Search for supersymmetry in events involving third generation squarks and sleptons with ATLAS

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CIPANP, May 29 - June 3, 2012
St. Petersburg, Florida

Introduction

- Supersymmetry (SUSY) – focus on R-parity conserving models
 - ▷ Stable LSP – large missing transverse momentum E_T^{miss}
- Left- and right-handed gauge states mix to form mass eigenstates
 - ▷ Large mixing $\rightarrow$ lighter 3rd generation squarks and sleptons
 - ▷ Sub-TeV stop/sbottom favored by the naturalness argument
- Scalar top ($\tilde{t}_1$) and bottom ($\tilde{b}_1$) – direct pair production or in $\tilde{g}$ - pair production
- Scalar tau ($\tilde{\tau}_1$) – lightest slepton, produced in cascade decays

General approach in ATLAS SUSY searches

- Trigger selection – three levels with increasing refinement
- Event quality pre-selection – Integrated luminosity 2.05 fb^{-1}
- Offline object selection assures plateau trigger efficiency
- Signal regions (SR) optimized for characteristic final states using bench mark models. Defined by: jets, b-jets, leptons, E_T^{miss} ,

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum_{\text{jets}} p_T (+ \sum_{\text{lep}} p_T) \quad m_T = \sqrt{2p_T^l E_T^{\text{miss}} - 2\mathbf{p}_T^l \cdot \mathbf{p}_T^{\text{miss}}}$$

- Background estimation
 - ▷ Data- and semi-data driven methods (details in backup)
- Systematic uncertainties
 - ▷ Detector related and theoretical
- In absence of significant excess: set model independent 95% C.L. upper limits on contribution from new physics using the CL_S prescription
- Results interpreted within context of various models
 - ▷ 95% C.L. exclusion limits on model parameters, particle masses

Searches for SUSY with jets, missing transverse momentum and one – two tau leptons

Publications:

- $1 \tau + E_T^{miss} + \text{jets}$ with 2 fb^{-1} : arXiv:1204.3852 submitted to PLB
- $2 \tau + E_T^{miss} + \text{jets}$ with 2 fb^{-1} : arXiv:1203.6580 submitted to PLB

Final states with ≥ 1 or ≥ 2 τ jets and E_T^{miss}

- Final states with taus studied in context of GMSB – light $\tilde{\tau}_1$
- Two analyses – common event preselection
 - E_T^{miss} and $p_T(j_1) > 130$ GeV (trigger offline)
 - Lepton (e, μ) veto
- Backgrounds: top, $W + jets$, $Z + jets$, multijet, real and fake τ
- ≥ 1 tight hadronic τ , $p_T > 20$ GeV
- $m_T^\tau > 110$ GeV
- $m_{eff} > 600$ GeV
- ≥ 2 loose hadronic τ , $p_T > 20$ GeV
- $m_{eff} > 700$ GeV
- $m_T^{\tau_1} + m_T^{\tau_2} > 80$ GeV

Final states with taus: Interpretation

- Data in agreement with SM prediction
 - ▷ Upper limit at 95% C.L.
- **GMSB** – grid
 - ▷ LSP is $\tilde{G}$, $m_{\tilde{G}} \ll 1$ keV
 - ▷ $M_{mess} = 250$ TeV, $N_5 = 3$, $\mu > 0$, $C_{grav} = 1$
- Free model parameters:
 - ▷ Λ – scale of the SUSY breaking
 - ▷ $\tan \beta$ – ratio of the two Higgsino doublet vacuum expectation value
- Gluino and squark production, decay to NLSP – $\tilde{\tau}_1$ in most of the parameter space
→ LSP + SM particles
- Exclusion limits on GMSB parameters
 - ▷ **1 τ** : $\Lambda < 30$ TeV,
best $\Lambda = 43$ TeV for high $\tan \beta$
 - ▷ **2 τ** : $\Lambda < 32$ TeV,
best $\Lambda = 47$ TeV $\tan \beta = 37$

ATLAS dilepton (e, μ) OS with 1 fb⁻¹ (ATLAS-CONF-2011-156)

Searches for SUSY with b-jets, missing transverse momentum and 0 or 1 leptons

Publications:

- arXiv:1203.6193 Accepted by PRD
- Gluino mediated sbottom production $\tilde{g} \rightarrow \tilde{b}_1 b \rightarrow b \bar{b} \tilde{\chi}_1^0$, $\tilde{g} \rightarrow b \bar{b} \tilde{\chi}_1^0$ via $\tilde{b}_1^*$
- Gluino mediated stop production $\tilde{g} \rightarrow \tilde{t}_1 t \rightarrow t \bar{t} \tilde{\chi}_1^0$, $\tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0$ via $\tilde{t}_1^*$
- A search sensitive to many scenarios

Final states with b-jets, jets, E_T^{miss} , 0-1 leptons

- 0-lepton channel optimized for $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$, 1-lepton for $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$,

Pre-selection	Signal Region name	Selection
no leptons, at least three jets, $p_T(j1) > 130$ GeV, $p_T(j2, j3) > 50$ GeV, $E_T^{miss} > 130$ GeV, $E_T^{miss}/m_{eff} > 0.25$, $\Delta\phi_{min} > 0.4$	SR0-A1 SR0-B1 SR0-C1 SR0-A2 SR0-B2 SR0-C2	at least one b -tag, $m_{eff} > 500$ GeV at least one b -tag, $m_{eff} > 700$ GeV at least one b -tag, $m_{eff} > 900$ GeV at least two b -tags, $m_{eff} > 500$ GeV at least two b -tags, $m_{eff} > 700$ GeV at least two b -tags, $m_{eff} > 900$ GeV
one lepton, at least four jets $p_T(j1) > 60$ GeV, $p_T(j2, j3, j4) > 50$ GeV, $E_T^{miss} > 80$ GeV, $m_T > 100$ GeV, at least one b -tag	SR1-D SR1-E	$m_{eff} > 700$ GeV $m_{eff} > 700$ GeV, $E_T^{miss} > 200$ GeV

- SM background: top (single and in pair), W/Z with heavy-flavor jets, multiple-jets

Final states with b-jets, jets, E_T^{miss} , 0-1 leptons: Results

0-lepton channel

SR	Top	W/Z	QCD/ di-boson	Total	Data
SR0-A1	705 ± 110 (725)	248 ± 150	53 ± 21	1000 ± 180	1112
SR0-B1	119 ± 26 (122)	67 ± 42	7.3 ± 4.7	190 ± 50	197
SR0-C1	22 ± 9 (22)	16 ± 11	1.5 ± 1	39 ± 14	34
SR0-A2	272 ± 70 (212)	22.5 ± 15	21 ± 12	316 ± 72	299
SR0-B2	47 ± 11 (37)	4.5 ± 3	2.8 ± 1.7	54 ± 11	43
SR0-C2	8.5 ± 3 (6.6)	0.8 ± 1	0.5 ± 0.4	9.8 ± 3.2	8

- Interpretation:
- MSSM Gluino-sbottom models: $m_{\tilde{g}} > m_{\tilde{b}_1}$
 - ▷ $\tilde{g} \rightarrow \tilde{b}_1 b$, $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$
- Gbb: simplified scenario, $m_{\tilde{g}} < m_{\tilde{b}_1}$
 - ▷ $\tilde{g}$ decay via $\tilde{b}_1^*$, $\tilde{b}_1^* \rightarrow b \tilde{\chi}_1^0$

1-lepton channel

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

MC yields in parenthesis

- Interpretation:
- MSSM Gluino-stop models $m_{\tilde{g}} > m_{\tilde{t}_1} + m_t$
 - ▷ $\tilde{g} \rightarrow \tilde{t}_1 t$, $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm$
- Gtt: simplified scenario $m_{\tilde{g}} < m_{\tilde{t}_1}$
 - ▷ $\tilde{g}$ decay via $\tilde{t}_1^*$, $\tilde{t}_1^* \rightarrow t \tilde{\chi}_1^0$

Final states with b-jets, jets, E_T^{miss} , 0-1 leptons: Limits

0-lep.
 $\tilde{b}_1$ -prod.

300

1-lep.
 $\tilde{t}_1$ -prod.

160

Searches for scalar bottom quark production 2 b-jets, 0 leptons and E_T^{miss}

Publications:

- PRL 108 (2012) 181802
- Direct sbottom pair production, $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$

Final states with 2 b-jets and E_T^{miss}

- Event selection:
- $p_T(j1), E_T^{miss} > 130$ GeV (trig.)
- Exactly 2 b-jets, lepton veto (e, μ)
- Signal region selection based on boost-corrected contranverse mass

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

- Sbottom pair production $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$
 m_{CT} endpoint at

$$\frac{m(\tilde{b}_1)^2 - m(\tilde{\chi}_1^0)^2}{m(\tilde{b}_1)}$$

- $t\bar{t}$ production endpoint at 135 GeV
- 3 signal regions:
 $m_{CT} > 100, 150, 200$ GeV

- Dominant SM backgrounds

- ▷ $m_{CT} > 100$ GeV:
Top, Z/W+ heavy flavor
- ▷ $m_{CT} > 150, 200$ GeV:
Z/W+ heavy flavor

m_{CT} : JHEP 0804, 034 (2008), JHEP 1003, 030 (2010)

Final states with 2 b-jets and E_T^{miss} : Results

- Good agreement data and SM prediction
- Interpretation within model with $\tilde{b}$ -pair production, assuming $\text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 1$
- Exclusion limits in $(m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0})$ plane
 - ▷ $m_{\tilde{b}_1} < 390$ GeV for $m_{\tilde{\chi}_1^0} = 0$ GeV
 - ▷ $m_{\tilde{\chi}_1^0} < 120$ GeV for $275 < m_{\tilde{b}_1} < 350$ GeV

m_{CT} GeV	top, W+hf TF (MC)	Z+hf 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

Searches for scalar top quark production 2 leptons and E_T^{miss}

Publications:

- 2 / SS + jets + E_T^{miss} : arXiv:1203.5763 Submitted to PRL
- 2 / SFOS + jets + E_T^{miss} : arXiv:1204.6736 Submitted to PLB

2 / SS + jets + E_T^{miss} : gluino mediated stop production

- Gluino is a Majorana-particle – equal probability for SS as for OS

- 2 leading leptons (e, μ) SS, $p_T > 20$ GeV

- $N_{jet} \geq 4$, $p_T(j_4) > 50$ GeV

▷ SR1: $E_T^{miss} > 150$ GeV

▷ SR2: $E_T^{miss} > 150$ GeV and $m_T > 100$ GeV

- Results in SR2 interpreted within $\tilde{g}\tilde{g}$ production

▷ Gtt simplified scenario: $m_{\tilde{g}} < m_{\tilde{t}_1}$, $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ via $\tilde{t}_1^*$

▷ MSSM scenario $\tilde{g} \rightarrow \tilde{t}_1 t$ and $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$

- No events observed with $E_T^{miss} > 150$ GeV

2 / SS + jets + E_T^{miss} : gluino mediated stop production

● Excluded:

$m_{\tilde{g}} < 650(720)$ GeV for $m_{\tilde{\chi}_1^0} < 215(100)$ GeV

$m_{\tilde{g}} < 670$ GeV for $m_{\tilde{t}_1} < 460$ GeV

2 | SFOS + jets + E_T^{miss} : direct stop, GMSB

- Direct stop pair production assuming GMSB: $\tilde{\chi}_1^0$ higgsino-like NLSP
 - Decay: $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ or $\tilde{t}_1 \rightarrow t\tilde{\chi}_{1,(2)}^0$ $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$ branching ratio 1-0.65

- SFOS pair with $86 < m_{\ell+\ell-} < 96$ GeV
- At least: $p_T(j_2) > 50$ GeV one b-tagged
 - SR1 $E_T^{miss} > 50$ GeV SR2 $E_T^{miss} > 80$ GeV

- Background: Top, Z+ heavy-flavor jets

- Excluded: $m_{\tilde{t}_1} < 310$ GeV for $115 < m_{\tilde{\chi}_1^0} < 230$ GeV

	$ee+\mu\mu$	
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)

Hunt for new phenomena using large jet multiplicity and E_T^{miss}

Publications:

- 6-9 jets + E_T^{miss} : ATLAS-CONF-2012-037
- Full 2011 data set 4.7 fb^{-1}

Multi-jets: Event selection

- Gluino pair production in scenarios with $m_{\tilde{g}} < m_{\tilde{q}}$, possibly dominant decay:

$$\tilde{g} + \tilde{g} \rightarrow (t + \tilde{t} + \tilde{\chi}_1^0) + (t + \tilde{t} + \tilde{\chi}_1^0)$$

Signal region	7j55	8j55	9j55	6j80	7j80	8j80
Isolated leptons (e, μ)	=0					
Jet p_T	> 55 GeV			> 80 GeV		
Jet $ \eta $	< 2.8					
Number of jets	≥ 7	≥ 8	≥ 9	≥ 6	≥ 7	≥ 8
$E_T^{\text{miss}} / \sqrt{H_T}$	> 4 GeV ^{1/2}					

- $E_T^{\text{miss}} / \sqrt{H_T}$ – estimate of the E_T^{miss} significance
- $H_T = \sum_i p_T(\text{jet}_i)$
- Background:
 - Multi-jet production, including fully hadronic top
 - Leptonic top, Z/W + jets
- Multi-jet background
 - Fully data driven estimate

Multi-jets: Results

Signal regions	7j55	8j55	9j55	6j80	7j80	8j80
Total SM	167 ± 34	17 ± 7	1.9 ± 0.8	107 ± 21	8.6 ± 2.5	0.8 ± 0.45
Data	154	22	3	106	15	1

- Most discrepant 7j80 – p-value = 0.07
- MSUGRA/CMSSM
 $\tan \beta = 10, A_0 = 0, \mu > 0$
- Excluded: $m_{\tilde{g}luino} < 850$ GeV

- Gtt: simplified scenario, $\tilde{g}\tilde{g}$ production
- $m_{\tilde{g}} < m_{\tilde{t}_1}$, decay $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ via $\tilde{t}_1^*$
- $m_{\tilde{g}} < 880$ GeV for $m_{\tilde{\chi}_1^0} < 100$ GeV

Conclusions

- ATLAS has a wide range of SUSY searches involving third generation squarks and sleptons
- No significant excess observed with respect to SM predictions
- 95% C.L. upper limits on number of events and visible cross sections for BSM contributions are set
- Results are interpreted within a variety of SUSY models

1 TeV

Gluinomed. $\tilde{b}(\tilde{g} \rightarrow b\tilde{\chi}_1^0):0\text{-lep}+b\text{-j's}+$	$E_{T,\text{miss}}$	$L=2.1\text{fb}^{-1}[2011][\text{ATLAS-CONF-2012-003}]$	900GeV	$\tilde{g}\text{mass}(m(\tilde{\chi}_1^0)<300\text{GeV})$
Gluinomed. $\tilde{t}(\tilde{g} \rightarrow t\tilde{\chi}_1^0):1\text{-lep}+b\text{-j's}+$	$E_{T,\text{miss}}$	$L=2.1\text{fb}^{-1}[2011][\text{ATLAS-CONF-2012-003}]$	710GeV	$\tilde{g}\text{mass}(m(\tilde{\chi}_1^0)<150\text{GeV})$
Gluinomed. $\tilde{t}(\tilde{g} \rightarrow t\tilde{\chi}_1^0):2\text{-lep(SS)}+j\text{'s}+$	$E_{T,\text{miss}}$	$L=2.1\text{fb}^{-1}[2011][\text{ATLAS-CONF-2012-004}]$	650GeV	$\tilde{g}\text{mass}(m(\tilde{\chi}_1^0)<210\text{GeV})$
Gluinomed. $\tilde{t}(\tilde{g} \rightarrow t\tilde{\chi}_1^0):\text{multi-j's}+$	$E_{T,\text{miss}}$	$L=4.7\text{fb}^{-1}[2011][\text{ATLAS-CONF-2012-037}]$	830GeV	$\tilde{g}\text{mass}(m(\tilde{\chi}_1^0)<200\text{GeV})$
Direct $b\tilde{b}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0):2b\text{-jets}+$	$E_{T,\text{miss}}$	$L=2.1\text{fb}^{-1}[2011][1112.3832]$	390GeV	$\tilde{b}\text{mass}(m(\tilde{\chi}_1^0)<60\text{GeV})$
Direct $\tilde{t}\tilde{t}(\text{GMSB}):Z(\rightarrow ll)+b\text{-jet}+$	$E_{T,\text{miss}}$	$L=2.1\text{fb}^{-1}[2011][\text{ATLAS-CONF-2012-036}]$	310GeV	$\tilde{t}\text{mass}(115<m(\tilde{\chi}_1^0)<230\text{GeV})$
GMSB:1- $\tau+j\text{'s}+$	$E_{T,\text{miss}}$	$L=2.1\text{fb}^{-1}[2011][\text{ATLAS-CONF-2012-005}]$	920GeV	$\tilde{g}\text{mass}(\tan\beta>20)$
GMSB:2- $\tau+j\text{'s}+$	$E_{T,\text{miss}}$	$L=2.1\text{fb}^{-1}[2011][\text{ATLAS-CONF-2012-002}]$	990GeV	$\tilde{g}\text{mass}(\tan\beta>20)$

- Results with 4.7fb^{-1} , the full 2011 data set, will be available soon
- Analysis of 8 TeV 2012 has data started

Back-up slides

Background estimation

- Dominant background in most analyses: top and Z/W +jets

- Semi-data driven method based on **transfer factors** T_f^{bkg}

$$N_{SR}^{bkg\ est} = \frac{N_{SR}^{bkg\ MC}}{N_{CR}^{bkg\ MC}} (N_{CR}^{data} - N_{CR}^{other\ MC}) = T_f^{bkg} (N_{CR}^{data} - N_{CR}^{other\ MC})$$

- If event kinematics similar in SR and CR

▷ Systematic uncertainties in numerator and denominator cancel out

- 0-lepton final states: **Jet smearing method** – data-driven

- ▷ Contribution due to fake E_T^{miss} – jet energy mismeasurement
- ▷ Jet energies in events with small E_T^{miss} (seed) smeared according to response functions
- ▷ Large sample of pseudo-events passed through the analysis – contribution estimated in a QCD-enhanced region

- 1/2-lepton final states: **Matrix method** – data-driven

- ▷ Estimates contributions from non-prompt leptons arising from b/c -decay, jet, γ
- ▷ Measure in data: probability of a “loose” lepton passing “tight” selection in “real” and “fake” enhanced control regions
- ▷ Solve equation(s) which give the composition of SR in terms of “real” and “fake” leptons

- **MC based predictions** for sub-dominant modes

Final states with b-jets, jets, E_T^{miss} , 0-1 leptons: Results

- Completing the results in slide 10,11
- Interpretation in Gtb: simplified scenario
 - ▷ $\tilde{b}_1$ and $\tilde{t}_1$ lightest, $m_{\tilde{g}} < m_{\tilde{b}_1, \tilde{t}_1}$
 - ▷ $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$, $\tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$

Result table - Multi-jets

Hunt for new phenomena using large jet multiplicity and E_T^{miss}

Signal region	7j55	8j55	9j55	6j80	7j80	8j80
Multi-jets	91±20	10±3	1.2±0.4	67±12	5.4±1.7	0.42±0.16
$t\bar{t} \rightarrow q\ell, \ell\ell$	55±18	5.7±6.0	0.70±0.72	24±13	2.8±1.8	0.38±0.40
W + jets	18±11	0.81±0.72	0+0.13	13±10	0.34±0.21	0+0.06
Z + jets	2.7±1.6	0.05±0.19	0+0.12	2.7±2.9	0.10±0.17	0+0.13
Total Standard Model	167±34	17±7	1.9±0.8	107±21	8.6±2.5	0.80±0.45
Data	154	22	3	106	15	1
$N_{\text{BSM,max}}^{95\%}$ (exp)	72	16	4.5	46	8.4	3.5
$N_{\text{BSM,max}}^{95\%}$ (obs)	64	20	5.7	46	15	3.8
$\sigma_{\text{BSM,max}}^{95\%} \cdot A \cdot \epsilon$ (exp) [fb]	15	3.4	0.96	9.8	1.8	0.74
$\sigma_{\text{BSM,max}}^{95\%} \cdot A \cdot \epsilon$ (obs) [fb]	14	4.2	1.2	9.8	3.2	0.81
p_{SM}	0.64	0.27	0.28	0.52	0.07	0.43