Run Number: 167776, Event Number: 129360643

Date: 2010-10-28, 10:41:18 CEST

# Searches for direct gaugino production with leptons at $\sqrt{s} = 7$ TeV

BNL Workshop on SUSY with $5\text{fb}^{-1}$ at the LHC


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on behalf of the ATLAS collaboration

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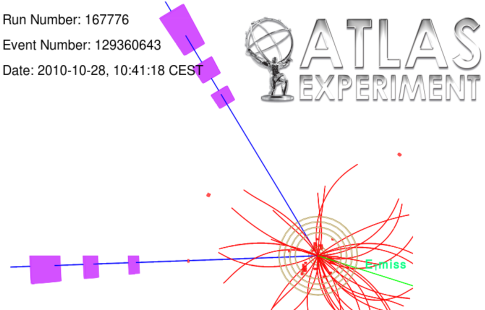
2 May 2012

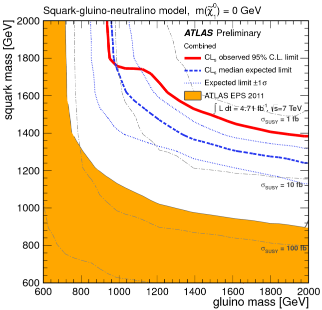
# Outline

- Motivations for direct gaugino searches
- SUSY frameworks used in our searches
- Overall search strategy
- Searches
    - Same-sign di-lepton with $1.04\text{fb}^{-1}$
    - Tri-lepton with $2.06\text{fb}^{-1}$
    - Four-lepton with $2.06\text{fb}^{-1}$
- Overview of $4.7\text{fb}^{-1}$ efforts
- Summary



Z->$\mu\mu$ + missing $E_T$ candidate event

# Motivation for direct gaugino searches




*ATLAS 4.7fb$^{-1}$ 0-lepton search*

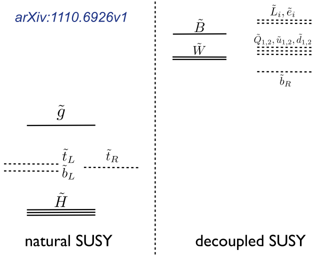
## *No strongly produced SUSY yet!*

- No excess seen in 0-lepton, 1-lepton, 2-lepton, or multijet channels $\rightarrow (m_{\tilde{q}} = m_{\tilde{g}}) > 1.4$ TeV
- Possible that gluinos and first two generation squarks are too heavy for direct production
- While *easiest* SUSY to search for, light squarks of the first two generations are not necessary for higgs mass stabilization

## *Naturalness considerations*

- To prevent fine tuning to higgs mass need light higgsinos
- Higgsinos masses directly depend on $\mu$
- $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ can be light

*arXiv:1110.6926v1*

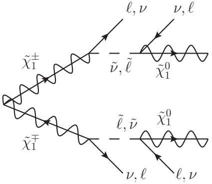



*If SUSY is discovered, gaugino searches will be critical for exploring SUSY structure*

# Two complimentary paradigms used in these analyses

## Simplified models

Considers a specific *process*

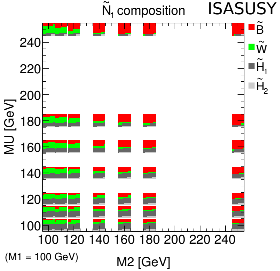



- Place limit on $\sigma \times \mathrm{BR}$ for each process
- Pro: Limits applicable to any model containing this process
- Pro: No assumptions about the SUSY breaking sector
- Pro: Useful for optimization
- Con: Have to decide what diagrams to investigate

## pMSSM

Based on 19-parameter pMSSM

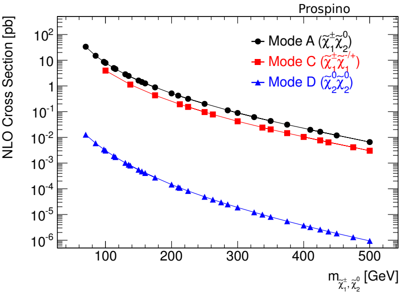
- If assuming that colored SUSY is heavy then only need M1, M2, $\mu$ and tan($\beta$)
- Pro: Contains mixtures of all processes




- Pro: Based on actual SUSY model
- Con: Assumes MSSM

# Direct gaugino search strategy

| Production | Decay | Signal region |
|---|---|---|
| $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ | $(\ell^+\ell^-\tilde{\chi}_1^0) + (\ell^\pm\nu\tilde{\chi}_1^0)$ | 3 lep |
| | $(\ell^+\ell^-_{\mathrm{miss}}\tilde{\chi}_1^0) + (\ell^\pm\nu\tilde{\chi}_1^0)$ | 2 lep (OS or SS) + jet veto |
| | $(\ell^+\ell^-\tilde{\chi}_1^0) + (qq\tilde{\chi}_1^0)$ | OS 2 lep + jets |
| $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ | $(\ell^+\nu\tilde{\chi}_1^0) + (\ell^-\nu\tilde{\chi}_1^0)$ | OS 2 lep + jet veto |
| $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ | $(\ell^+\ell^-\tilde{\chi}_1^0) + (\ell^+\ell^-\tilde{\chi}_1^0)$ | 4 lepton |




Decays with and without intermediate-$\tilde{\ell}$ possible
No sensitivity in no-$\tilde{\ell}$ case in 4.7fb$^{-1}$

$\mathrm{BR}(W/Z \to \ell)$ kills yield

## $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$

- Best covered by 3-lepton
- SS 2-lepton also has power for cases where one $\ell$ is not reconstructed
- Statistically combining SS and 3-lepton seen to have further reach than SS inclusive

# $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ search using same-sign dileptons in 1.04fb$^{-1}$

*Searches for supersymmetry using final states with two-leptons and missing transverse momentum with the ATLAS detector in sqrt(s) = 7 TeV proton-proton collisions*

Phys. Lett. B709 (2012) 137-157

# Signal region definition

Designed for strong production, also sensitive to weak production

## Lepton $p_{\mathrm{T}}$'s

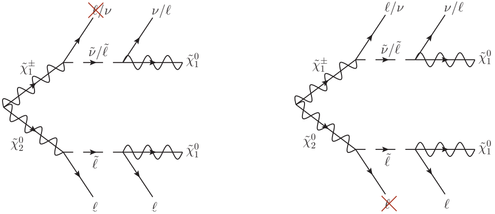
Leading lepton has higher requirement due to trigger

- $e^{\pm}e^{\pm}$ 25, 20 GeV
- $\mu^{\pm}\mu^{\pm}$ 20, 10 GeV
- $e^{\pm}\mu^{\pm}$ 25, 10 GeV
- $\mu^{\pm}e^{\pm}$ 20, 20 GeV

## Event selection

- 2 same-sign leptons
- Primary vtx. $>$ 5 tracks
- Cosmic muon veto
- $m_{\ell\ell} > 12$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV
- Inclusive jets

## The relevant direct gaugino processes




## Primary backgrounds

- Events with fake leptons
  - QCD
  - $W \to \ell\nu$
  - $t\bar{t}$
- Charge flipped electrons ($e^{\pm}e^{\pm}$ & $e^{\pm}\mu^{\pm}$)
  - $WW$
  - $t\bar{t}$
- $WZ$, $ZZ$, and $W^{\pm}W^{\pm}jj$ (taken from MC)

# Matrix method

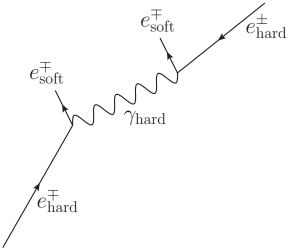
The matrix method employs a set of linear equations relating kinematic properties of the leptons to the real and fake lepton composition

- Use isolation to define "loose" and "tight" leptons
  - "tight" are the signal leptons
  - "loose" leptons have more relaxed isolation requirements
- The fake rate $f$ is the probability that a loose fake lepton passes tight requirements
- The real efficiency $r$ is the probability that a loose real lepton passes tight requirements

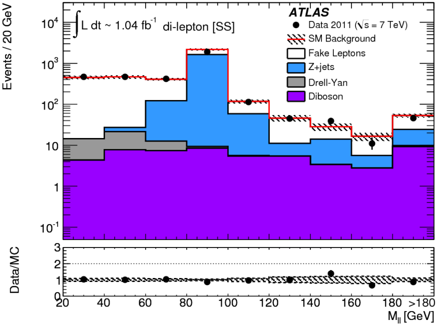
$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} rr & rf & fr & ff \\ r(1-r) & r(1-f) & f(1-r) & f(1-f) \\ (1-r)r & (1-r)f & (1-f)r & (1-f)f \\ (1-r)(1-r) & (1-r)(1-f) & (1-f)(1-r) & (1-f)(1-f) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

From all events with at least two loose in signal region can get an estimate for the number of fake events

# Charge flip electrons



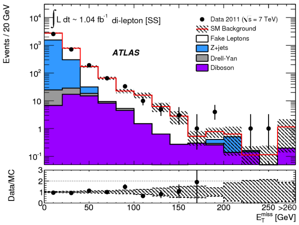

$\Rightarrow$




1. Measure the charge flip rate using $Z \to ee$ MC truth
2. Rate adjusted by a flat factor to reproduce SS $Z$-peak
   - Necessary as flip rate in data not same as in MC
3. Apply this rate to the OS $WW$ and $t\bar{t}$ events to get estimate

# $1.04\text{fb}^{-1}$ SS results

| Same Sign [SS-SR1] | $e^{\pm}e^{\pm}$ | $e^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}$ |
|---|---|---|---|
| Fake | $3.5 \pm 1.6$ | $14.4 \pm 4.4$ | $9.2 \pm 3.3$ |
| Charge flip | $0.73 \pm 0.08$ | $1.1 \pm 0.14$ | *neg.* |
| Dibosons | $0.79 \pm 0.27$ | $1.7 \pm 0.5$ | $1.1 \pm 0.22$ |
| Standard Model | $5.0 \pm 1.65$ | $17.2 \pm 4.4$ | $10.3 \pm 3.3$ |
| Cosmic rays | $< 10^{-3}$ | $< 10^{-3}$ | $< 10^{-3}$ |
| Observed | 6 | 14 | 5 |

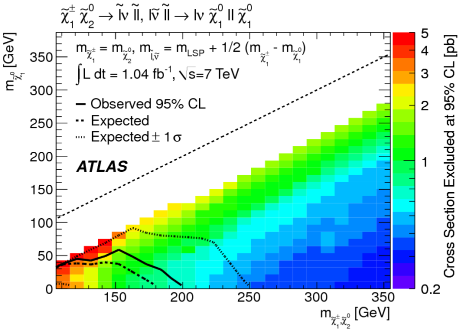


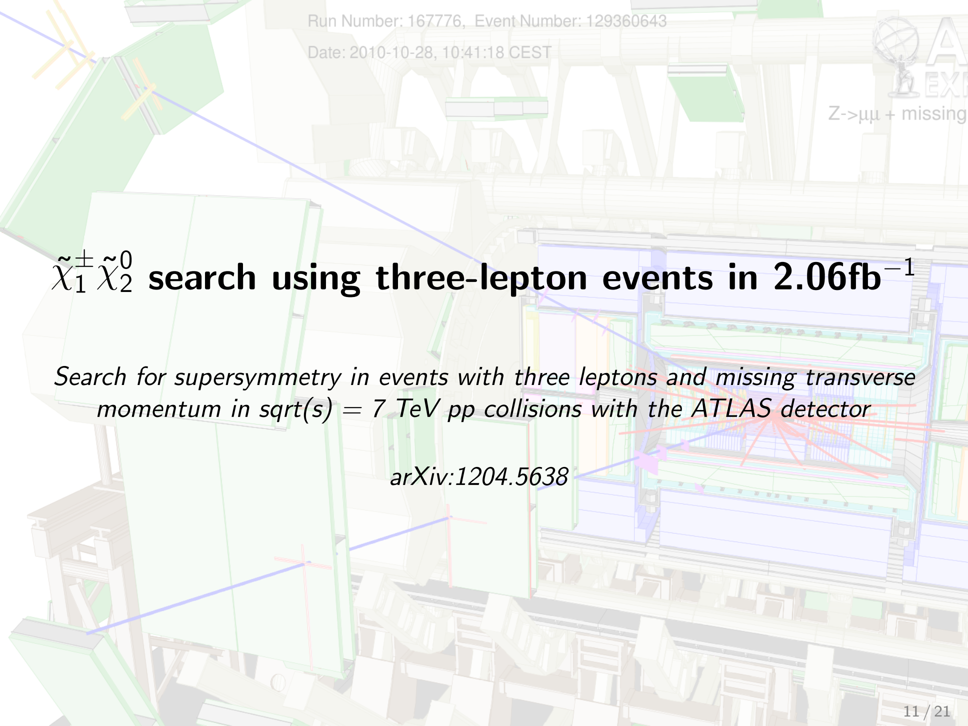

## Model-independent $A \times \epsilon \times \sigma$ limit

| Background | Obs. | 95% CL$_s$ |
|---|---|---|
| $32.6 \pm 7.9$ | 25 | 14.8 fb |

## $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \tilde{\ell}\nu\tilde{\ell}\ell \to \ell\nu\tilde{\chi}_1^0\ell\ell\tilde{\chi}_1^0$ limits

- Assumes $m_{\tilde{\ell}}$ midway between degenerate $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$
  - Also explored fractions of 1/4 and 3/4
- Colors are limit on cross section of diagram
- Curve is limit using pure weakino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$



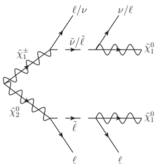



# $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ search using three-lepton events in 2.06fb$^{-1}$

*Search for supersymmetry in events with three leptons and missing transverse momentum in sqrt(s) = 7 TeV pp collisions with the ATLAS detector*

*arXiv:1204.5638*

# Analysis overview




## $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production decaying via $\tilde{\ell}$ is a three-lepton process

### Leptons

Electrons: $p_{\mathrm{T}} > 10$ GeV

- 15GeV in calorimeter crack

Muons: $p_{\mathrm{T}} > 10$ GeV

Using single-lepton triggers $\rightarrow$ leading lepton $p_{\mathrm{T}}$

- $> 25$ GeV if $e$
- $> 20$ GeV if $\mu$

### Event selection

- Primary vertex $> 5$ tracks
- Cosmic muon veto
- 3 leptons
- At least one SFOS pair
  - $m_{\ell\ell} > 20$ GeV

Two orthogonal signal regions

### SR1 ($Z$-veto)

- Veto events with $|m_{\mathrm{SFOS}} - m_Z| < 10$ GeV
- Veto events with $b$-jets
  - $b$-jet's tagged with a neural network
  - Cut is 60% efficient

### SR2 ($Z$-rich)

- Require $|m_{\mathrm{SFOS}} - m_Z| < 10$ GeV
- Inclusive with respect to $b$-jets

# Three-lepton background overview

## Irreducible background from MC

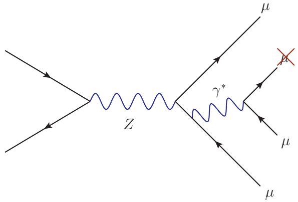
- $ZZ$ and $WZ$
- $t\bar{t} + V$

## Fake leptons

- Matrix method
- Leading lepton in 3-lepton events is real 99% of time
- Use $4 \times 4$ matrix with $2^{\mathrm{nd}}$ and $3^{\mathrm{rd}}$ leptons
- Includes contribution from internal conversion to electrons

## Internal conversions to muons

- Use $\mu\mu$ and $\mu\mu\mu$ events with $E_{\mathrm{T}}^{\mathrm{miss}} < 50\ \mathrm{GeV}$ to determine the probability of conversion.
- $N_{conv.} =$($N_{\mu\mu}$ passing all SR cuts but the 3-lepton requirement)$\times$(Probability of conversion)



# 3-lepton fakes

## Primary sources of fakes

- Heavy flavor quark decay
- Electrons from $\gamma$ conversion

## Fake rates measured in

- $t\bar{t}$ MC
- boson MC

**Fake rate used for SR:** $f_{SR} = \sum_{ij}(SF^i \times R^{ij}_{SR} \times f^{ij})$

$i$ → Type of fake: heavy flavor jet or electron conversion
$j$ → Source of fake: $t\bar{t}$ or bosons
$SF^i$ → Scale factor for fake type $i$
$R^{ij}_{SR}$ → MC-derived fraction of fake type $i$ and process $j$ in SR
$f^{ij}$ → Fake rate for fake type $i$ from process $j$

**MC fake rates normalized to data using scale factors**

- Heavy flavor SF obtained from HF tag and probe
- Conversion SF obtained from $Z \to \mu\mu + \gamma$ sample

# Data prediction comparisons

In addition to the SR's there are two validation regions

**VR1**

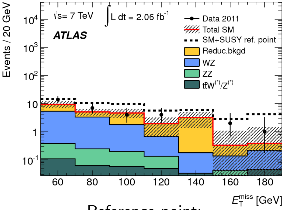
- Dominated by $Z/\gamma^*$
- 3 signal leptons
- $30 < E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV

**VR2**

- Dominated by $t\bar{t}$
- 3 signal leptons
- Veto on SFOS pairs
- $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV

| Selection | VR1 | VR2 | SR1 | SR2 |
|---|---|---|---|---|
| $t\bar{t}\,W^*/Z^*$ | 1.4±1.1 | 0.7±0.6 | 0.4±0.3 | 2.7±2.1 |
| $ZZ^*$ | 6.7±1.5 | 0.03±0.04 | 0.7±0.2 | 3.4±0.8 |
| $WZ^*$ | 61±11 | 0.4±0.2 | 11±2 | 58±11 |
| Reducible Bkg. | 56±35 | 14±9 | 14±4 | 7.5±3.9 |
| Total Bkg. | 125±37 | 15±9 | 26±5 | 72±12 |
| Data | 122 | 12 | 32 | 95 |

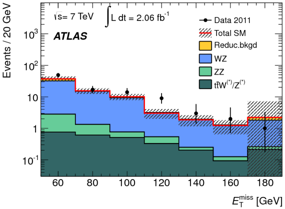
## SR1




Reference point:

$$(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}}, m_{\tilde{\chi}_1^0}) = (250, 250, 175, 100)\ \mathrm{GeV}$$

## SR2

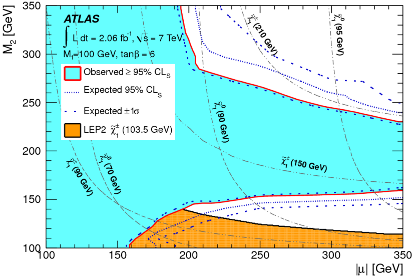


# Results

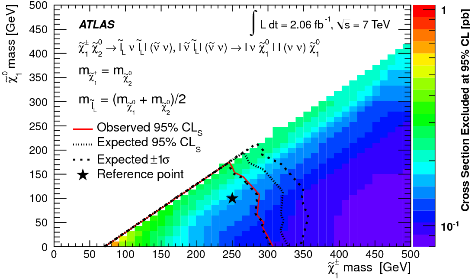
## Model-independent $A\times\epsilon\times\sigma$ limit

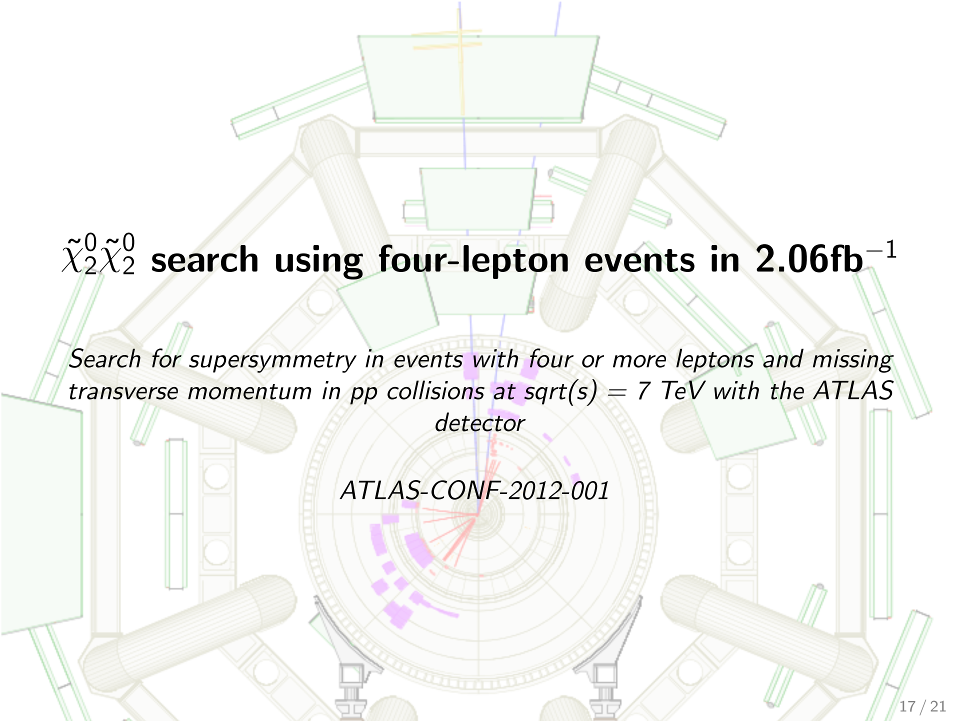
| SR | 95% $CL_s$ limit expected [fb] | 95% $CL_s$ limit observed [fb] |
|---|---|---|
| SR1 ($Z$-veto) | 7.1 | 9.9 |
| SR2 ($Z$-rich) | 14.1 | 23.8 |

## Limit in pMSSM




## Limit in $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ simplified models





# $\tilde{\chi}_2^0 \tilde{\chi}_2^0$ search using four-lepton events in $2.06\text{fb}^{-1}$

*Search for supersymmetry in events with four or more leptons and missing transverse momentum in pp collisions at sqrt(s) = 7 TeV with the ATLAS detector*

*ATLAS-CONF-2012-001*

# Analysis overview

## Leptons

Electrons: $p_{\mathrm{T}} > 10$ GeV

- $15\mathrm{GeV}$ in calorimeter crack

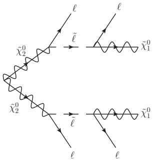
Muons: $p_{\mathrm{T}} > 10$ GeV

Using single-lepton triggers $\rightarrow$ leading lepton $p_{\mathrm{T}}$

- $> 25$ GeV if $e$
- $> 20$ GeV if $\mu$

## Event selection

- Primary vertex $> 5$ tracks
- Cosmic muon veto
- *At least* 4 leptons
- Veto on events with a SFOS pair with $m_{\mathrm{SFOS}} < 20$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV



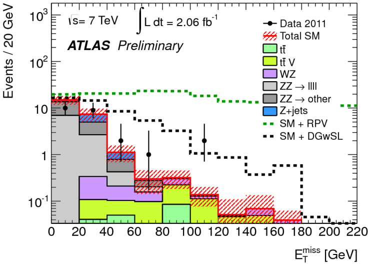

Backgrounds from MC

Most negligible

- Only processes resulting in $\geq 2$ true leptons considered
  - MC studies of $W \rightarrow \ell\nu$ verify negligible contribution from 0 and 1 lepton processes
- $Z \rightarrow \ell\ell + \gamma^*$ negligible
  - Not in MC
  - Measure probability in data from ratio of $N_{\ell\ell\gamma}$ to $N_{\ell\ell\ell\ell}$ where $|m_{\ell\ell\gamma} - m_Z|$ and $|m_{\ell\ell\ell\ell} - m_Z| < 10$ GeV
  - $N_{Z\rightarrow\ell\ell+\gamma^*}$ =($N_{\ell\ell\gamma}$ passing all but 4-lepton cut)$\times$(Probability of conv.)

# Results

| | All | $eeee$ | $eee\mu$ | $ee\mu\mu$ | $e\mu\mu\mu$ | $\mu\mu\mu\mu$ |
|---|---|---|---|---|---|---|
| $t\bar{t}$ | 0.17±0.14 | 0.011±0.042 | 0.027±0.042 | 0.09±0.06 | 0.05±0.07 | 0±0.018 |
| Single $t$ | 0±0.04 | 0±0.04 | 0±0.04 | 0±0.04 | 0±0.04 | 0±0.04 |
| $t\bar{t}V$ | 0.48±0.21 | 0.072±0.037 | 0.12±0.06 | 0.14±0.07 | 0.08±0.04 | 0.059±0.032 |
| $ZZ$ | 0.44±0.19 | 0.14±0.08 | 0.016±0.012 | 0.21±0.12 | 0.047±0.032 | 0.025±0.045 |
| $WZ$ | 0.25±0.10 | 0.015±0.022 | 0.07±0.04 | 0.050±0.032 | 0.11±0.06 | 0±0.011 |
| $WW$ | 0±0.015 | 0±0.015 | 0±0.015 | 0±0.015 | 0±0.015 | 0±0.015 |
| $Z\gamma$ | 0±0.5 | 0±0.5 | 0±0.5 | 0±0.5 | 0±0.5 | 0±0.5 |
| $Z$+($u$, $d$, $s$ jets) | 0.33±0.67 | 0.33±0.67 | 0±0.29 | 0±0.29 | 0±0.29 | 0±0.29 |
| $Z$+($c$, $b$ jets) | 0.024±0.035 | 0±0.17 | 0±0.17 | 0±0.17 | 0.024±0.035 | 0±0.17 |
| Drell-Yan | 0±0.05 | 0±0.05 | 0±0.017 | 0±0.017 | 0±0.016 | 0±0.017 |
| Σ SM | 1.7±0.9 | 0.6±0.8 | 0.24±0.57 | 0.5±0.6 | 0.32±0.55 | 0.08±0.57 |
| Data | 4 | 0 | 1 | 2 | 0 | 1 |




## Model-independent $A \times \epsilon \times \sigma$ limit

Expected: 2.1 fb    Observed: 3.5 fb

← DGwSL is from the pMSSM

- M1 = 100GeV
- M2 = 250GeV
- $\mu$ = 160 GeV
- $\tan(\beta)$ = 6

# $5\text{fb}^{-1}$ efforts and the future

*Searching for weakly produced SUSY in 2 and 3-lepton channels*

## 2-leptons

A completely new analysis

- $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production in OS+jet veto
- $\tilde{\chi}_1^+ \tilde{\chi}_2^0$ production in SS+jet veto
- $\tilde{\ell}$ pair production in OS+jet veto
- Also a search in OS+jets channel

## 3-lepton

Extend the $2\text{fb}^{-1}$ analysis

- Try to reduce systematic uncertainties
- Improvement of $WZ$ estimate
- Improvement of fake estimate

*Moving on to 2012*

- Increased luminosity $\rightarrow$ modes with out intermediate sleptons may become viable.
- Investigation of predominately-higgsino decays
- Inclusion of $\tau$'s
- Closer collaboration between two and multi-lepton searches $\rightarrow$ combined limits

# Summary

*No SUSY yet!*

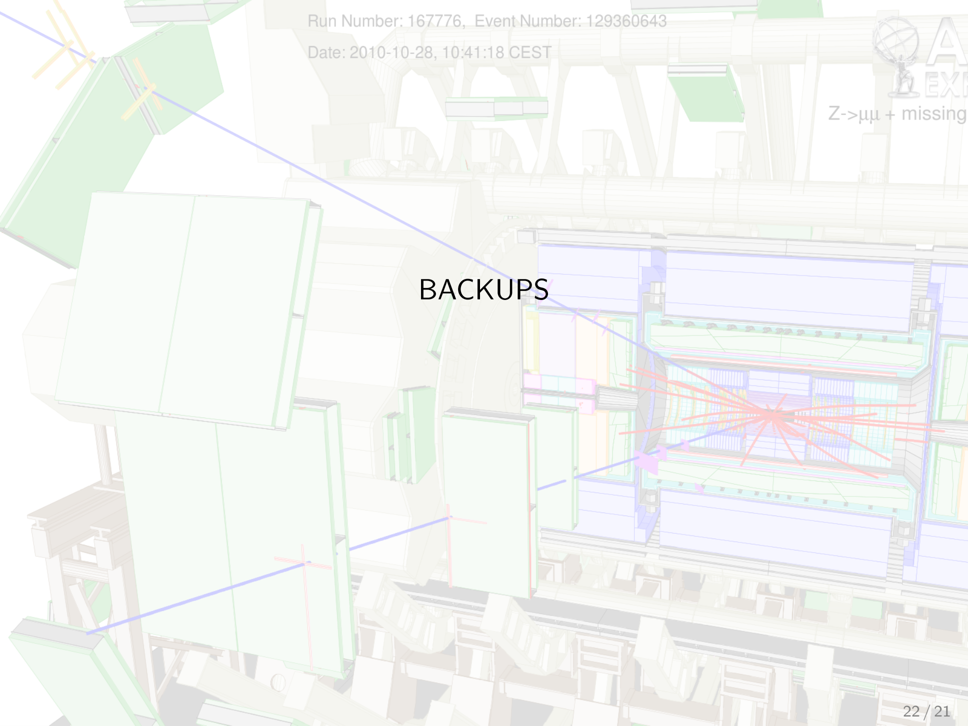
- Strongest limits include the first two generations of $\tilde{q}$'s
- No naturalness requirement for these to be light
- To satisfy naturalness gauginos should be relatively light
- Direct gaugino limits much weaker

*Significant team at ATLAS committed to direct gaugino searches*

- Using 2, 3, and 4-lepton channels
- Have already produced limits using all three channels

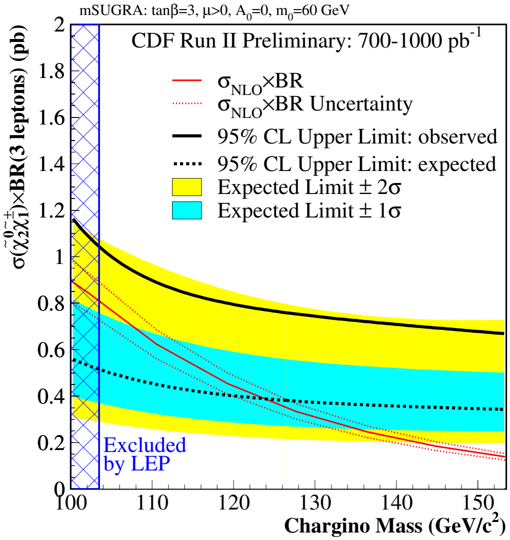
*Have been focusing on the case with intermediate $\tilde{\ell}$'s*

- Limited sensitivity in 4.7fb$^{-1}$ for no-$\tilde{\ell}$ case due to $\mathrm{BR}(W/Z \to \ell)$
- Should be able to explore no-$\tilde{\ell}$ case in 2012
- Developing expertise for 2012
    - Signal region optimization
    - Data driven background techniques


Run Number: 167776, Event Number: 129360643
Date: 2010-10-28, 10:41:18 CEST
Z->μμ + missing

# BACKUPS

# CDF Results




*PRL 99, 191806 (2007)*