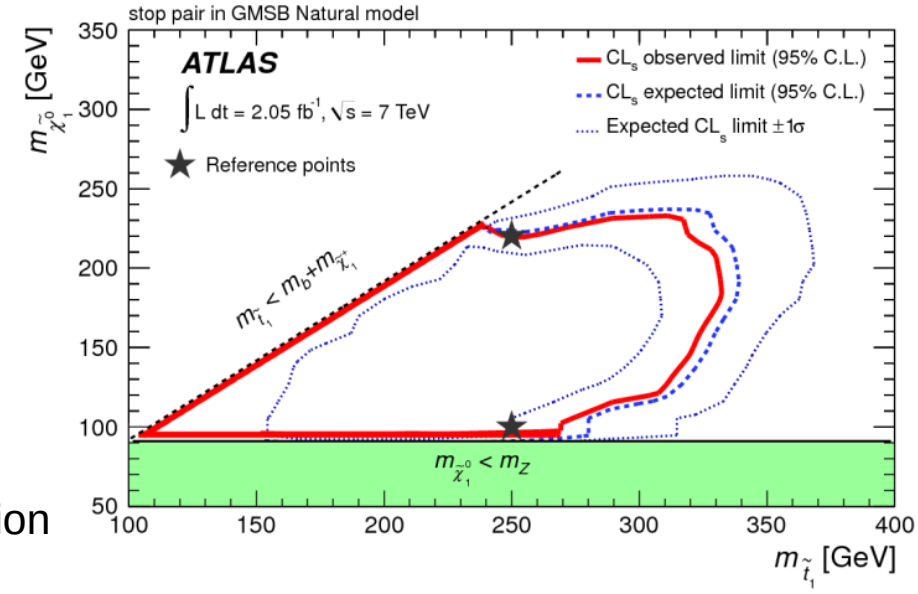
Expected and observed number of events after selection

- Observed number of events after selection agree well with SM estimation.

arXiv:1204.6736, accepted by PLB



E_T^{miss} distribution after event selection



95% CL Exclusion limits

stop→b+chargino

- Decay mode as b+chargino might be dominant if t+LSP decay is kinematically forbidden.
  - We assume the chargino decay via W+neutralino, thus SM-BR are considered.

$$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+ \,/\, \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + W^+ *$$

- Two possible scenarios are assumed for the mass hierarchy between charginos and neutralino:
  - gaugino universality mass relation: $m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0)$
  - fixed mass of the chargino: chosen as slightly above LEP limit and equivalent to Tevatron assumption. $m(\tilde{\chi}_1^{\pm}) = 106\ \mathrm{GeV}$

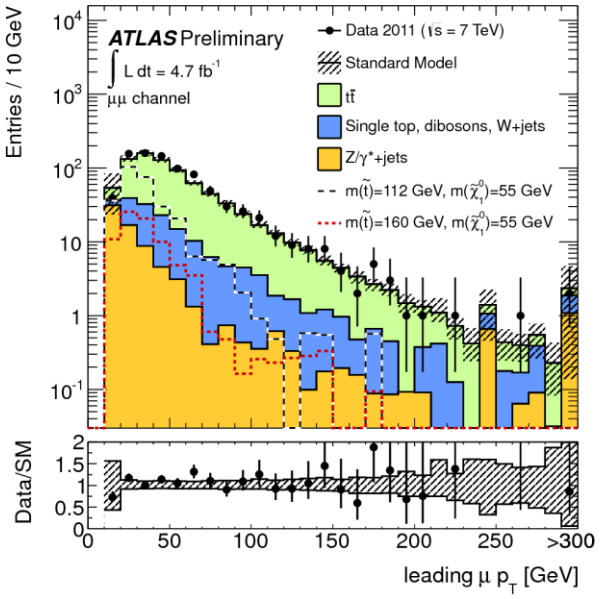
Light Stop Search

- Search for stop with $m(\tilde{t}_1) < m(t)$

ATLAS-CONF-2012-059

Event selection
- exactly 2 opposite-sign lepton (*ee*, *eμ* or *μμ*)

p_T < 30 GeV
- m_{ll} > 20 GeV
- m_{ll} < 81 GeV, 101 GeV < m_{ll} (*ee* or *μμ*)
- jet p_T > 25 GeV
- E_T^{miss} > 20 GeV
- $E_T^{miss}/\sqrt{H_T}$ > 7.5 GeV$^{1/2}$



Leading lepton p_T distribution without this p_T cut.

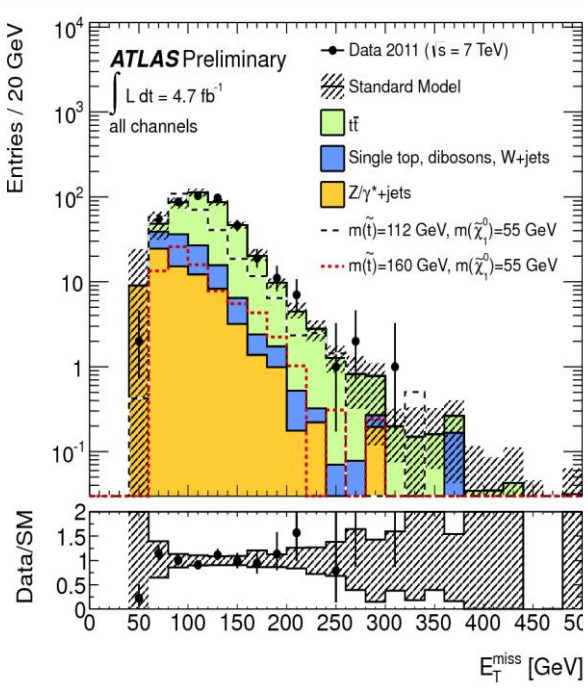
Light Stop Search

- Observed number of events after selection agree well with SM estimation.

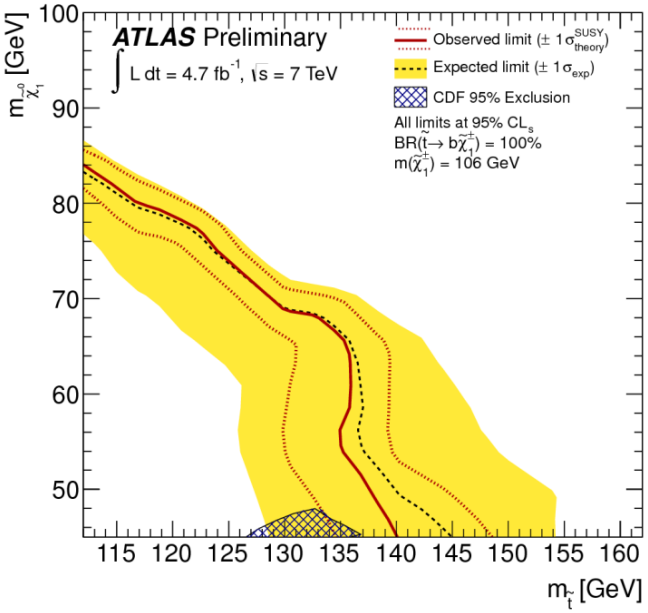
ATLAS-CONF-2012-059

	all
$t\bar{t}$	293 ± 12 ± 34
Z/γ^*+jets	76 ± 16 ± 27
Single top	28 ± 2 ± 5
W+jets	13 ± 3 ± 3
Diboson	22 ± 1 ± 3
multijet	8.0 ± 3.7 ± 2.3
Total	440 ± 21 ± 43
Data	431
σ_{vis} (exp. limit) [fb]	22.0
σ_{vis} (obs. limit) [fb]	21.0
$m(\tilde{t}, \tilde{\chi}_1^0) = (112, 55)$ GeV	322 ± 13
$m(\tilde{t}, \tilde{\chi}_1^0) = (160, 55)$ GeV	76.6 ± 4.3

Expected and observed number of events after selection



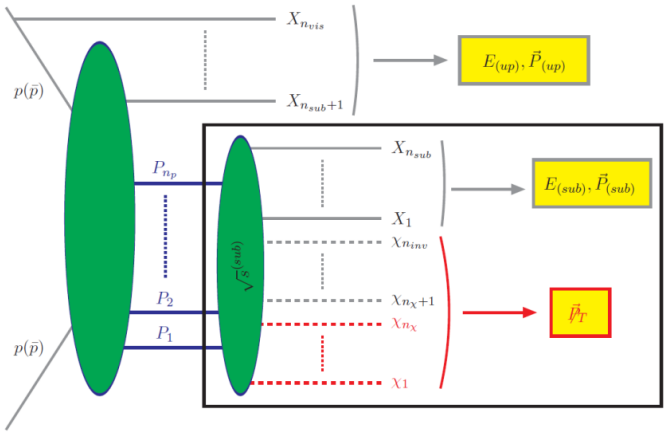
E_T^{miss} distribution after selection

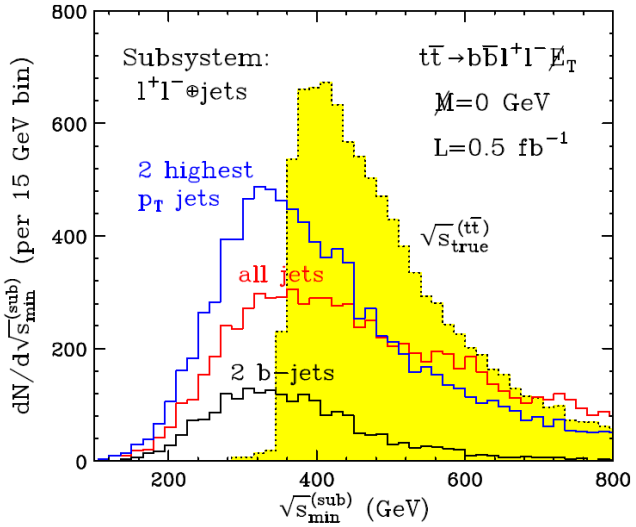


95% CL exclusion limits with fixed. $m(\tilde{\chi}_1^{\pm}) = 106$ GeV

Reco. level subsystem $\sqrt{s}_{min}$

P. Konar et al, JHEP 1106 (2011) 041





- Minimum mass compatible with subsystem
- Subsystem defined form ttbar decay products

$\sqrt{s}_{min}^{(sub)}$ distributions for dileptonic decay of ttbar

$$\sqrt{s}_{\min}^{(\mathrm{sub})} = \left\{ \left(\sqrt{m_{(\mathrm{sub})}^2 + p_{\mathrm{T(sub)}}^2} + \sqrt{(m^{\mathrm{miss}})^2 + (E_{\mathrm{T}}^{\mathrm{miss}})^2} \right)^2 - \left(\mathbf{p}_{\mathrm{T(sub)}} + \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}} \right)^2 \right\}^{\frac{1}{2}}$$

For ttbar production:

- $m^{\mathrm{miss}} = 0$ is assumed.
- $\sqrt{s}_{min}^{(sub)}$ expected to peak at ~ $m(t\bar{t}) = 2m(t)$

$\sqrt{s}_{min}^{(sub)}$ expected to be lower for stop pair production with

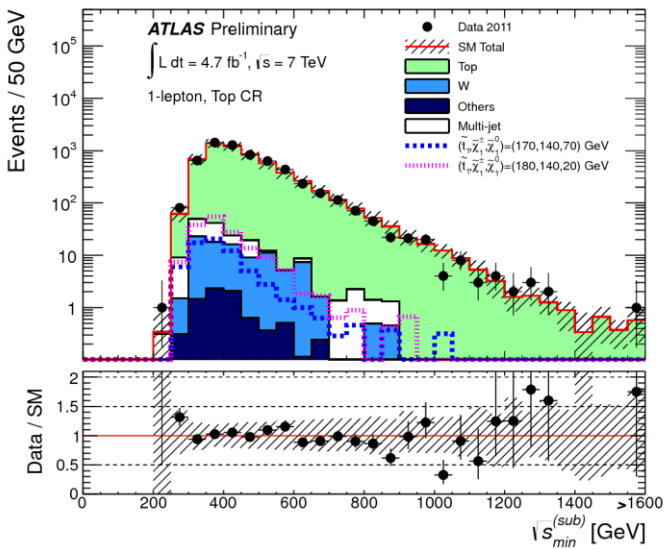
$$m(\tilde{t}_1) - m(\tilde{\chi}_1^0) < m(t)$$

stop→b+chargino:1,2-lepton

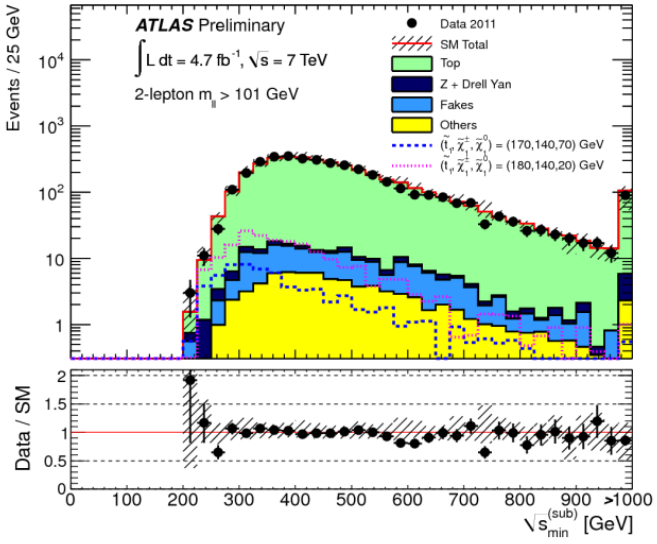
ATLAS-CONF-2012-070

Event selection (1-lepton)
- exactly 1 lepton (*e* or μ)
- m_T > 30 GeV
- E_T^{miss} > 40 GeV
- 4 jet p_T > 20 GeV
- at least 2 *b*-tagged, 2 non-*b*-tagged jets
- $m_t^{had} < \mu - 0.5\,\sigma$
- $\sqrt{s}_{min}^{(sub)}$ < 250 GeV

Event selection (2-lepton)
- exactly 2 opposite-sign lepton (*ee*, *e*μ or $\mu\mu$)
- 30 GeV < m_{ll} < 81 GeV
- E_T^{miss} > 40 GeV
- 2 jet p_T > 20 GeV
- at least 1 *b*-tagged jet
- $\sqrt{s}_{min}^{(sub)}$ < 225 GeV (SR1) or 235 GeV with m_{lljj} < 140 GeV (SR2)



$\sqrt{s}_{min}^{(sub)}$ distributions after 1-lepton (left) and 2-lepton (right) selection

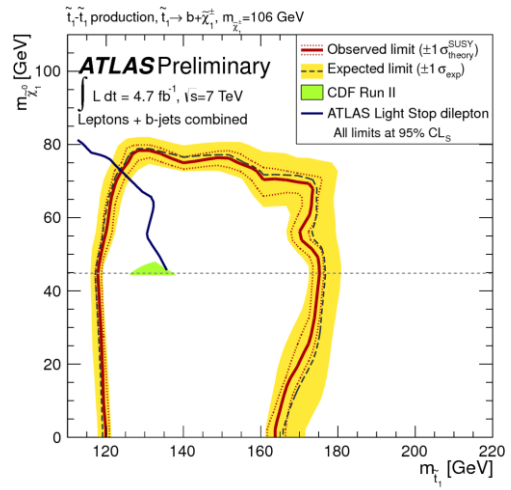


stop→b+chargino:1,2-lepton

	Number of events		
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	$0.5 \pm 0.3 \pm 0.3$	$11 \pm 4 \pm 3$	$3 \pm 1 \pm 1$
Fake leptons	$7 \pm 1 \pm 2$	$12 \pm 5 \pm 11$	$6 \pm 4 \pm 4$
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	$26 \pm 2 \pm 6$	$57 \pm 3 \pm 6$	$36 \pm 2 \pm 4$
$m_{\tilde{t}_1} = 180$ GeV, $m_{\tilde{\chi}_1^0} = 20$ GeV	$20 \pm 2 \pm 4$	$41 \pm 3 \pm 5$	$27 \pm 2 \pm 3$
	95% CL upper limits		
σ_{vis} (expected) [fb]	4.2	9.3	4.6
σ_{vis} (observed) [fb]	6.1	11	5.2

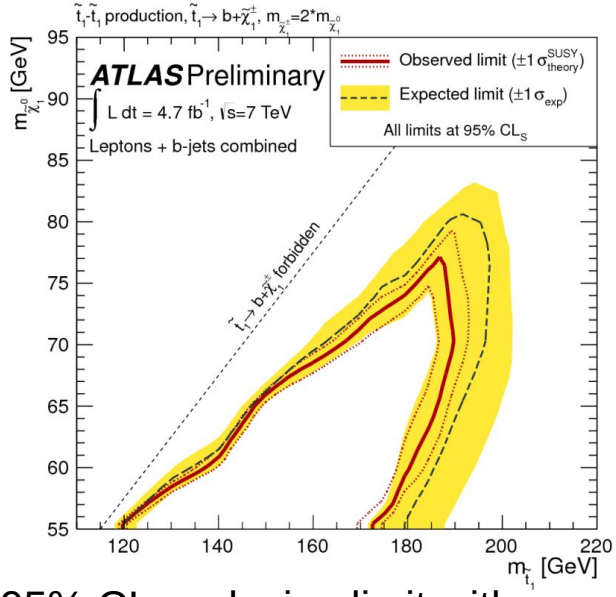
- Observed number of events after selection agree well with SM estimation.

ATLAS-CONF-2012-070



Expected and observed number of events after selection

95% CL exclusion limit with $m(\tilde{\chi}_1^\pm) = 106$ GeV

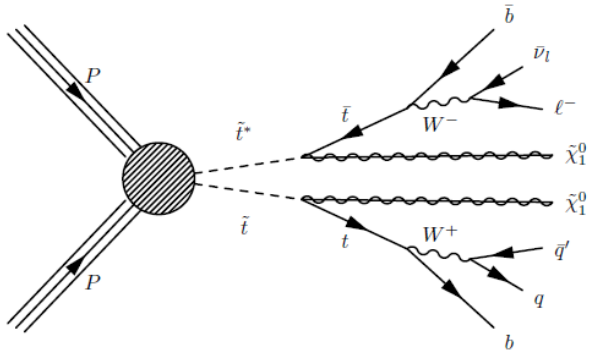


95% CL exclusion limit with $m(\tilde{\chi}_1^\pm) = 2m(\tilde{\chi}_1^0)$

stop→t+LSP

- If kinematically allowed, stop can decay to t+neutralino.
  - Final states can be classified into all hadronic, semi-leptonic and di-leptonic as same as ttbar production.
  - Difference with ttbar production is the existence of additional missing momentum source due to neutralinos, which is LSP.

In the following searches, decay to t+LSP is assumed to be 100%.



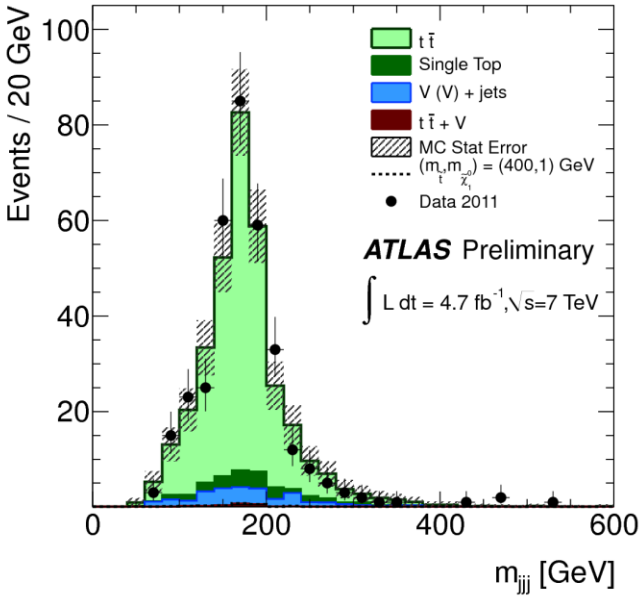
example of stop pair production with a semi-leptonic decay (~t_1→t+LSP)

stop→t+LSP: 0-lepton

Event selection
- lepton veto (e or μ)
- jet p_T >130 GeV
- 6 jet p_T > 30 GeV
- at least one b-tagged jet (ε=60%) or two b-tagged jets (ε=75%)
- $\Delta\varphi(j_i - E_T^{miss}) > \pi/5$ rad (i=1,2,3)
- $E_T^{miss,track} > 30$ GeV
- $\Delta\varphi(E_T^{miss}, E_T^{miss,\,track}) < \pi/3$
- $m_T(\tau\text{-jet-like}) > 100$ GeV
- 80 GeV < $m_{jjj}^{(0)}$, $m_{jjj}^{(1)}$ < 270 GeV
- $m_T(j_i, E_T^{miss}) > 175$ GeV (i=1,2,3) or $m_T(b, E_T^{miss}) > 175$ GeV
- $E_T^{miss} > 150$ (260) GeV

Due to requirement from jet+E_T^{miss} trigger, event selection is optimized for higher stop mass.

ATLAS-CONF-2012-074



The m_{jjj} distribution in 1-lepton control region.

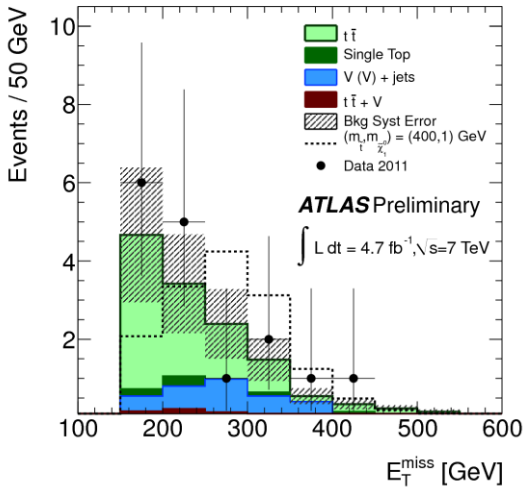
stop→t+LSP: 0-lepton

	E_T^{miss} > 150 GeV	> 260 GeV
$t\bar{t}$	9.2 ± 2.7	2.3 ± 0.6
$t\bar{t} + W/Z$	0.8 ± 0.2	0.4 ± 0.1
Single top	0.7 ± 0.4	$0.2 \pm {}^{0.3}_{0.2}$
Z+jets	$1.3 \pm {}^{1.1}_{1.0}$	$0.9 \pm {}^{0.8}_{0.7}$
W+jets	$1.2 \pm {}^{1.4}_{1.0}$	0.5 ± 0.4
Diboson	$0.1 \pm {}^{0.2}_{0.1}$	$0.1 \pm {}^{0.2}_{0.1}$
Multi-jets	0.2 ± 0.2	0.02 ± 0.02
Total SM	$13.5 \pm {}^{3.7}_{3.6}$	$4.4 \pm {}^{1.7}_{1.3}$
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
Visible cross section [fb]	2.9 (2.5)	1.3 (1.3)

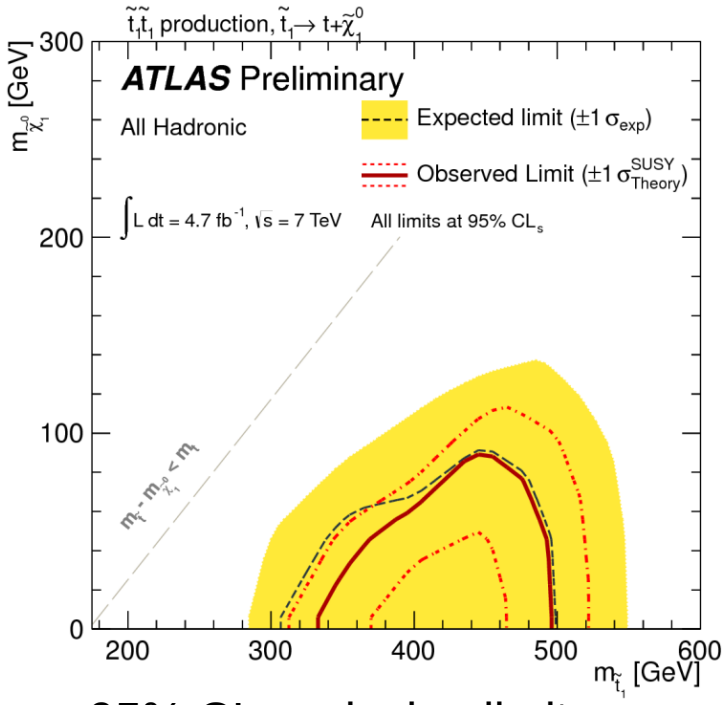
Expected and observed number of events after selection

- Observed number of events after selection agree well with SM estimation.

ATLAS-CONF-2012-074



E_T^{miss} distribution after selection



95% CL exclusion limit

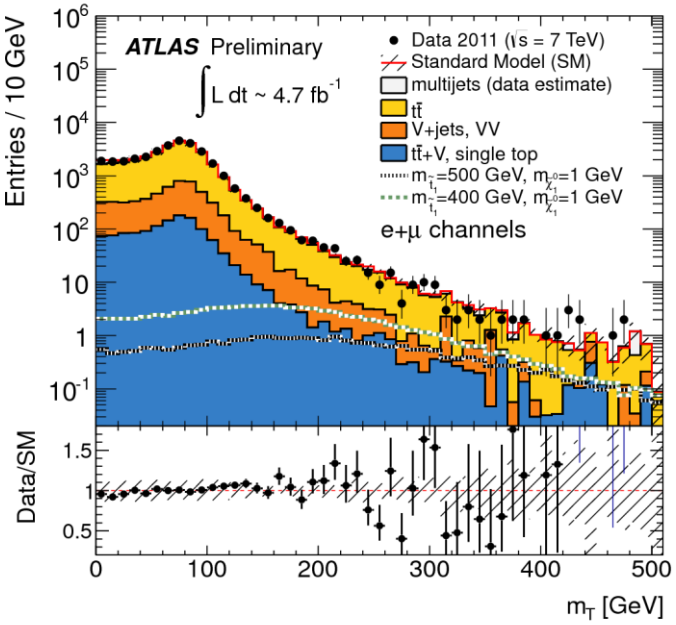
stop→t+LSP: 1-lepton

Event selection
- exactly 1-lepton (*e* or μ)
- jet p_T > 80, 60, 40, 25 GeV
- at least one *b*-tagged jet
- $\varphi_{min}(j_1,j_2 - E_T^{miss}) > 0.8$ rad
- m_{jj} > 60 GeV
- 130 GeV < m_{jjj} < 205 GeV

ATLAS-CONF-2012-073

Further event selection

	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



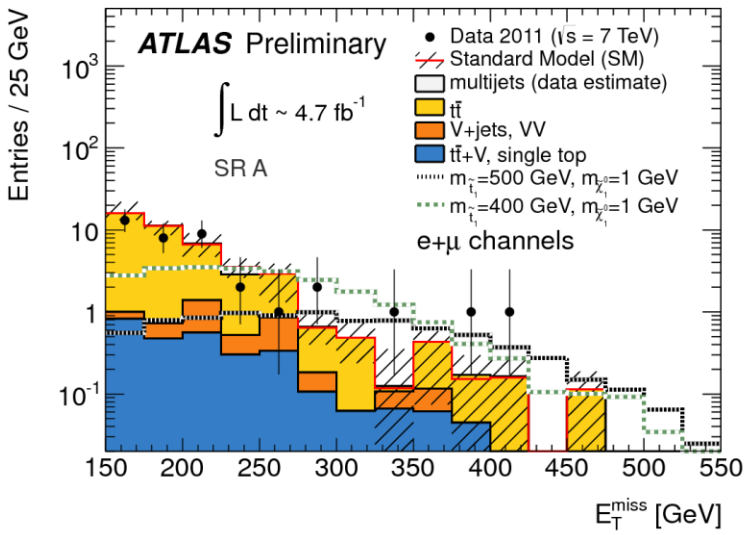
The m_T distribution with E_T^{miss} > 40 GeV

stop→t+LSP: 1-lepton

Regions	SR A	SR B	SR C	SR D	SR E
$t\bar{t}$	36 ± 5	27 ± 4	11 ± 2	4.9 ± 1.3	1.3 ± 0.6
$t\bar{t}+V$, single top	2.9 ± 0.7	2.5 ± 0.6	1.6 ± 0.3	0.9 ± 0.3	0.4 ± 0.1
V+jets, VV	2.5 ± 1.3	1.7 ± 0.8	0.4 ± 0.1	0.3 ± 0.1	0.1 ± 0.1
Multijet	$0.4^{+0.4}_{-0.4}$	$0.3^{+0.3}_{-0.3}$	$0.3^{+0.3}_{-0.3}$	$0.3^{+0.3}_{-0.3}$	$0.0^{+0.3}_{-0.0}$
Total background	42 ± 6	31 ± 4	13 ± 2	6.4 ± 1.4	1.8 ± 0.7
Signal benchmark 1 (2)	25.6 (8.8)	23.0 (8.1)	17.5 (6.9)	13.5 (6.2)	7.1 (4.5)
Observed events	38	25	15	8	5
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)

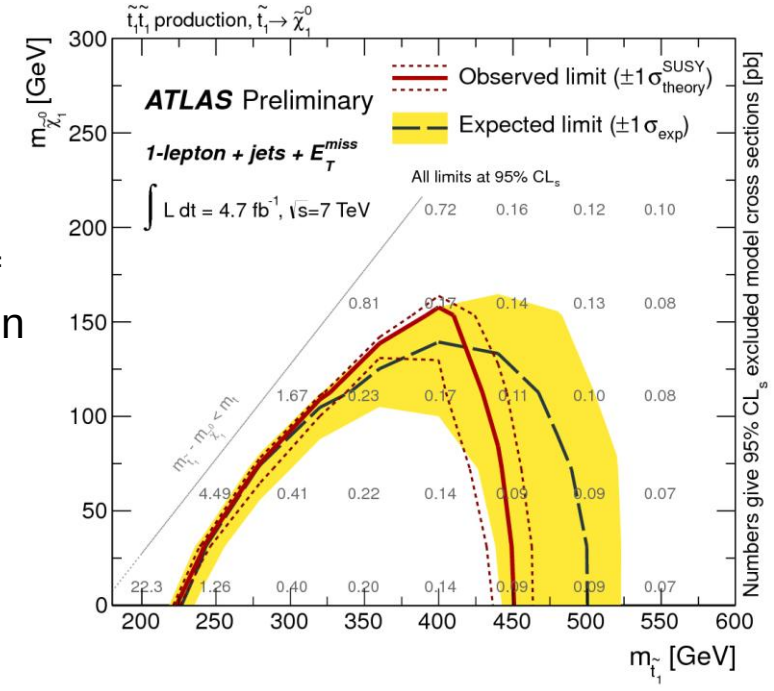
- Observed number of events after selection agree well with SM estimation.

ATLAS-CONF-2012-073



Expected and observed number of events after selection

E_T^{miss} distribution in SR A.

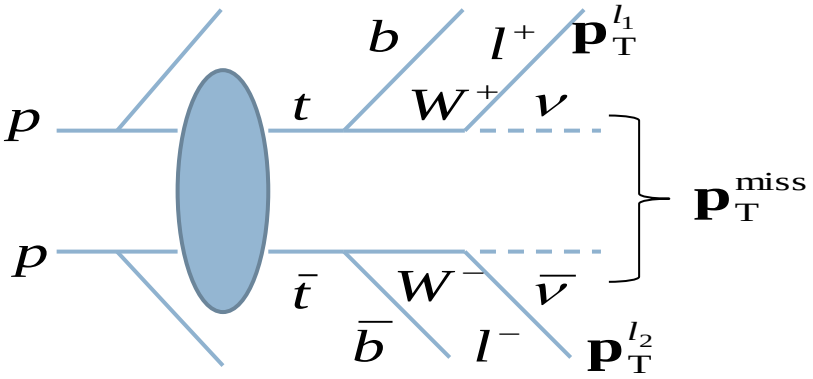


95% CL exclusion limit

stop→t+LSP: 2-lepton

Event selection
- exactly opposite-sign 2-lepton (*ee*, *eμ*, *μμ*), $m_{ll} > 20$ GeV
- $m_{ll} < 71$ GeV, 111 GeV $< m_{ll}$ (for *ee* or *μμ*)
- jet $p_T > 50, 25$ GeV
- at least one *b*-tagged jet
- $m_{T2} > 120$ GeV

W.S.Cho et al, JHEP 0802 (2008) 035
M.Burns et al, JHEP 0903 (200) 143



$$m_{T2} = \min_{\mathbf{q}_T + \mathbf{r}_T = \mathbf{p}_T^{miss}} \left\{ \max[m_T(\mathbf{p}_T^{l_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{l_2}, \mathbf{r}_T)] \right\}$$

- m_{T2} reconstructed from two lepton p_T and E_T^{miss} should have a endpoint at m_W.

⇕

- stop pair production has higher endpoint.

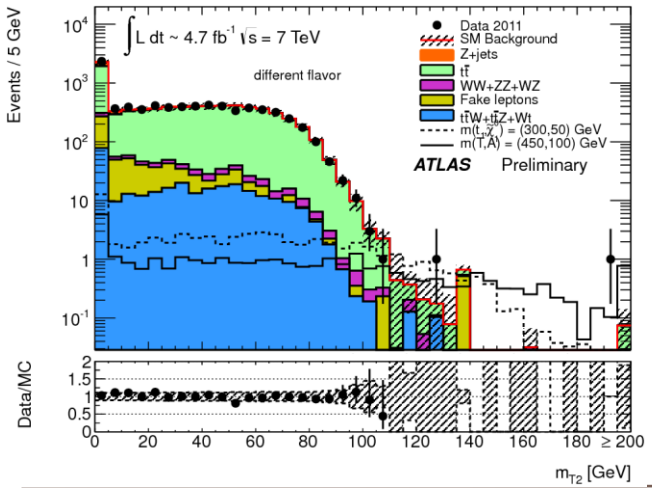
stop→t+LSP: 2-lepton

	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 $\sigma_{\text{vis}}^{\text{obs}}$[fb]	0.86	1.08
95% CL limit on $\sigma_{\text{vis}}^{\text{exp}}$[fb]	0.89	0.79

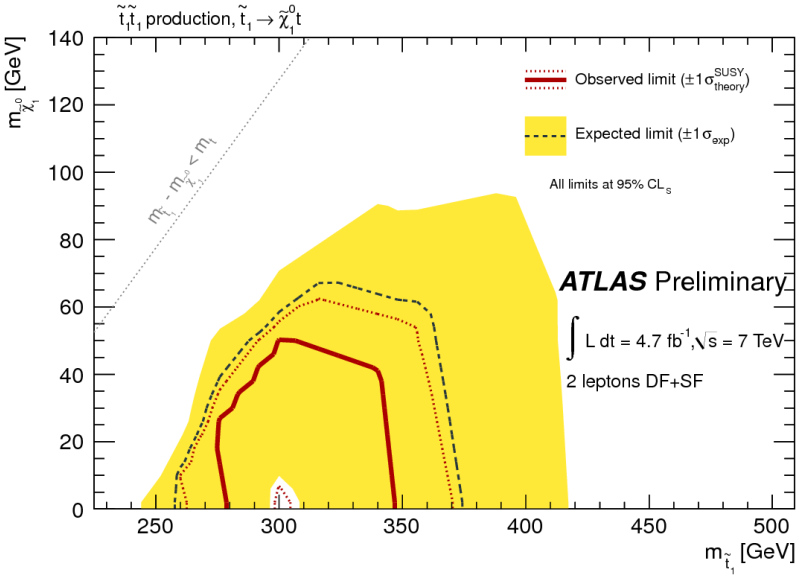
Expected and observed number of events after selection

- Observed number of events after selection agree well with SM estimation.

ATLAS-CONF-2012-071



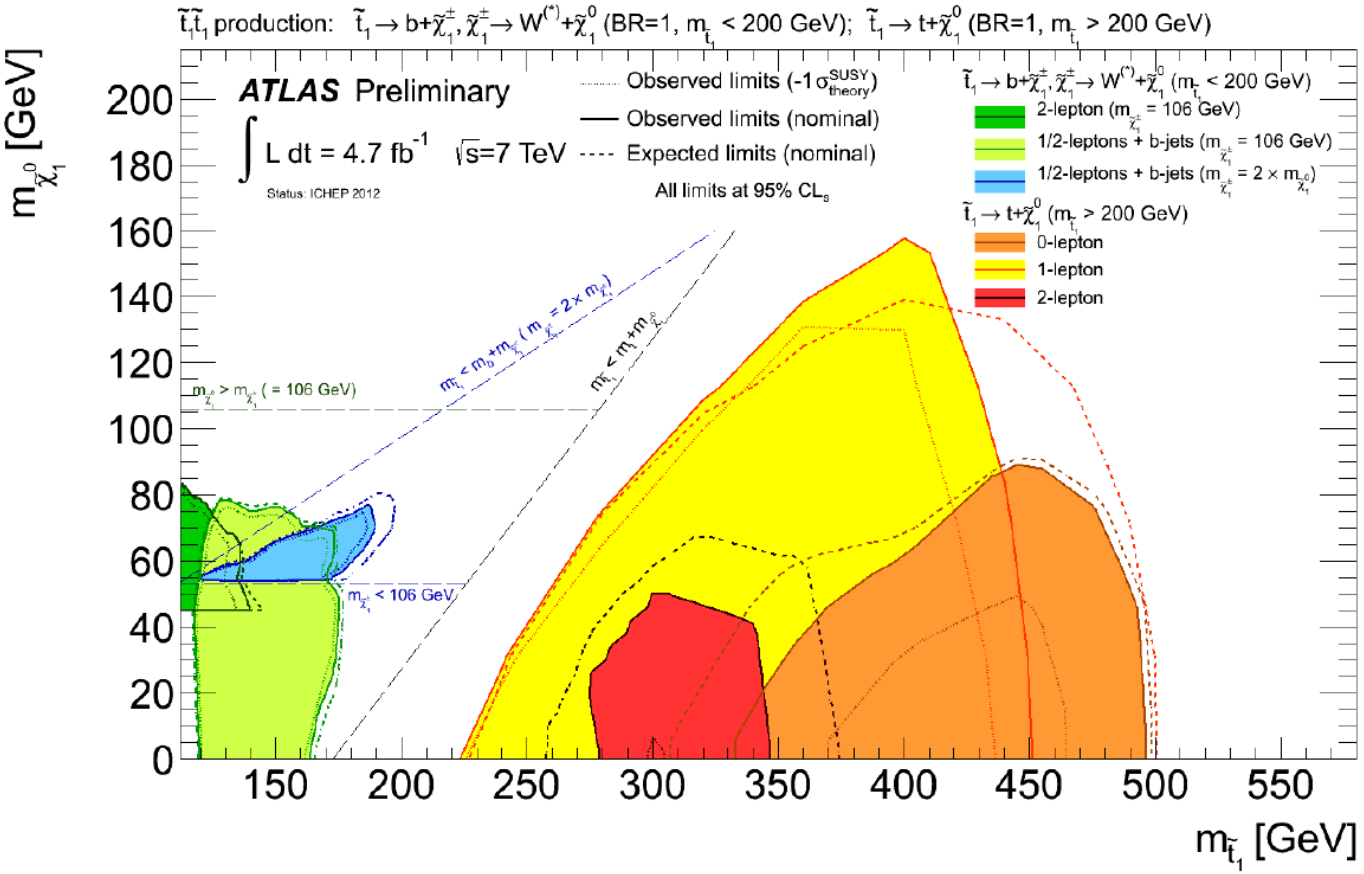
m_{T2} distribution after selection in $e\mu$ channel



95% CL exclusion limit

Exclusion Limit Summary

- Summary of the exclusion limits shown so far.



Conclusion

- Stop is expected to be lighter than the other colored susy particles.
- In ATLAS, various searches for direct stop pair production has been performed with $\sqrt{s}$=7 TeV *pp* collision data.
- However, no significant excess from SM expectation is seen so far.

Backup

Trigger

- jet + E_T^{miss}
  - jet p_T > 130 GeV, E_T^{miss} > 160 GeV
- 1-electron
  - electron p_T > 25 GeV
- 1-muon (+jet)
  - muon p_T > 20 GeV (+ jet p_T > 60 GeV)
- 2-elecron
  - 2 electron p_T > 17 GeV
- 2-muon
  - 2 muon p_T > 12 GeV

Preselection

- Primary vertex
  - the sum of track p_T^2 is largest.
  - at least four vertex p_T > 400 MeV.
- Bad muon rejection
- Cosmic muon rejection
  - $|z_0|$ > 1 mm or d_0 > 0.2 mm

Object Definition

Electron
preselection
- "medium" shower, track quality criteria
- p_T > 20 GeV
- $|\eta|$ < 2.47

tight selection
- track around electron $\Sigma p_T^{track}/p_T$ < 0.1
- "tight" criteria

Muon
preselection
- ID-MS combined
- p_T > 10 GeV
- $|\eta|$ < 2.4

tight selection
- Σp_T^{track} < 1.8 GeV

Jet
preselection
- anti-k_t algorithm with topological clusters, distance parameter R=0.4
- EM+JES calibration
- p_T > 20 GeV
- $|\eta|$ < 4.5

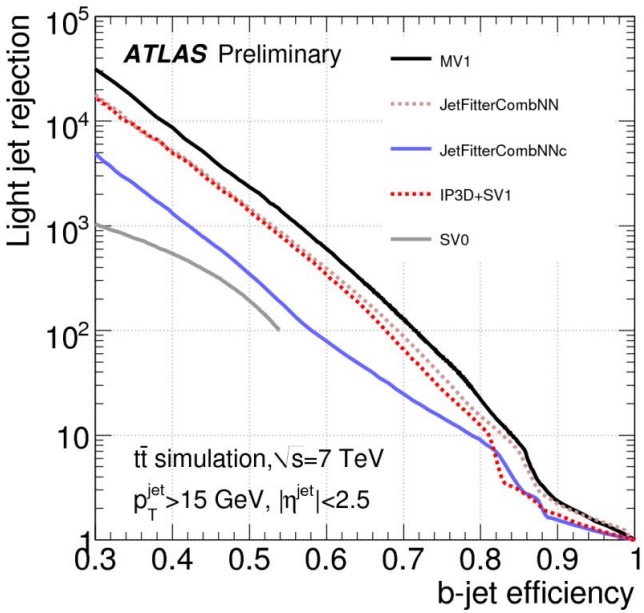
tight selection
- |h| < 2.5
- Jet vertex faction > 0.75

E_T^{miss}
- vector sum of all identified objects and other calorimeter clusters (CellOut) with $|\eta|$ < 4.5

$$\mathbf{p}_T^{miss} = -\sum \mathbf{p}_T^{jet} - \sum \mathbf{p}_T^{electron} - \sum \mathbf{p}_T^{muon} - \sum \mathbf{p}_T^{CellOut}$$

b-tagging

- MV1: neural network output using JetFitter+IP3D, IP3D, SV1
  - t+LSP 1-lepton: 75%
  - t+LSP 0-lepton: 60%, 75%
- JetFitterCOMBNN: neural network output of JetFitter, IP3D
  - b+chargino (light stop, 1-2-lepton): 60%
  - t+LSP 2-lepton: 60%



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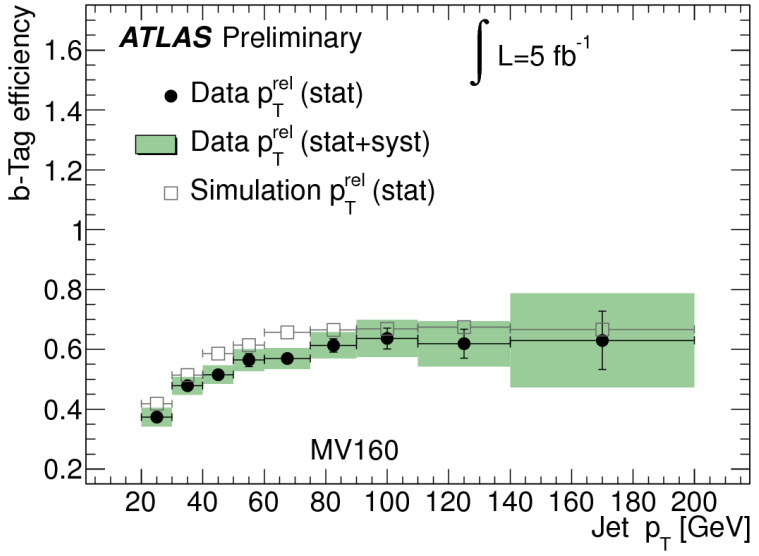

b-tagging efficiency of MV1 as a function of jet p_T at ~60% operation point.