# Search for supersymmetry in 2 lepton final states

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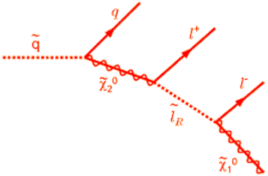
# Outline

- introduction to supersymmetry and searches for it
- SUSY searches in 2L searches .... ATLAS
- SM background
    - fake lepton background
- results
- interpretation

## Introduction to Supersymmetry and searches for it

- many extensions to the Standard Model (SM) predict the existence of new states that lead to new invisible particles
  - new coloured particles, such as the squarks, $\tilde{q}$, and gluinos, $\tilde{g}$, of supersymmetric (SUSY) theories, are among those predicted
- in R-parity conserving SUSY models, the lightest supersymmetric particle (LSP) is stable and weakly interacting, and SUSY particles are pair-produced.
  - the LSP escapes detection, giving rise to events with significant missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$



**Typical SUSY cascade. SUSY particles are created in pairs giving two such cascades in each event**

- the dominant SUSY production channels at the LHC are: squark-(anti)squark, squark-gluino and gluino pair production
- weak gauginos and sleptons may also be pairproduced, albeit with smaller cross sections
  - dilepton searches are potentially very sensitive to direct weak gaugino production

# SUSY searches in ATLAS

- two different searches for the production of supersymmetric particles decaying into final states with missing transverse momentum and exactly two isolated leptons are considered
  - in the following leptons only refer to $e$ or $\mu$
- study is performed using a total integrated luminosity of $1fb^{1}$ of $\sqrt{s} = 7$ TeV proton-proton collisions recorded with the ATLAS detector
- in each SUSY event there are two independent cascade decays
- two leptons are produced in events in which two gauginos decay via cascade:

  (a) $\tilde{\chi}_i^0 \to l^{\pm}\nu\tilde{\chi}_j^{\mp} \to SS, OS$, occur in both legs

  (b) $\tilde{\chi}_i^{\pm} \to l^{\pm}\nu\tilde{\chi}_j^{0} \to SS, OS$, occur in both legs

  ...or events in which one gaugino decays via cascade:

  (c) $\tilde{\chi}_i^0 \to l^{\pm}l^{\mp}\tilde{\chi}_j^{0} \to OS$, occur in only one leg

  (d) $\tilde{\chi}_i^{\pm} \to l^{\pm}l^{\mp}\tilde{\chi}_j^{\pm} \to OS$, occur in only one leg

# SUSY searches in ATLAS

The following 5 signal regions were studied:

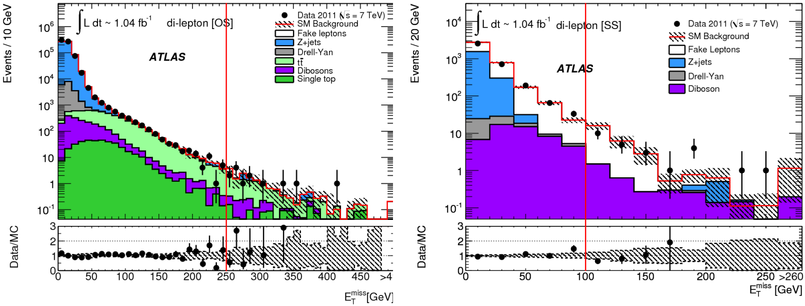
- Opposite-Sign
  1. (OS-SR1) $E_T^{miss} > 250$ GeV
  2. (OS-SR2) 3-jets ($p_T > 80, 40, 40$ GeV), $E_T^{miss} > 220$ GeV
  3. (OS-SR3) 4-jets ($p_T > 100, 70, 70, 70$ GeV), $E_T^{miss} > 100$ GeV
- Same-Sign
  1. (SS-SR1) $E_T^{miss} > 100$ GeV
  2. (SS-SR2) 2-jets ($p_T > 50, 50$ GeV), $E_T^{miss} > 80$ GeV

Results are interpreted using different SUSY models:

- Simplified Model Grids
  - involve the minimal particle contents necessary to produce SUSY-like events and are parametrized directly in terms of the sparticle masses
  - no assumption about the relative couplings at each vertex.
  - results are expressed in terms of limits on cross-section times branching ratios as a function of new particle masses
- gauge-mediated supersymmetry breaking (GMSB) scenario
  - GMSB model is fully described by six parameters: $\Lambda$, $M_{mes}$, $N_5$, $\tan\beta$, sign($\mu$) and $C_{grav}$
  - $\Lambda$ is the SUSY breaking scale felt by the low energy sector
  - $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets

# SM backgrounds

- SM backgrounds to each search are evaluated using a combination of MC simulation and data-driven techniques
- in opposite sign channels the $t\bar{t}$ background dominates
- in same sign channels the fake lepton background dominates



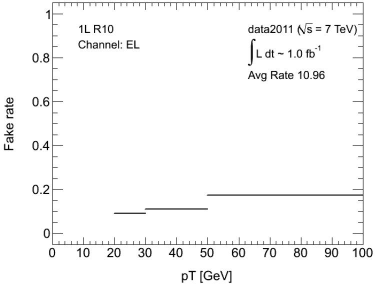
# “Fake” lepton background estimation

- the fully data driven Matrix Method is used to estimate the “fake” lepton contribution - 2 step procedure
  1. measure a fake rate, $f$, and real efficiency, $r$
  2. using the observed number of events in a particular region and inverting the Matrix (dep. on r and f) we can estimate the fake background

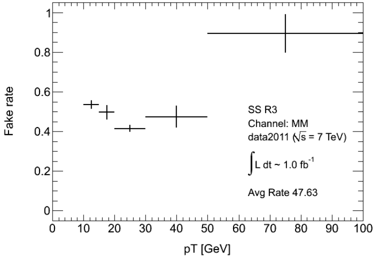
**1.** measure $f$ and $r$:

- use a loose and tight selection of leptons
  - *tight*: same as the signal leptons
  - *loose*: remove the isolation requirements (electrons and muons) and loosen a few other of the identification criteria (electrons only)
- measure a $f$ from a QCD dominated control region (low $E_{\mathrm{T}}^{\mathrm{miss}}$)
  - $f$ is the probability for a fake lepton to pass the *tight* requirement
- measure $r$ from a OS Z-region
  - $r$ is the probability for a real lepton to pass the *tight* requirement

**Electrons**




**Muons**



# Fake lepton background estimation

**2.** find the observed number of events in the signal region and invert the matrix

- count how many $TT$, $Tl$, $lT$ and $ll$ events in our signal region
  - T refer to a lepton passing tight
  - l refer to a lepton **not** passing tight
- by inverting the matrix we obtain the number of real-real, real-fake, fake-real and fake-fake lepton pairs
  - we extrapolate this into our signal region by multiplying these estimates with $rr$, $rf$, $fr$ and $ff$ respectively

$$\begin{bmatrix} N_{TT} \\ N_{Tl} \\ N_{lT} \\ N_{ll} \end{bmatrix} = \begin{bmatrix} rr & rf & fr & ff \\ r(1-f) & r(1-r) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

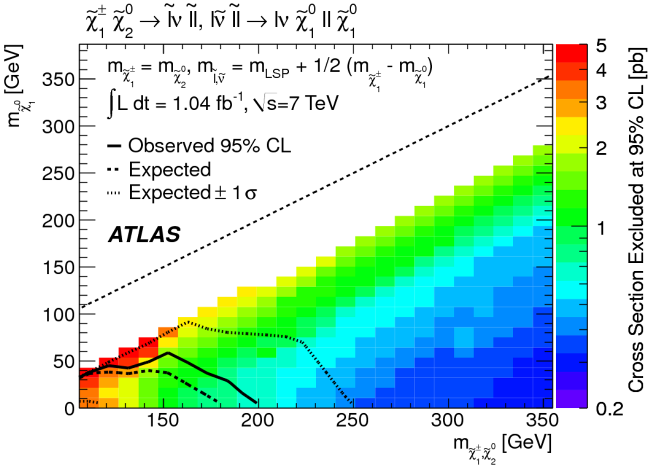
# Results

- predicted number of background events, observed number of events and the corresponding 95% CL upper limit on $A \times \epsilon \times \sigma$, for each opposite-sign and samesign signal region.
  - used the CLs technique to calculate limits
  - $A$ is the fraction of events passing geometric and kinematic cuts at particle level
  - $\epsilon$ is the detector reconstruction and identification efficiency

| | Background | Obs. | 95% CL |
|---|---|---|---|
| OS-SR1 | $15.5 \pm 4.0$ | 13 | 9.9 fb |
| OS-SR2 | $13.0 \pm 4.0$ | 17 | 14.4 fb |
| OS-SR3 | $5.7 \pm 3.6$ | 2 | 6.4 fb |
| SS-SR1 | $32.6 \pm 7.9$ | 25 | 14.8 fb |
| SS-SR2 | $24.9 \pm 5.9$ | 28 | 17.7 fb |

# Interpretation - simplified models

- SS-SR1 ($E_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV) is particularly sensitive to low mass weak gaugino production and the cascade decays into leptons
- cross section upper limits on $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production
- results are for slepton masses between $m_{\tilde{\chi}_1^0}$ (LSP) and $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{l},\tilde{\nu}} = m_{LSP} + 1/2(m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0})$ and the hierarchy $m_{\tilde{\chi}_1^{\pm}} = m_{\tilde{\chi}_2^0}$

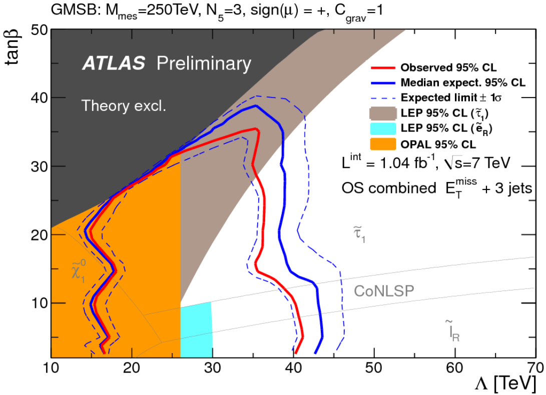



- if decays to sleptons are dominant, charginos with masses up to 200 GeV are excluded

# Interpretation - GMSB

- 2 lepton analysis also interpreted in the GMSB model
- cascade decays with the final decay of the next-to-lightest SUSY particle (NLSP) into its SM partner and the lightest supersymmetric particle (LSP)
- scenarios:
  - NLSP: $\tilde{\tau}_1$, $\tilde{l}_R$ or $\tilde{\chi}_1^0$
  - LSP: a nearly massless gravitino ($\tilde{G}$)
  - exact same analysis using signal region OS-SR2: 3-jets ($p_T > 80, 40, 40$ GeV), $E_T^{miss} > 220$ GeV

| | $e^{\pm}e^{\pm}$ | $e^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}$ |
|---|---|---|---|
| Standard Model | 1.9±0.9 | 7.9±3.1 | 3.2±1.0 |
| Cosmic rays | $< 10^{-3}$ | $< 10^{-3}$ | $< 10^{-3}$ |
| Observed | 3 | 9 | 5 |




- exclusion in $\Lambda$-$\tan\beta$ plane
- $ee + \mu\mu + e\mu$ channel

# Conclusion

- Searches for supersymmetry with 2 leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$(and jets) using $1fb^{-1}$
  - good agreement between SM background prediction and observed number of events in the signal regions
- SM backgrounds are estimated using combinations of MC and data-driven techniques
  - the fake lepton background is estimated in a fully data driven way
- model-independent limits are quoted on the cross section multiplied by acceptances and efficiencies for the inclusive analysis
- new limits have been presented on the chargino mass in direct weak gaugino production modes using simplified models.
  - charginos with masses up to 200 GeV are excluded, under the assumptions of these models.
- we've also extended the limits in the GMSB model

More information:

| title | lumi [$fb^{-1}$] | link |
|---|---|---|
| identical flavour lepton pairs and Etmiss | 0.035 | http://arxiv.org/abs/1103.6208 |
| lepton pairs and Etmiss | 0.035 | http://arxiv.org/abs/1103.6214 |
| lepton pairs and Etmiss | 1.04 | http://arxiv.org/abs/1110.6189 |
| Additional 2lepton+jets+Etmiss interpretation | 1.04 | http://cdsweb.cern.ch/record/1398247 |

# BACKUP

# More detailed backgrounds - SS

| Same Sign [SS-SR1] | $e^{\pm}e^{\pm}$ | $e^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}$ |
|---|---|---|---|
| Fake | 3.5±1.6 | 14.4±4.4 | 9.2±3.3 |
| Charge flip | 0.73±0.08 | 1.1±0.14 | *neg.* |
| Dibosons | 0.79±0.27 | 1.7±0.5 | 1.1±0.22 |
| Standard Model | 5.0±1.6 | 17.2±4.4 | 10.3±3.3 |
| Cosmic rays | $< 10^{-3}$ | $< 10^{-3}$ | $< 10^{-3}$ |
| Observed | 6 | 14 | 5 |

| Same Sign [SS-SR2] | $e^{\pm}e^{\pm}$ | $e^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}$ |
|---|---|---|---|
| Fake | 1.5±0.9 | 13.4±4.1 | 6.7±2.7 |
| Charge flip | 0.59±0.06 | 1.4±0.14 | *neg.* |
| Dibosons | 0.25±0.14 | 0.86±0.21 | 0.64±0.05 |
| Standard Model | 2.4±0.9 | 15.6±4.1 | 6.9±2.7 |
| Cosmic rays | $< 10^{-3}$ | $< 10^{-3}$ | $< 10^{-3}$ |
| Observed | 4 | 14 | 10 |

# More detailed backgrounds - OS

| Opposite Sign [OS-SR1] | $e^{\pm}e^{\mp}$ | $e^{\pm}\mu^{\mp}$ | $\mu^{\pm}\mu^{\mp}$ |
|---|---|---|---|
| $t\bar{t}$ | 1.8±0.5 | 5.1±1.4 | 3.3±0.9 |
| $Z/\gamma^*$+jets | 0.01±0.67 | 1.03±0.42 | 0.81±0.27 |
| Fakes | 0.17±0.21 | 0.92±0.97 | -0.08±0.03 |
| Dibosons | 0.54±0.30 | 0.04±0.04 | 0.67±0.40 |
| Single-top | 0.11±0.12 | 0.47±0.23 | 0.48±0.19 |
| Standard Model | 2.7±1.3 | 7.6±1.9 | 5.3±1.4 |
| Cosmic rays | $< 10^{-3}$ | $< 10^{-3}$ | $< 10^{-3}$ |
| Observed | 2 | 8 | 3 |

| Opposite Sign [OS-SR2] | $e^{\pm}e^{\mp}$ | $e^{\pm}\mu^{\mp}$ | $\mu^{\pm}\mu^{\mp}$ |
|---|---|---|---|
| $t\bar{t}$ | 1.4±0.3 | 3.9±1.0 | 2.6±0.6 |
| $Z/\gamma^*$+jets | 0.45±50 | 0.84±0.67 | 0.27±0.30 |
| Fakes | 0.01±0.14 | 2.8±2.6 | -0.13±0.06 |
| Dibosons | *neg.* | 0.03±0.04 | 0.24±0.21 |
| Single-top | 0.05±0.10 | 0.39±0.30 | 0.09±0.17 |
| Standard Model | 1.9±0.9 | 7.9±3.1 | 3.2±1.0 |
| Cosmic rays | $< 10^{-3}$ | $< 10^{-3}$ | $< 10^{-3}$ |
| Observed | 3 | 9 | 5 |

| Opposite Sign [OS-SR3] | $e^{\pm}e^{\mp}$ | $e^{\pm}\mu^{\mp}$ | $\mu^{\pm}\mu^{\mp}$ |
|---|---|---|---|
| $t\bar{t}$ | 0.77±0.52 | 2.1±1.6 | 1.4±0.9 |
| $Z/\gamma^*$+jets | 0.01±0.17 | *neg.* | 0.27±0.51 |
| Fakes | 0.13±0.14 | 0.91±0.96 | -0.03±0.02 |
| Single-top | *neg.* | 0.00±0.02 | 0.10±0.11 |
| Standard Model | 0.91±0.70 | 3.1±1.7 | 1.8±1.4 |
| Cosmic rays | $< 10^{-3}$ | $< 10^{-3}$ | $< 10^{-3}$ |
| Observed | 0 | 1 | 1 |

# Flavour subtraction analysis

- limits are set on the excess number of identical-flavour events
- the flavour-subtraction limits are set using toy pseudo-experiments
- the identical flavour excess is quantified using the quantity S, defined as

$$\mathcal{S} = \frac{N(e^{\pm}e^{\mp})}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^{\pm}\mu^{\mp})}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^{\pm}\mu^{\mp})}{(1-(1-\tau_\mu)^2)} \quad (1)$$

- $\tau_e$ and $\tau_\mu$ are the electron and muon plateau trigger efficiencies respectively
- $\beta$ is ratio of electron to muon efficiency times acceptance

- Flavour Subtraction signal regions
  1. (FS-SR1) $E_T^{miss} > 80$ GeV, Z-veto ($80 < m_{ll} < 100$ GeV)
  2. (FS-SR2) $E_T^{miss} > 80$ GeV and at least 2 jets
  3. (FS-SR3) $E_T^{miss} > 250$ GeV

# Flavour subtraction analysis II

| | $\mathcal{S}_{obs}$ | $\bar{\mathcal{S}}_b$ | RMS |
|---|---|---|---|
| FS-SR1 | 131.6±2.5(sys) | 118.7±27.0 | 48.6 |
| FS-SR2 | 142.2±1.0(sys) | 67.1±28.6 | 49.0 |
| FS-SR3 | -3.06±0.04(sys) | 0.7±1.6 | 4.5 |

The observed values of $\mathcal{S}$ ($\mathcal{S}_{obs}$, left column), mean (middle column) and root-mean-squared (RMS, right column) of the distributions of the expected $\mathcal{S}_b$ from one million hypothetical signal-free pseudo-experiments.

| | $\mathcal{S} > \mathcal{S}_{obs}$ (%) | Limit $\bar{\mathcal{S}}_s$ (95% CL) |
|---|---|---|
| FS-SR1 | 39 | 94 |
| FS-SR2 | 6 | 158 |
| FS-SR3 | 79 | 4.5 |

Consistency of the observation with the SM expectation (middle column), computed as the percentage of signal-free pseudo-experiments giving values of $\mathcal{S}$ greater than the observation, $\mathcal{S}_{obs}$. Observed limit (right column) on the numbers of same-flavour events from new phenomena multiplied by detector acceptances and efficiencies in each signal region.