Third-generation Squark Searches at ATLAS

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Why heavy flavor SUSY signatures?

SUSY resolves the hierarchy problem and stabilizes the Higgs mass, BUT:

- SUSY, if it exists, is a broken symmetry
- Higgs couplings strongest for the heaviest quark (top)
- stop ($\tilde{t}$) light (≈1 TeV) to avoid fine-tuning (*naturalness*)
- sbottom ($\tilde{b}$) light as well to avoid too much weak isospin violation
- Left/right-handed squark mixing provides possible mechanism

Light third-generation squarks mean:

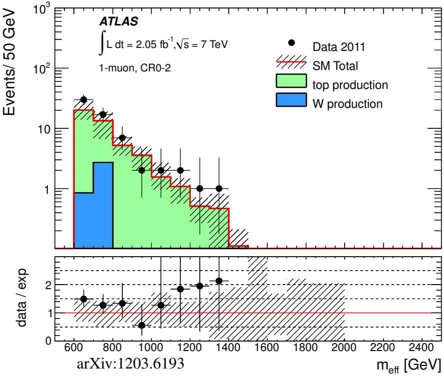
- High decay branching ratios from gluino/direct production cross sections
- With R-parity conservation, final states with b-jets + $\not{E}_T$

Semi-Data-Driven Background Estimation

All analyses discussed in this talk make use of a common technique to estimate their dominant (typically top) or co-dominant (top and Z+h.f.) backgrounds.

- Choose one or more control regions (CRs) kinematically similar to signal regions (SRs) but preferably enriched in the dominant background
- Take the ratio of the SR yield to the CR yield in Monte Carlo (MC) as a transfer factor

Example CR



arXiv:1203.6193

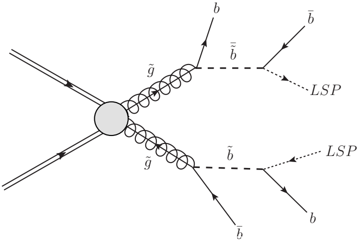
Predicted yield in SR is MC Ratio × 1 l-CR yield (corrected for other backgrounds):

$$N_{SR}^{dom} = \left(\frac{N_{SR}}{N_{CR}}\right)_{MC}^{dom} \times [N_{CR}^{data} - N_{CR}^{others}]$$

MC ratio allows partial cancellation of detector and theoretical uncertainties

Details for each analysis are in the backup slides.

Gluino-mediated Simplified Models



- Gluino ($\tilde{g}$)-mediated sbottom/stop ($\tilde{b}/\tilde{t}$) decays (gluino-mediated bottom decay diagram shown).
- Two related phenomenological models used for optimization and limits, both with 4 b-jets + $\not{E}_T$ final state signature
- For more information on simplified models, see arXiv:1105.2838

Cascade (on-shell $\tilde{b}/\tilde{t}$):

- $m_{\tilde{g}} > m_{\tilde{b}/\tilde{t}} > m_{\tilde{\chi}^0}$
- $m_{\tilde{q}_{1,2}} >> m_{\tilde{b}/\tilde{t}}$
- $m_{\tilde{g}}$ and $m_{\tilde{b}/\tilde{t}}$ varied
- $m_{\tilde{\chi}^0}$ set to 60 GeV

3-body (off-shell $\tilde{b}/\tilde{t}$):

- $m_{\tilde{b}/\tilde{t}} >> m_{\tilde{g}} > m_{\tilde{\chi}^0}$
- $m_{\tilde{q}_{1,2}} >> m_{\tilde{b}/\tilde{t}}$
- $m_{\tilde{g}}$ and $m_{\tilde{\chi}^0}$ varied
- $\tilde{b}/\tilde{t}$ is off-shell, decay chain is effectively $\tilde{g} \rightarrow b\bar{b}/t\bar{t} + \tilde{\chi}^0$

$\tilde{g} \rightarrow \tilde{b}$ *Baseline Offline Selections - arXiv:1203.6193*

- 2.05 fb^{-1} of data collected with the ATLAS detector in 2011 (same for all analyses in this talk)
- Single jet + $\not{E}_T$ trigger (hadronic channel)
- Baseline offline selections have several different motivations
- Total top uncertainty is between 15-40%, as is the total background uncertainty

Motivation	Cut	Details
Trigger	1 jet with $p_{\mathrm{T}} > 130$ GeV $\not{E}_T > 130$ GeV	Turn-on plateau Turn-on plateau
QCD Rejection	$\Delta\phi(J1/2/3, \not{E}_T) > 0.4$ $\not{E}_T/m_{eff} > 0.25$	Fake $\not{E}_T$ due to mis-measured jets
Signal Enhancement	Lepton vetos (e, μ) 2 additional jets with $p_{\mathrm{T}} > 50$ GeV $\geq$1 b-tagged jets (60% eff.)	No loose e or μ "JetFitter" + neural network

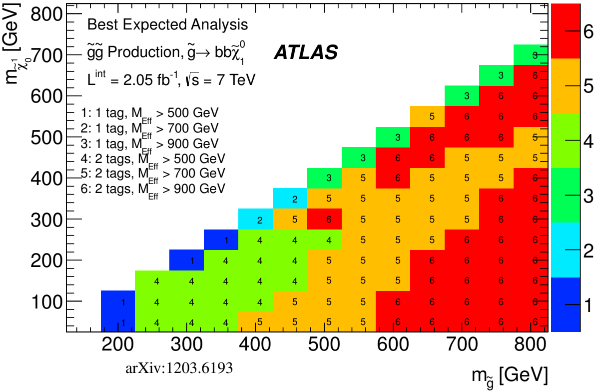
$$m_{eff} \equiv \sum_{1,2,3} p_T^{jet} + \not{E}_T$$

$\tilde{g} \rightarrow \tilde{b}$ *Signal Regions*

Multivariate optimization procedure:

- Use discovery significance predictions from Monte Carlo simulation
- Create large set of "optimal" signal regions (SRs), one for each point in the signal grids
- Reduce systematically the number of signal regions while ensuring broad sensitivity.

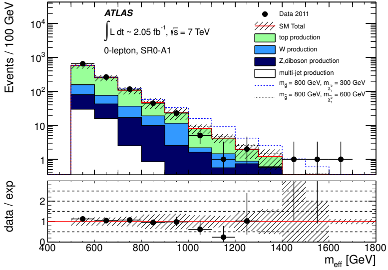
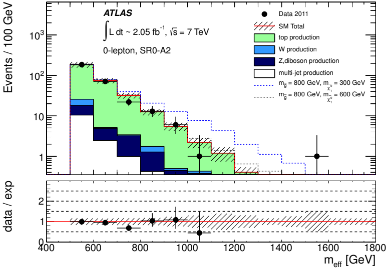
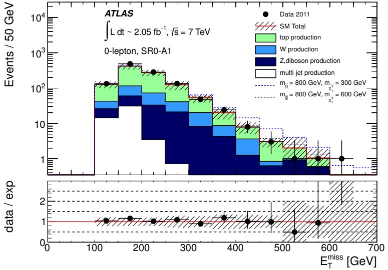
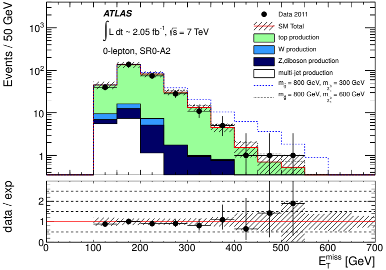
Most sensitive SR



arXiv:1203.6193

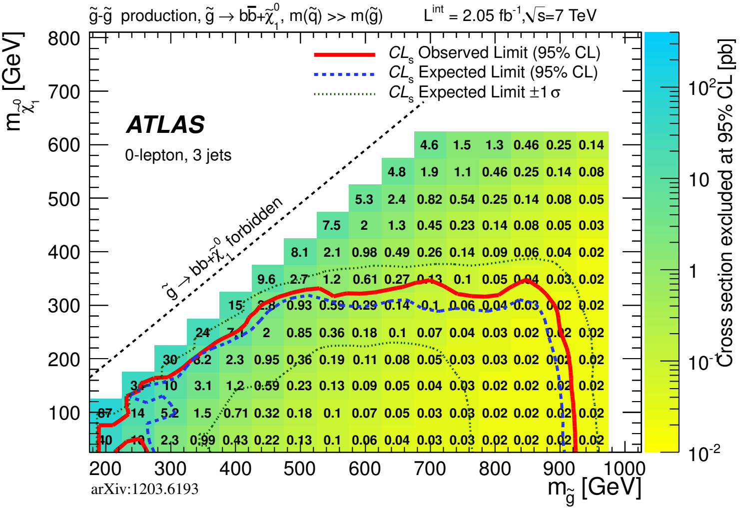
	$m_{eff} > 500$ GeV	$m_{eff} > 700$ GeV	$m_{eff} > 900$ GeV
≥ 1 b-tag	SR0-A1	SR0-B1	SR0-C1
≥ 2 b-tag	SR0-A2	SR0-B2	SR0-C2

$\tilde{g} \rightarrow \tilde{b}$ Signal Region Data/Simulation Comparisons

	≥ 1 b-tag	≥ 2 b-tags
m_{eff}		
$\not\!\!E_T$		

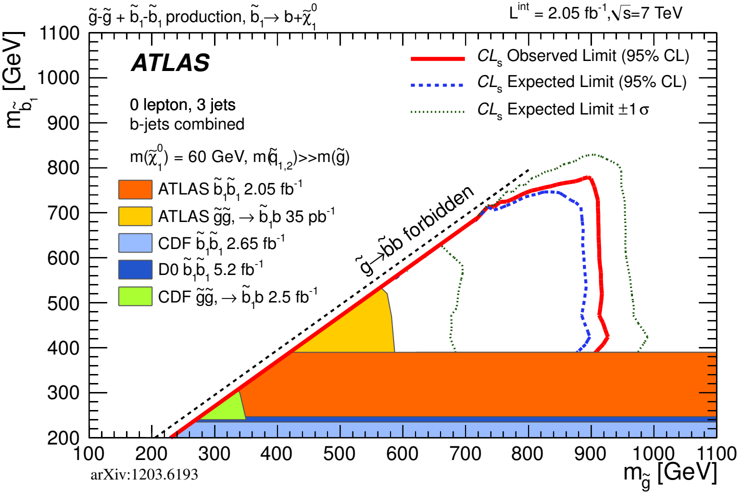
arXiv:1203.6193

Limits on 3-body $\tilde{g} \rightarrow \tilde{b}$ Models ($\tilde{g} \rightarrow b\bar{b} + \tilde{\chi}^0$)



LSP masses below 300 GeV are excluded for gluino masses in the range 200-900 GeV, if $m_{\tilde{g}} - m_{\tilde{\chi}^0} > 100$ GeV

Limits on Cascade $\tilde{g} \rightarrow \tilde{b}$ Models ($\tilde{g} \rightarrow \tilde{b}$, $\tilde{b} \rightarrow b + \tilde{\chi}^0$)



Gluino and sbotttom masses below 900 GeV and 750 GeV, respectively, are excluded for $m_{\tilde{\chi}^0} = 60$ GeV.

$\tilde{g} \rightarrow \tilde{t}$ Signal Regions - arXiv:1203.6193

- 2.05 fb^{-1} of data collected with the ATLAS detector in 2011
- Single lepton (+ jet) triggers
- Top/W/Z/diboson estimate done together with semi-DD approach
- Total background systematic uncertainty 35% to 55%

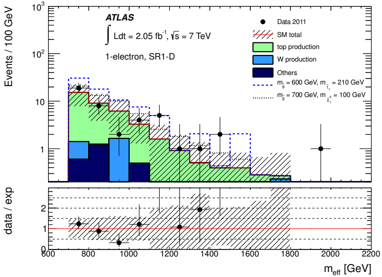
Motivation	Cut	Details
Trigger	1 $e(\mu)$ with $p_{\mathrm{T}} > 25(20)$ GeV 1 jet with $p_{\mathrm{T}} > 60$ GeV	Turn-on plateau Turn-on plateau (muon)
W+jets Rej.	$m_T > 100$ GeV	$\not{E}_T$ from $W \rightarrow l\nu$
Signal Enhancement	$\not{E}_T > 80$ GeV 3 additional jets with $p_{\mathrm{T}} > 50$ GeV $\geq$1 b-tagged jets (60% eff.)	"JetFitter" + neural network
Signal Regions	$m_{eff} > 700$ GeV $m_{eff} > 700$ GeV, $\not{E}_T > 200$ GeV	SR1-D SR1-E

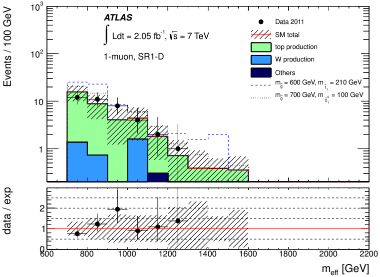
$$m_T \equiv \sqrt{2 \times p_T^{lep} \times \not{E}_T \times (1 - cos(\Delta\phi_{lep,\not{E}_T}))}$$

$$m_{eff} \equiv \sum_{1,2,3,4} p_T^{jet} + p_T^{lep} + \not{E}_T$$

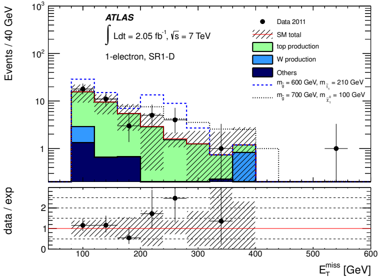
$\tilde{g} \to \tilde{t}$ Signal Region Data/Simulation Comparisons

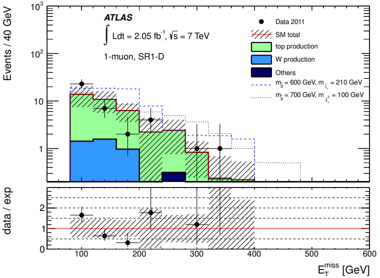
1-electron | 1-muon





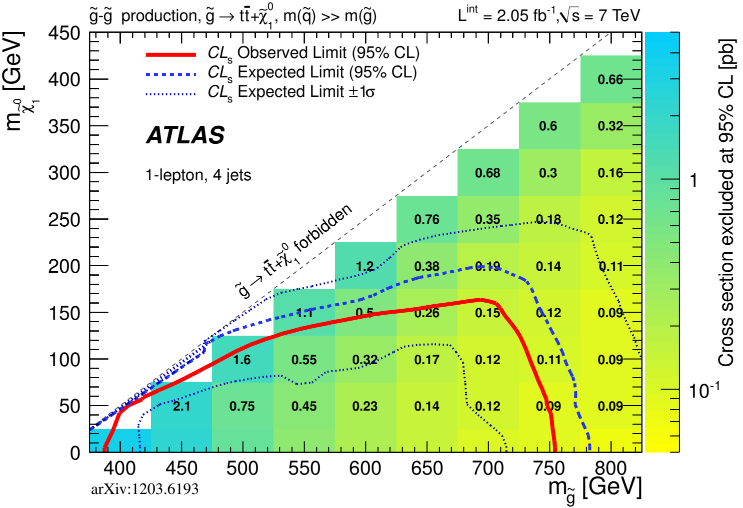
m_{eff}





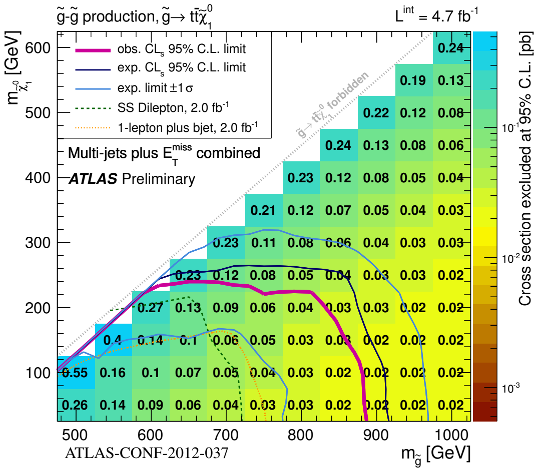
$\not{E}_T$

Limits on 3-body $\tilde{g} \rightarrow \tilde{t}$ Models ($\tilde{g} \rightarrow t\bar{t} + \tilde{\chi}^0$)



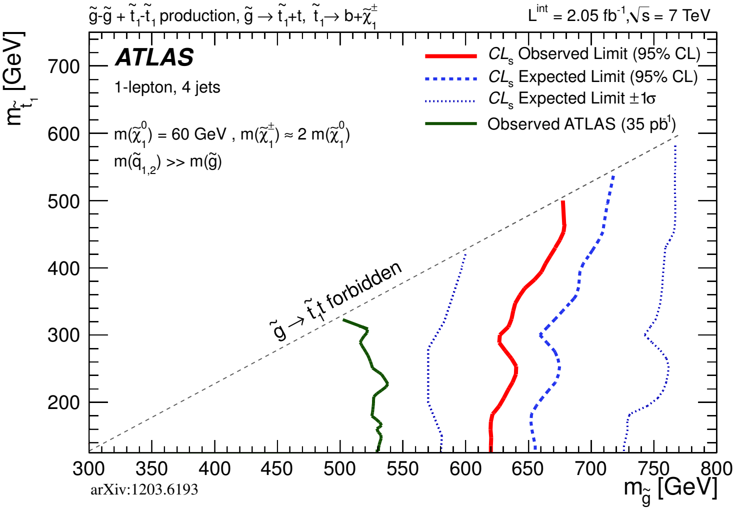
LSP masses below 50 GeV are excluded for gluino masses below 750 GeV while LSP masses below 160 GeV are excluded for $m_{\tilde{g}}$ = 700 GeV

$4.7\ fb^{-1}$ Inclusive Jets + $\not\!\!E_T$ Limits on 3-body $\tilde{g} \to \tilde{t}$ Models



Much better ATLAS limits on this model exist courtesy of the $4.7\ \text{fb}^{-1}$ inclusive jets + $\not\!\!E_T$ analysis (Devin Harper's talk, the first in this session).

Limits on Cascade $\tilde{g} \rightarrow \tilde{t}$ Models ($\tilde{g} \rightarrow \tilde{t}$, $\tilde{t} \rightarrow t + \tilde{\chi}^0$)

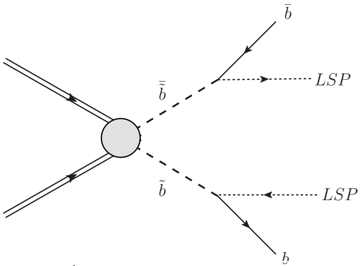


Gluino and sbotttom masses below 620 GeV and 440 GeV, respectively, are excluded for $m_{\tilde{\chi}^0} = 60$ GeV.

$\tilde{b}\tilde{b}$ Event Selection - arXiv:1112.3832

Sbottom Pair Simplified Model

- 2.05 fb^{-1} (ATLAS 2011)
- Single jet + $\not{E}_T$ trigger
- Total σ_{bkg} (Top/W+h.f. and Z+h.f. dominant) 17% to 43%
- Final state signature 2 b-jets + $\not{E}_T$

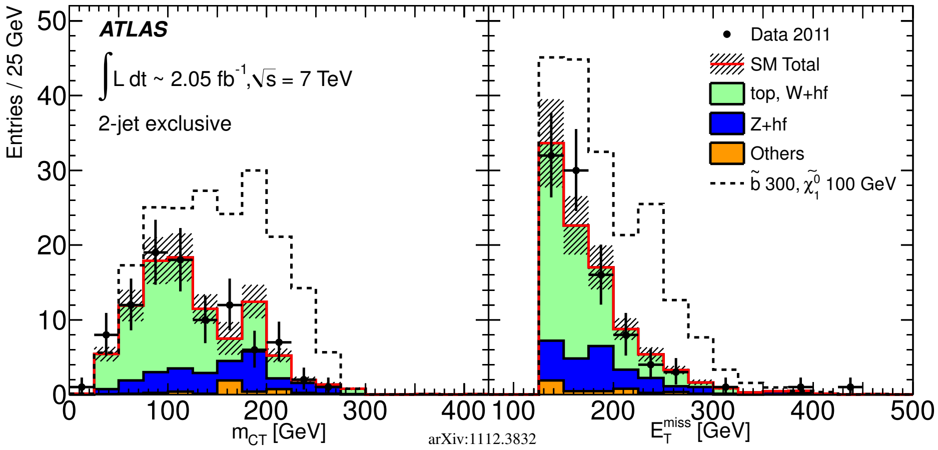


Motivation	Cut	Details
QCD Rejection	$\Delta\phi(J1/2, \not{E}_T) > 0.4$ $\Delta\phi(J3, \not{E}_T) > 0.2$ $\not{E}_T/m_{eff} > 0.25$	Fake $\not{E}_T$ due to mis-measured jets
Signal Enhancement	==1 additional jet, p_T> 50 GeV 2 leading jets b-tagged	"JetFitter" + neural network

Signal regions defined by contransverse mass (m_{CT}), for $t\bar{t}$ reduction

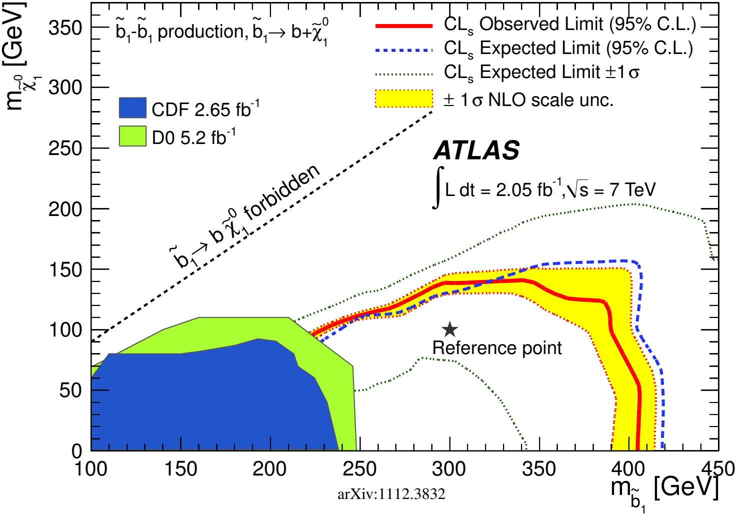
$$m_{CT}^2(b_1, b_2) = [E_T(b_1) + E_T(b_2)]^2 - [\mathbf{p_T}(b_1) - \mathbf{p_T}(b_2)]^2$$

$\tilde{b}\tilde{b}$ Signal Region Data/Simulation Comparisons



arXiv:1112.3832

Limits on $\tilde{b}\tilde{b}$ Production ($\tilde{b} \rightarrow b + \tilde{\chi}^0$)



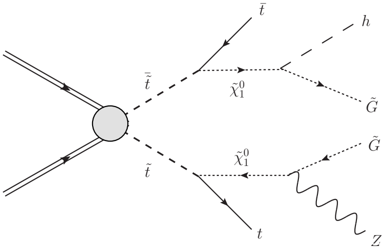
arXiv:1112.3832

LSP masses below 100 GeV are excluded for sbottom masses in the range 250-390 GeV

$\tilde{t}\tilde{t}$ GMSB Event Selection - ATLAS-CONF-2012-036

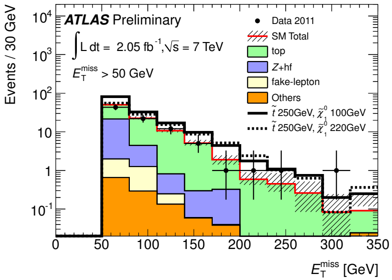
M. Asano et al., JHEP 12, 019 (2010)

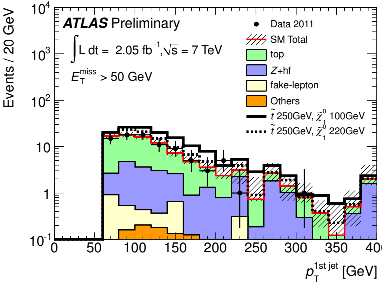
- 2.05 fb^{-1} (ATLAS 2011)
- Single lepton (+ jet) triggers
- Total σ_{bkg} 21% (SR1) and 14% (SR2)
- Final state signature $\geq$ 1 b-jets, 2 opposite-sign same-flavor leptons consistent with m_Z, and $\not{E}_T$

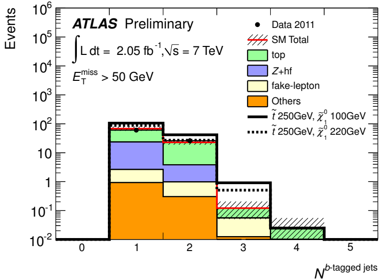


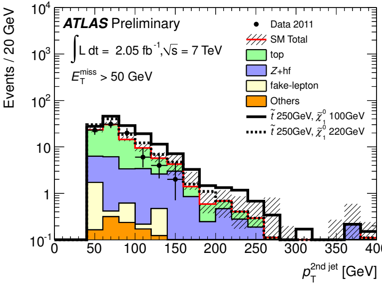
Motivation	Cut	Details
Trigger	1 $e(\mu)$ with $p_T >$ 25(20) GeV 1 jet with $p_T >$ 60 GeV	Turn-on plateau Turn-on plateau (muon)
Signal Enhancement	2 SF/OS lepton, 86 GeV $< m_{ll} <$ 96 GeV 1 additional jet with $p_T >$ 50 GeV $\geq$1 b-tagged jets (60% eff.)	Z mass window "JetFitter" + neural network
Signal Regions	$\not{E}_T > 50$ GeV $\not{E}_T > 80$ GeV	SR1, large $\Delta m(\tilde{t},\tilde{\chi}^0)$, light $\tilde{t}$ SR2, small $\Delta m(\tilde{t},\tilde{\chi}^0)$

$\tilde{t}\tilde{t}$ GMSB Signal Region Data/Simulation Comparisons



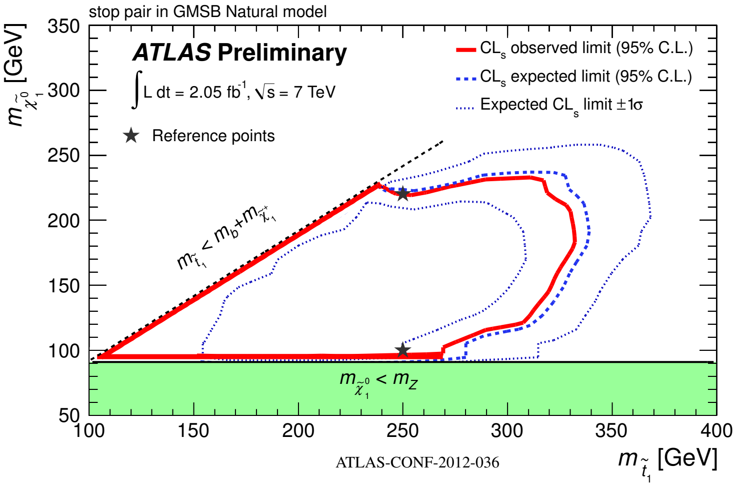






ATLAS-CONF-2012-036

Limits on $\tilde{t}\tilde{t}$ Production (GMSB)

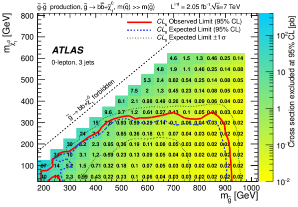


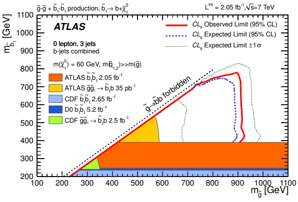
Neutralino masses below 220 GeV are excluded for stop masses below 270 GeV, and below stop masses of 310 GeV for 125 GeV $< m_{\tilde{\chi}^0} <$ 220 GeV

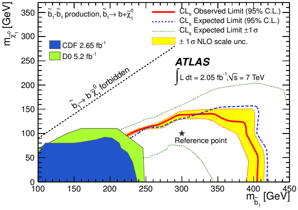
Summary of 2.05 fb^{-1} Heavy Flavor SUSY Searches

3-body | Cascade | Direct

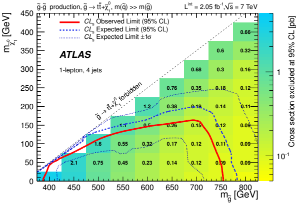
$\tilde{b}$

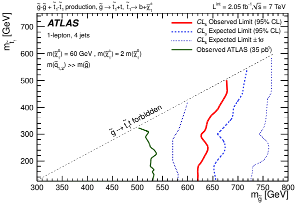


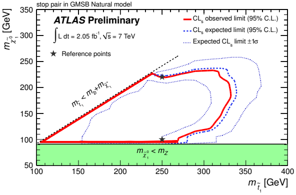




$\tilde{t}$







Looking forward to many full 5 fb^{-1} 7 TeV results and to analyzing the incoming 8 TeV data!

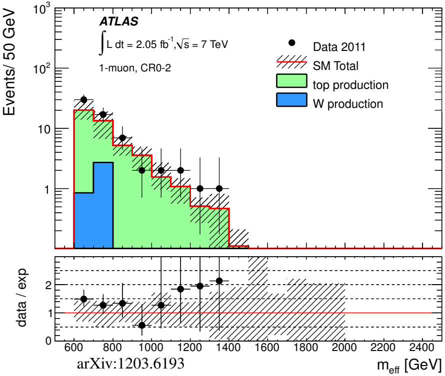
Backup

$\tilde{g} \rightarrow \tilde{b}$ Top Background Estimation

For top backgrounds (dominant) a semi data-driven approach based on 1-lepton control regions (CRs) was used:

- Exactly 1 electron (muon) with $p_T > 25$ (20) GeV
- $\geq$3 jets with $p_T > 130, 50$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV
- $40 < m_T$ (transverse mass of lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$) < 100 GeV
- $m_{eff} > 600$ GeV
- $\geq$1, $\geq$2 b-tags

Example CR



arXiv:1203.6193

Predicted yield in SR is MC Ratio $\times$ 1 l-CR yield (corrected for non-t):

$$N_{SR}^{top} = \left(\frac{N_{SR}}{N_{CR}}\right)_{MC}^{top} \times [N_{CR}^{data} - N_{CR}^{W/Z,MC} - N_{CR}^{others,MC} - N_{CR}^{QCD}]$$

MC ratio allows partial cancellation of detector and theoretical uncertainties

Total top uncertainty is between 15-40%, as is the total background uncertainty

$\tilde{g} \rightarrow \tilde{b}$ *W/Z and QCD Backgrounds*

The W/Z backgrounds were estimated using Monte Carlo simulation.

The QCD background was estimated from data, as leading-order Monte Carlo was not sufficient to provide a reliable estimate.

Fundamental Assumption: $\not\!\!E_T$ in QCD multi-jet background due to mis-measured jets

- Jet momenta in data events with low $\not\!\!E_T$ significance smeared with a jet response function to generate pseudoevents with large $\not\!\!E_T$.
- Validated by comparing data and pseudoevent distributions in QCD-enriched ($\Delta\phi(jet, \not\!\!E_T) < 0.4$) control regions.

$\tilde{g} \rightarrow \tilde{b}$ Background Systematic Uncertainties

MC-based (W/Z) - 30-80%

- Jet energy scale/resolution: 20-40%
- *b*-tagging efficiency: 20-35%
- Theoretical: 25-30%
- W/Z+heavy flavor: 70%
- Integrated luminosity: 3.7%

QCD - 50-70%

- Smearing function dependency on flavor composition of the low-$\not{E}_T$ unsmeared sample, jet response tuning

Top - 15-40%

SR	JES/ JER	*b*-tag	lepton ID	top theory	others	total
SR0-A1	4	3	2	11	10	15
SR0-B1	3	3	2	20	10	22
SR0-C1	3	4	2	35	11	37
SR0-A2	3	3	2	15	17	23
SR0-B2	3	4	2	20	10	22
SR0-C2	3	2	2	30	12	32

arXiv:1203.6193

$\tilde{g} \rightarrow \tilde{b}$ *Signal Region Data/Simulation Comparisons*

Good agreement is observed between the Standard Model expectation and data for all signal regions.

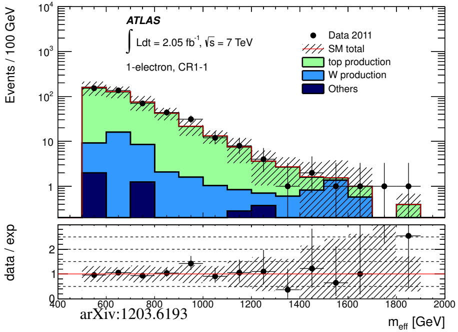
SR	Top	W/Z	multi-jet/ di-boson	Total	Data
SR0-A1	705 ± 110	248 ± 150	53 ± 21	1000 ± 180	1112
SR0-B1	119 ± 26	67 ± 42	7.3 ± 4.7	190 ± 50	197
SR0-C1	22 ± 9	16 ± 11	1.5 ± 1	39 ± 14	34
SR0-A2	272 ± 70	22.5 ± 15	21 ± 12	316 ± 72	299
SR0-B2	47 ± 11	4.5 ± 3	2.8 ± 1.7	54 ± 11	43
SR0-C2	8.5 ± 3	0.8 ± 1	0.5 ± 0.4	9.8 ± 3.2	8

arXiv:1203.6193

For top/W/Z/diboson backgrounds (dominant) the same semi data-driven approach used for the top estimation in the $\tilde{g} \rightarrow \tilde{b}$ analysis was also used, though the CR differs (red):

- Exactly 1 electron (muon) with $p_T > 25$ (20) GeV
- ≥ 4 jets with $p_T > 60$, 50 GeV
- $\not{E}_T > 80$ GeV
- $40 < m_T < 100$ GeV
- $m_{eff} > 600$ GeV
- ≥ 1 b-tag

Example CR



arXiv:1203.6193

Predicted yield in SR is MC Ratio × 1 l-CR yield (corrected for QCD):

$$N_{SR}^{non-QCD} = \left(\frac{N_{SR}}{N_{CR}}\right)_{MC}^{non-QCD} \times [N_{CR}^{data} - N_{CR}^{QCD}]$$

Total background systematic uncertainty between 35-55%

$\tilde{g} \rightarrow \tilde{t}$ Signal Region Data/Simulation Comparisons

Good agreement is observed between the Standard Model expectation and data for all signal regions.

SR	SM background	Data
SR1-D (e)	39 ± 12 (39)	43
SR1-D (μ)	38 ± 14 (37)	38
SR1-E (e)	8.1 ± 3.4 (7.9)	11
SR1-E (μ)	6.3 ± 4.2 (6.1)	6

arXiv:1203.6193

$\tilde{g} \to \tilde{b}/\tilde{t}$ Effective Cross Section Limits

Signal-independent upper limits on the non-SM contributions to each signal region can be defined in terms of event yield and effective cross section ($\sigma_{eff} = \sigma \times BR \times \epsilon$).

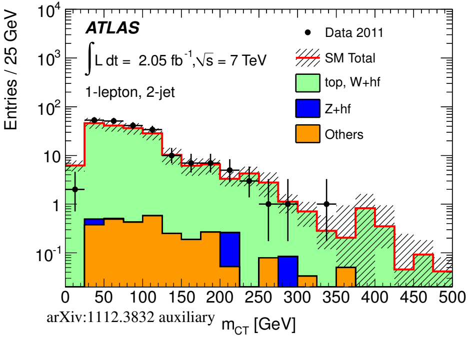
SR	95% CL upper limit	
	N events obs. (exp.)	σ_{vis}(fb) obs. (exp.)
SR0-A1	578 (516)	282 (251)
SR0-B1	133 (133)	65 (65)
SR0-C1	31.6 (34.6)	15.4 (16.9)
SR0-A2	124 (134)	61 (66)
SR0-B2	29.6 (31.0)	14.4 (15.0)
SR0-C2	8.9 (10.3)	4.3 (5.0)
SR1-D	45.5 (42.1)	22.2 (20.5)
SR1-E	17.5 (15.3)	8.5 (7.5)

arXiv:1203.6193

For top/W+h.f. backgrounds a 1-lepton control region was used:

- Exactly 1 electron (muon) with $p_T > 25$ (20) GeV
- $\geq$2 b-tagged jets with $p_T >$ 130, 50 GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV
- $40 < m_T < 100$ GeV

Example CR



arXiv:1112.3832 auxiliary

Predicted yield in SR is MC Ratio $\times$ 1l-CR yield (corrected for non-t/W+h.f.):

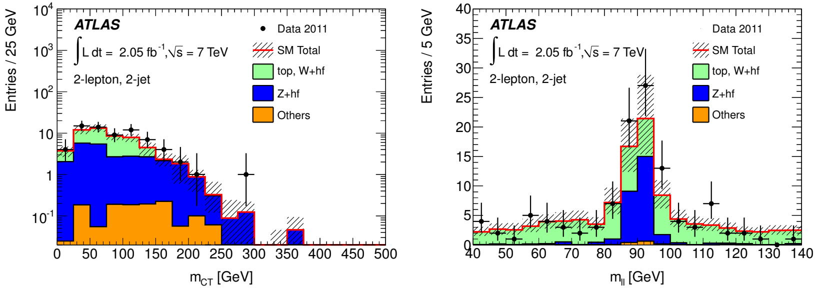
$$N_{SR}^{top/W+h.f.} = \left(\frac{N_{SR}}{N_{CR}}\right)_{MC}^{top/W+h.f.} \times [N_{CR}^{data} - N_{CR}^{Z,MC} - N_{CR}^{others,MC} - N_{CR}^{QCD}]$$

$\tilde{b}\tilde{b}$ $Z \rightarrow \nu\nu + bb$ Background Estimation

For the Z+h.f. background a 2-lepton opposite-sign same-flavor control region was used:

- Exactly 2 electrons (muons) with $p_T > 25$ (20) GeV
- $\geq$2 b-tagged jets with $p_T > 80$, 50 GeV
- "adjusted" $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV
- $80 < m_{ll} < 101$ GeV (Z mass window)

The momenta of the leptons were added to the $\not{E}_T$ to mimic a $Z \rightarrow \nu\nu$ decay. The $t\bar{t}$ contribution to this CR is significant ($\approx 50\%$) and was subtracted using a sideband estimate.



arXiv:1112.3832 auxiliary

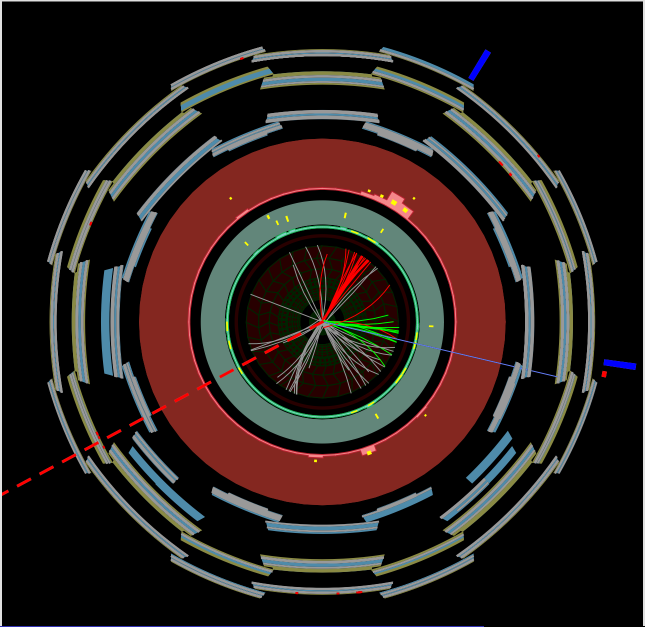
$\tilde{b}\tilde{b}$ Background Systematic Uncertainties

The total systematic uncertainty on the background estimates varies from 21% to 44%, increases with increasing m_{CT} cut, and is dominated by CR statistical uncertainties.

Sub-dominant uncertainties include:

- Top/W+h.f. theoretical uncertainties, 10-15%. Evaluated using additional MC samples with alternative generator, initial/final state radiation parameters, and fragmentation model
- Jet energy scale/resolution, 6-9%
- *b*-tagging efficiency, 5-8%
- W/Z+h.f. theoretical uncertainties, <5%

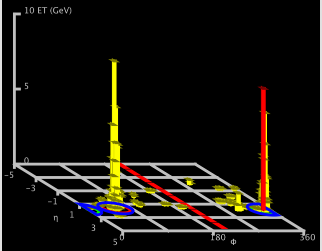
$\tilde{b}\tilde{b}$ Signal Region Event



ATLAS EXPERIMENT

Run Number: 182787, Event Number: 13824019

Date: 2011-05-29 11:51:09 CEST



$\tilde{b}\tilde{b}$ Signal Region Data/Simulation Comparisons

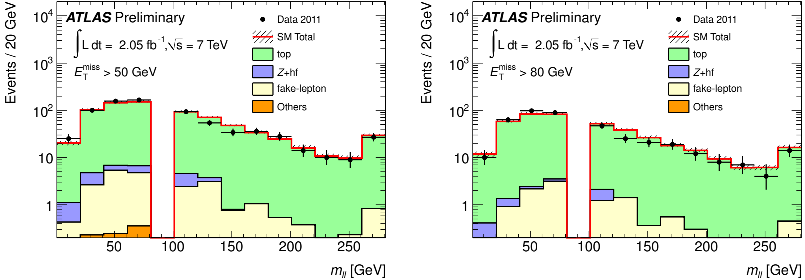
Good agreement is observed between the Standard Model expectation and data for all signal regions.

m_{CT} GeV	top, W+h.f. TF (MC)	Z+h.f. TF (MC)	Others MC+JS	Total SM	Data
0	67 ± 10 (60 ± 25)	23 ± 8 (16 ± 9)	3.6 ± 1.5	94 ± 16 (80 ± 35)	96
100	36 ± 10 (34 ± 16)	23 ± 9 (12 ± 7)	3.1 ± 1.6	62 ± 13 (49 ± 25)	56
150	12 ± 5 (13 ± 8)	12 ± 6 (8.3 ± 4.7)	2.7 ± 0.9	27 ± 8 (24 ± 13)	28
200	3.2 ± 1.6 (4.1 ± 3.4)	3.9 ± 3.2 (2.8 ± 1.5)	1.0 ± 0.9	8.1 ± 3.5 (8.0 ± 4.9)	10

arXiv:1203.6193

$\tilde{t}\tilde{t}$ Top Background Estimation

For top backgrounds a reversed m_Z control region was used: 15 GeV $< m_{ll} <$ 81 GeV or $m_{ll} >$ 101 GeV



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Predicted yield in SR is MC Ratio × 1l-CR yield (corrected for non-t):

$$N_{SR}^{top} = \left(\frac{N_{SR}}{N_{CR}}\right)_{MC}^{top} \times [N_{CR}^{data} - N_{CR}^{Z,MC} - N_{CR}^{others,MC} - N_{CR}^{"fake-lepton"}]$$

ATLAS Detector

The ATLAS detector is one of two general-purpose detectors built to collect pp collision data from the Large Hadron Collider at CERN. It consists of 4 major components: the inner detector (tracking), the calorimeters (energy measurements), the muon spectrometer, and the magnet and cooling systems.