Multi-lepton SUSY searches with the ATLAS detector

Katarina Pajchel - for the ATLAS collaboration

University of Oslo

SUSY09, Boston, June 7, 2009

- Introduction
 - ▷ Why multi-lepton SUSY searches are complementary to other searches in the mSUGRA context
- Two analysis approaches – jet exclusive and jet inclusive
 - ▷ Analysis, results
 - ▷ Trigger efficiencies, systematic uncertainties
- Conclusions

Introduction

- Minimal gravity mediated supersymmetry, mSUGRA, as example signature (R-parity conservation)
- 4 parameters: $m_0, m_{1/2}, A_0, \tan \beta$ and a sign
 - ▷ Common scalar mass (m_0) at GUT scale: sets squark and slepton mass
 - ▷ Common gaugino mass ($m_{1/2}$) at GUT scale: sets neutralino, chargino and gluino mass
- Translates into:
 - ▷ $m_{\tilde{g}} : m_{\tilde{\chi}_2^0} : m_{\tilde{\chi}_1^0} \approx 6 : 2 : 1$ at Electro Weak scale
 - ▷ Similar quasi-fixed hierarchy in the scalar sector, e.g. $m_{\tilde{q}} > m_{\tilde{l}}$
- With one exception, all ATLAS benchmark points have sparticle masses below 1 TeV

Typical mSUGRA benchmark point

Non-typical mSUGRA benchmark point

Multi-lepton SUSY signal

- Final states with 3 or more leptons from decay of heavy gauginos
 - ▷ If squark and gluino are light – they will dominate the SUSY cross section
 - ▷ Leptons from long decay chains
 - ▷ Hard jets
 - ▷ Large $\cancel{E}_T$
 - ▷ If squarks, sleptons and possibly also gluinos are heavy – direct gaugino production becomes important
 - ▷ Gauginos may decay leptonically through real or virtual $W^\pm$, Z^0 (or sleptons, if these are not too heavy)
 - ▷ Low jet activity
 - ▷ Relatively low $\cancel{E}_T$ – the gauginos are produced back to back

Gaugino pair production

- The so-called “Focus point region” of the SUSY parameter space (SU2) is particularly interesting
- Characterised by very heavy squarks and sleptons
- The gauginos are light and dominate the production cross-section
- Trilepton signal mainly from the pair production of $\chi_1^\pm \chi_2^0$

Point	m_0	$m_{1/2}$	A_0	$\tan \beta$	$\text{sign} \mu$	σ_{LO} [pb]	Point Characteristics
SU2	3550	300	0	10	+	4.86	Focus point region
SU1	70	350	0	10	+	7.43	Coannihilation region
SU3	100	300	-300	6	+	18.56	Bulk region
SU4	200	160	-400	10	+	262.00	Low mass point
SU8	210	360	0	40	+	6.44	Funnel region

- The Monte Carlo simulations are done for 14 TeV CM energy

SM Background

- The trilepton requirement gives strong SM background suppression

The main SM backgrounds

- $t\bar{t}$ – additional lepton from semileptonic b-decay
- Zb – additional lepton from semileptonic b-decay
- SM counterpart: diboson production, WZ , ZZ , WW , $Z\gamma$ – additional leptons from photon conversion

Process	σ [pb]	k-factor	$\int dt \mathcal{L} [fb^{-1}]$
WW	24.5	1.67	1.22
WZ	7.8	2.05	2.98
ZZ	2.1	1.88	12.7
$Z\gamma$	2.6	1.30	2.98
Zb	154	1	0.75
$t\bar{t}$	450	-	0.92

Object selection

- This analysis requires:
 - ▷ Efficient selection of high quality leptons
 - ▷ Powerful rejection of leptons from jets and leptonic b-quark decays
- Electrons, muons and jets
 - ▷ $p_T > 10$ GeV and within the central barrel region $|\eta| < 2.5$
- Lepton isolation:
 - ▷ Less than 10 GeV of transverse energy in a $\Delta R = 0.2$ cone around the track
- Leptons within $\Delta R < 0.4$ of a jet are rejected. ($\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$)

Event selection

- 1 At least one pair of opposite sign, same flavour leptons (SFOS) (e^+e^- or $\mu^+\mu^-$) with $M_{l+l-} > 20$ GeV
- 2 $N_\ell \geq 3$ ($\ell \in \{e, \mu\}$)
- 3 $p_{T\text{track,max}}^{\Delta R=0.2} < 2$ GeV for electrons, $p_{T\text{track,max}}^{\Delta R=0.2} < 1$ GeV for muons, where $p_{T\text{track,max}}^{\Delta R=0.2}(\ell)$ is the maximum p_T of any track in a $\Delta R = 0.2$ cone around the lepton
- 4 No SFOS dilepton pair with invariant mass in the Z^0 -mass window
 $|M_{\text{SFOS}} - M_Z| > 10$ GeV
- 5 $\cancel{E}_T > 30$ GeV – a moderate $\cancel{E}_T$ cut
- 6 Optional – no jet with $p_T > 20$ GeV – referred to as the Jet Veto

Event selection

- 1 At least one pair of opposite sign, same flavour leptons (SFOS) (e^+e^- or $\mu^+\mu^-$) with $M_{l^+l^-} > 20$ GeV
- 2 $N_\ell \geq 3$ ($\ell \in \{e, \mu\}$)
- 3 $p_{T\text{track,max}}^{\Delta R=0.2} < 2$ GeV for electrons, $p_{T\text{track,max}}^{\Delta R=0.2} < 1$ GeV for muons, where $p_{T\text{track,max}}^{\Delta R=0.2}(\ell)$ is the maximum p_T of any track in a $\Delta R = 0.2$ cone around the lepton
- 4 No SFOS dilepton pair with invariant mass in the Z^0 -mass window
 $|M_{\text{SFOS}} - M_Z| > 10$ GeV
- 5 $\cancel{E}_T > 30$ GeV – a moderate $\cancel{E}_T$ cut
- 6 Optional – no jet with $p_T > 20$ GeV – referred to as the Jet Veto

Event selection

- 1 At least one pair of opposite sign, same flavour leptons (SFOS) (e^+e^- or $\mu^+\mu^-$) with $M_{l^+l^-} > 20$ GeV
- 2 $N_\ell \geq 3$ ($\ell \in \{e, \mu\}$)
- 3 $p_{T\text{track,max}}^{\Delta R=0.2} < 2$ GeV for electrons, $p_{T\text{track,max}}^{\Delta R=0.2} < 1$ GeV for muons, where $p_{T\text{track,max}}^{\Delta R=0.2}(\ell)$ is the maximum p_T of any track in a $\Delta R = 0.2$ cone around the lepton
- 4 No SFOS dilepton pair with invariant mass in the Z^0 -mass window
 $|M_{\text{SFOS}} - M_Z| > 10$ GeV
- 5 $\cancel{E}_T > 30$ GeV – a moderate $\cancel{E}_T$ cut
- 6 Optional – no jet with $p_T > 20$ GeV – referred to as the Jet Veto

Event selection

- 1 At least one pair of opposite sign, same flavour leptons (SFOS) (e^+e^- or $\mu^+\mu^-$) with $M_{l+l-} > 20$ GeV
- 2 $N_\ell \geq 3$ ($\ell \in \{e, \mu\}$)
- 3 $p_{T\text{track,max}}^{\Delta R=0.2} < 2$ GeV for electrons, $p_{T\text{track,max}}^{\Delta R=0.2} < 1$ GeV for muons, where $p_{T\text{track,max}}^{\Delta R=0.2}(\ell)$ is the maximum p_T of any track in a $\Delta R = 0.2$ cone around the lepton
- 4 No SFOS dilepton pair with invariant mass in the Z^0 -mass window $|M_{\text{SFOS}} - M_Z| > 10$ GeV
- 5 $\cancel{E}_T > 30$ GeV – a moderate $\cancel{E}_T$ cut
- 6 Optional – no jet with $p_T > 20$ GeV – referred to as the Jet Veto

M_{SFOS} after cut 3

Event selection

- 1 At least one pair of opposite sign, same flavour leptons (SFOS) (e^+e^- or $\mu^+\mu^-$) with $M_{l+l-} > 20$ GeV
- 2 $N_\ell \geq 3$ ($\ell \in \{e, \mu\}$)
- 3 $p_{T\text{track,max}}^{\Delta R=0.2} < 2$ GeV for electrons, $p_{T\text{track,max}}^{\Delta R=0.2} < 1$ GeV for muons, where $p_{T\text{track,max}}^{\Delta R=0.2}(\ell)$ is the maximum p_T of any track in a $\Delta R = 0.2$ cone around the lepton
- 4 No SFOS dilepton pair with invariant mass in the Z^0 -mass window $|M_{\text{SFOS}} - M_Z| > 10$ GeV
- 5 $\cancel{E}_T > 30$ GeV – a moderate $\cancel{E}_T$ cut
- 6 Optional – no jet with $p_T > 20$ GeV – referred to as the Jet Veto

Event selection

- 1 At least one pair of opposite sign, same flavour leptons (SFOS) (e^+e^- or $\mu^+\mu^-$) with $M_{l+l-} > 20$ GeV
- 2 $N_\ell \geq 3$ ($\ell \in \{e, \mu\}$)
- 3 $p_{T\text{track,max}}^{\Delta R=0.2} < 2$ GeV for electrons, $p_{T\text{track,max}}^{\Delta R=0.2} < 1$ GeV for muons, where $p_{T\text{track,max}}^{\Delta R=0.2}(\ell)$ is the maximum p_T of any track in a $\Delta R = 0.2$ cone around the lepton
- 4 No SFOS dilepton pair with invariant mass in the Z^0 -mass window $|M_{\text{SFOS}} - M_Z| > 10$ GeV
- 5 $\cancel{E}_T > 30$ GeV – a moderate $\cancel{E}_T$ cut
- 6 Optional – no jet with $p_T > 20$ GeV – referred to as the Jet Veto

The discovery potential

- Signal significance $\mathcal{S} = \frac{S}{\sqrt{S+B}}$
 - ▷ S = number of signal events and B = number of background events
- It has been studied for two cases:
 - ▷ *Jet Veto* - all event selection cuts, including the jet veto
 - ▷ *Jet inclusive* - all event selection cuts, except the jet veto
- **The tri-lepton analysis including the jet veto with 10 fb^{-1} :**
 - ▷ 29 Focus point region signal events (all *direct gaugino*),
210 SM-background events, dominated by ZW
 - ▷ Significance: $\mathcal{S}=1.9$, which yields a 5σ discovery after $\sim 71 \text{ fb}^{-1}$
- **The tri-lepton jet inclusive analysis with 10 fb^{-1} :**
 - ▷ 177 Focus point region signal events (95 of them *direct gaugino*),
718 SM-background events, dominated by $t\bar{t}$
 - ▷ *Inclusive SUSY*: $\mathcal{S}=5.9$
 - ▷ *Direct gaugino*: $\mathcal{S}=3.3$

The discovery potential – summary

	Focus p.	Focus $\chi\chi$	Focus +JV
$\mathcal{S}, 10 \text{ fb}^{-1}$	5.9	3.3	1.9
$\int dt \mathcal{L}$ for 5σ	7	23	71
	Bulk p.	Bulk $\chi\chi$	Bulk +JV
$\mathcal{S}, 10 \text{ fb}^{-1}$	17	1.9	1.4
$\int dt \mathcal{L}$ for 5σ	0.8	67	119

No jet veto

	Low mass	Bulk	Coan.	Funnel
$\mathcal{S}, 10 \text{ fb}^{-1}$	69	17	7.7	1.9
$\int dt \mathcal{L}$ for 5σ	0.1	0.8	4.2	71

- **The jet inclusive tri-lepton analysis** yields a 5σ discovery signal after less than $\sim 10 \text{ fb}^{-1}$ for all except one studied benchmark point.
- Including the background uncertainty (20%), only Low Mass point (SU4) has a 5σ discovery signal after $\sim 1 \text{ fb}^{-1}$

Multi-lepton SUSY with jets, 1 fb^{-1}

- This *3-leptons + jet* analysis aims at multi-lepton production in association with jets
 - ▷ Cut 1: $N_\ell \geq 3$ isolated leptons (leptons with $M_{l+l-} < 20$ GeV are discarded)
 - ▷ Cut 2: At least one jet with $p_T > 200$ GeV
- The effect of the single lepton triggers are included (efficiency $\sim 95\%$)
- $Z_n > 5$ for points for the Low Mass and Bulk points (SU4, SU3) even with 100% background uncertainty

All numbers normalized to 1 fb⁻¹.

Sample	Cut 1	Cut 2	S/B	$S/\sqrt{B}$	Z_n
Focus p.	35	13	1.1	3.7	2.7
Bulk p.	139	94	7.8	27.1	11.5
Low mass	1284	312	26.0	90.0	24.4
$t\bar{t}$	455	11	—	—	—
ZZ	59	0	—	—	—
ZW	193	1	—	—	—
WW	3	0	—	—	—
$Z + \gamma$	9	0	—	—	—
Zb	656	0	—	—	—

- Z_n – significance including the background uncertainty of 20%

$Z_n = \sqrt{2} \operatorname{erf}^{-1}(1 - 2p)$ where p is the Poisson probability that the background fluctuates to the observed signal. The approximate uncertainties for 1 fb^{-1} are estimated to be 20%.

Lepton Trigger Studies - trilepton events

- Direct gaugino production, unlike most SUSY searches:
 - ▷ Jet or $\cancel{E}_T$ triggers are not efficient
- Suitable triggers during early low luminosity running at $\mathcal{L} = 10^{31-32} \text{ cm}^{-2} \text{ s}^{-1}$
 - ▷ Single-lepton: L2_e22i and L2_mu20
 - ▷ Studies at Level 2 (L2) – high probability to also pass the Event Filter
- Requiring 3 leptons with $p_T > 10 \text{ GeV}$ – high probability that at least one has high p_T
- The OR combination shows good and stable performance after the $N_l \geq 3$ cut

Selection Stage	SU2 χ			SU3 χ			SU3 incl.		
	L2_e22i	L2_mu20	U	L2_e22i	L2_mu20	U	L2_e22i	L2_mu20	U
SFOS pair	41%	54%	89%	42%	54%	92%	51%	51%	94%
SFOS+3 rd ℓ	58%	67%	93%	59%	63%	95%	66%	68%	98%
after all cuts	57%	66%	92%	58%	57%	94%	66%	64%	97%

- ATLAS has three trigger levels:
 - ▷ First level (L1) – hardware trigger
 - ▷ Second level (L2) – software-based
 - ▷ Event filter (EF) – software-based
- Trigger labels
 - ▷ e22i – electron, $p_T > 22 \text{ GeV}$, isolated
 - ▷ mu20 – muon, $p_T > 20 \text{ GeV}$

Systematic uncertainties - direct gaugino (Focus p.)

- The sources of systematic uncertainties in multi-lepton search channels are different to other SUSY channels
- For $\int dt \mathcal{L} = 10 \text{ fb}^{-1}$ it is estimated to be less than 10%

- 1 Background production rates – large contributions from Diboson production
- 2 Lepton Efficiency – based on “tag-and-probe” method
- 3 Trilepton channel is very sensitive to the rate of leptons from b-decays
- 4 Relevant only when using the jet veto
- 5 Using the jet veto – the majority of the missing energy will recoil against the leptons leading to a small missing energy scale uncertainty

Source	Uncertainty	
	No jet veto	With jet veto
1 Background production rates	0.8%	1.9%
2 Lepton Efficiency	2.3%	2.3%
3 Fakes ($R_{b \rightarrow \ell}$)	4.0%	1.2%
4 Hadronic energy scale	–	1.8%
5 Missing energy scale	1.5%	1.0%
<i>Total systematic</i>	4.9%	3.8%
<i>Statistical</i>	3.7%	6.9%
<i>Statistical + Systematic</i>	6.2%	7.9%

- Eventually – all estimates will be done based on real data

Conclusions

- If squarks and gluinos are heavy – dominant process: direct gaugino production
 - ▷ Including the jet veto – 5σ discovery after 71 fb^{-1}
- Jet inclusive searches:
 - ▷ Sensitive to multi-lepton signal from a broad range of scenarios
 - ▷ Without the jet veto 5σ discovery after $\sim 10 \text{ fb}^{-1}$ for most benchmark points
 - ▷ For the “Low mass point” SU4 5σ discovery after $\sim 1 \text{ fb}^{-1}$
 - ▷ 3-leptons + *jet* – strong background suppression, promising discovery potential, even with 1 fb^{-1}
- High trigger efficiency – OR combination of lepton triggers
- Multi-lepton searches are part of the ATLAS early physics strategies