Searches for supersymmetry in final states with two or more leptons in ATLAS

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University of Wisconsin at Madison

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Outline

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2. ATLAS & leptons
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   - $e\mu$ resonance
4. Summary & conclusions

Motivation

Why look for SUSY in final states with many leptons?

R-parity conserving (RPC) scenarios

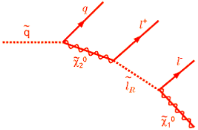
Strong production dominates at the LHC
$\Rightarrow \tilde{q}, \tilde{g}$ decay products can include charginos and neutralinos

$$\tilde{g} \to \tilde{q}\bar{q}, q\bar{\tilde{q}} \qquad (1)$$

$$\tilde{q} \to q\tilde{\chi}_2^0, q'\tilde{\chi}_2^{\pm} \qquad (2)$$

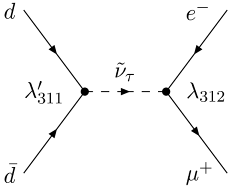
which in turn decay leptonically

$$\tilde{\chi}_2^0(\to \tilde{\ell}^{\pm}\ell^{\mp}) \to \tilde{\chi}_1^0\ell^{\pm}\ell^{\mp} \qquad (3)$$



$\Rightarrow$ Plenty of leptons in final state (possibly opposite-sign same-flavor pairs)

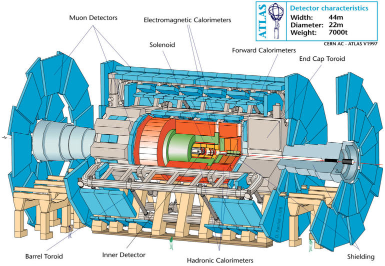
R-parity violating (RPV) SUSY or lepton flavor violating (LFV) decays of Z'-like particle

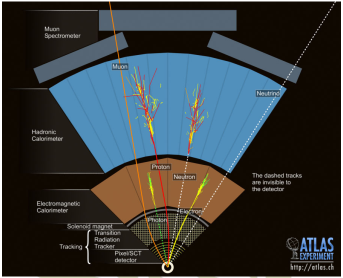


$$\tilde{\nu}_\tau \to e^{\pm}\mu^{\mp} \qquad (4)$$

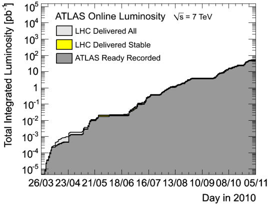
$$Z' \to e^{\pm}\mu^{\mp} \qquad (5)$$

ATLAS & leptons





~3000 physicists & engineers from 38 countries



~45 pb^{-1} "ready" recorded, 35 pb^{-1} usable for physics analysis

Main lepton identification tools

- Electrons: liquid Ar-based, finely segmented EM calorimeter, and transition radiation tracker (e/π separation)
- Muons: Monitored Drift Tubes for precision muon tracking, matched with inner detector track for combined reconstruction

$2\ell+E_{\mathrm{T}}^{\mathrm{miss}}$, opposite sign & same sign - selections

Search for dilepton excess in the two charge configurations separately

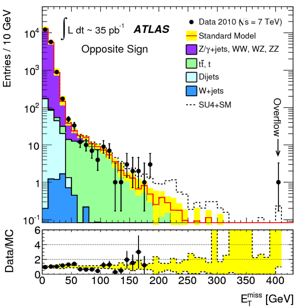
- Single-lepton trigger
- Exactly two leptons (ee, $e\mu$, $\mu\mu$), each with $p_{\mathrm{T}} > 20$ GeV
- $m_{\ell\ell} > 5$ GeV

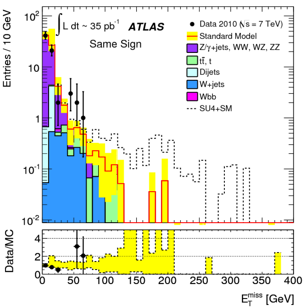
Opposite Sign (OS)

- Signal region: $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV

Same Sign (SS)

- Signal region: $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV





$2\ell+E_{\mathrm{T}}^{\mathrm{miss}}$, opposite sign & same sign - results

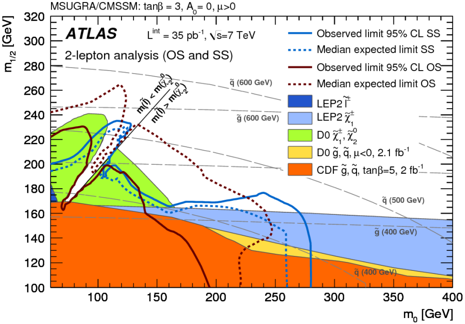
- Fake-lepton background estimated from $Z \to \ell^{\pm}\ell^{\mp}$ and QCD dijet control samples and evaluating $P(\text{ tight reco} \mid \text{loose real })$ and $P(\text{ tight reco} \mid \text{loose fake })$, respectively
- Top bg normalized in control region

Expected and observed yields per channel

Same Sign, $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV			
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Data	0	0	0
Fakes	0.12 ± 0.13	0.030 ± 0.026	0.014 ± 0.010
Di-bosons	0.015 ± 0.005	0.035 ± 0.012	0.021 ± 0.009
Charge-flip	0.019 ± 0.008	0.026 ± 0.011	-
Cosmics	-	$0^{+1.17}_{-0}$	-
Total	0.15 ± 0.13	$0.09^{+1.17}_{-0.03}$	0.04 ± 0.01

Opposite Sign, $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV			
	$e^{+}e^{-}$	$e^{\pm}\mu^{\mp}$	$\mu^{+}\mu^{-}$
Data	1	4	4
$t\bar{t}$	$0.62^{+0.31}_{-0.28}$	$1.24^{+0.62}_{-0.56}$	$1.00^{+0.50}_{-0.45}$
Z+jets	0.19 ± 0.15	0.08 ± 0.08	0.14 ± 0.17
Fakes	-0.02 ± 0.02	-0.05 ± 0.04	-
Single top	0.03 ± 0.05	0.06 ± 0.08	0.10 ± 0.07
Di-bosons	0.09 ± 0.03	0.06 ± 0.03	0.15 ± 0.03
Cosmics	-	-0.2 ± 1.18	-0.43 ± 1.27
Total	$0.92^{+0.42}_{-0.40}$	$1.43^{+1.45}_{-0.59}$	$1.39^{+1.41}_{-0.53}$

mSUGRA/CMSSM 95% C.L. exclusion limits ($\tan\beta = 3,\ A_0 = 0,\ \mu > 0$)

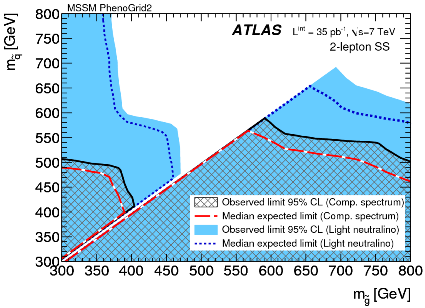


95% upper limits on $\sigma \times \text{acc.} \times \text{eff.}$:

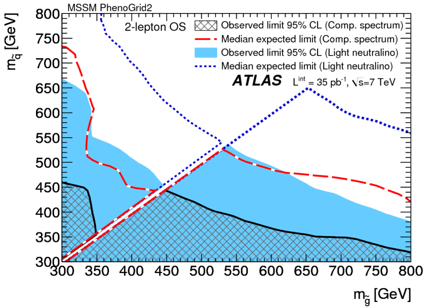
- SS: 0.07 pb
- OS: $e\mu$: 0.22 pb, ee: 0.09 pb, $\mu\mu$: 0.21 pb

$2\ell+E_T^{miss}$, opposite sign & same sign - results

- Interpretations in more general 24-parameter MSSM framework (see back-up slides for details)
- Two grids
  - compressed particle spectrum $\Rightarrow$ softer leptons
  - more favorable mass hierarchy $\Rightarrow$ harder leptons



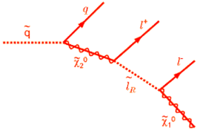
Same sign



Opposite sign

$2\ell+E_{\mathrm{T}}^{\mathrm{miss}}$ with flavor subtraction - idea & selections

Search for excess of same-flavor opposite-sign (SFOS) lepton pairs over different-flavor opposite sign (DFOS) lepton pairs. Selection similar to same-sign dilepton, i.e. $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV.



- Possible flavor and charge correlations for leptons from SUSY cascade decays: $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\ell^{\pm}\ell^{\mp}$
- No excess of SFOS over DFOS pairs expected from SM (except from $Z/\gamma*$)

Expression $\mathcal{S}$ estimates excess of SFOS pairs over DFOS pairs:

$$\mathcal{S} = \frac{N(e^{\pm}e^{\mp})}{\beta(1-(1-\tau_e)^2)} - \frac{N(e^{\pm}\mu^{\mp})}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^{\pm}\mu^{\mp})}{1-(1-\tau_e)^2} \tag{6}$$

where $\beta = \epsilon_e/\epsilon_\mu$ and τ_e and τ_e are the trigger efficiencies for e and μ, respectively

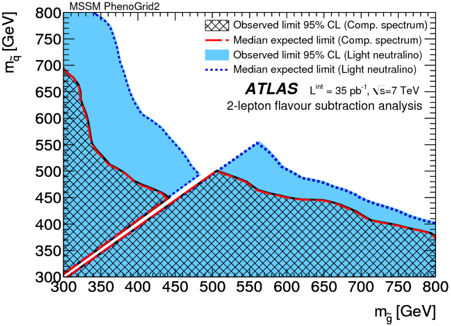
$2\ell+E_{\mathrm{T}}^{\mathrm{miss}}$ with flavor subtraction - results

Evaluating $\mathcal{S}$ in signal region yields

- $\mathcal{S}_{\text{obs.}} = 1.98 \pm 0.15(\beta) \pm 0.02(\tau_e) \pm 0.06(\tau_\mu)$
- $\mathcal{S}_{\text{bg}} = 2.06 \pm 0.79(\text{stat.}) \pm 0.78(\text{sys.})$

$\Rightarrow$ Good agreement, no SFOS pair excess observed

Interpreted as limits in same phenomenological 24-parameter MSSM framework $\Rightarrow$



Model-independent 95% CL limit on $\bar{\mathcal{S}}_s$, the average contribution to $\mathcal{S}$ from new physics:

- $\bar{\mathcal{S}}_s < 8.8$, assuming $\mathcal{B}(ee) = \mathcal{B}(\mu\mu)$, $\mathcal{B}(e\mu) = 0$
- $\bar{\mathcal{S}}_s < 12.6$, assuming $\mathcal{B}(ee) = \mathcal{B}(\mu\mu) = 2 \times \mathcal{B}(e\mu)$

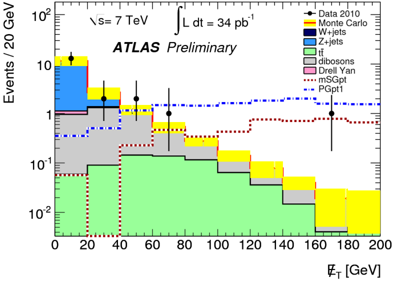
(Observed limit very similar to that of same-sign selection, very good agreement with expected median limit)

$\geq 3\ell + E_{\mathrm{T}}^{\mathrm{miss}}$+jets - selections

Requiring $\geq 3\ell$ greatly reduces background - "Golden channel" at the Tevatron

Selection

- $\geq 3\ell$ with $p_{\mathrm{T}} > 20$ GeV
  (10 GeV if third leading is μ)
  - no requirements on sign/flavor
- ≥ 2 jets with $p_{\mathrm{T}} > 50$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV
- Veto
  - $m_{\ell^+\ell^-} < 20$ GeV (D-Y)
  - $86 < m_{\ell^+\ell^-} < 96$ GeV (Z)



Expected and observed yields before $m_{\ell\ell}$-veto and cuts on jets and $E_{\mathrm{T}}^{\mathrm{miss}}$

- Main background Z+jets in low-$E_{\mathrm{T}}^{\mathrm{miss}}$ region, only low diboson/top bg in signal region
- Background from pure QCD jet production processes suppressed by high lepton multiplicity and $E_{\mathrm{T}}^{\mathrm{miss}}$ requirements

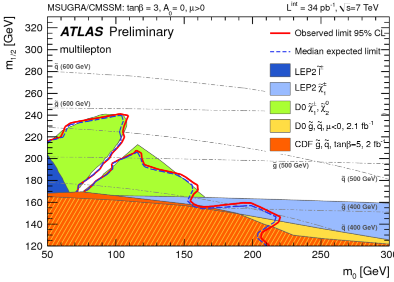
$\geq 3\ell + E_T^{miss}$+jets - results

Breakdown of yields per flavor configuration, before $m_{\ell\ell}$-veto and cuts on jets and E_T^{miss}.

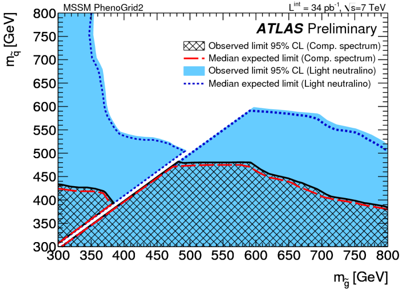
After final selection:

0 observed, 0.1 expected

Multilep. events	All	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
$t\bar{t}$	0.68±0.16	0.032±0.016	0.24±0.07	0.31±0.08	0.096±0.030
Z backgrounds	15.6±1.3	3.8±0.8	1.60±0.34	7.9±1.0	2.4±0.4
Other backgrounds	0.28±0.13	0.02±0.14	0.03±0.06	0.21±0.09	0.01±0.11
Total SM	16.6±1.3	3.8±0.8	1.9±0.4	8.4±1.0	2.5±0.4
Data	19	2	1	10	6



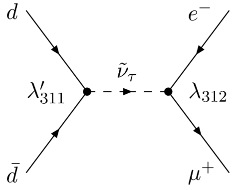
mSUGRA/CMSSM - similar to Tevatron limits



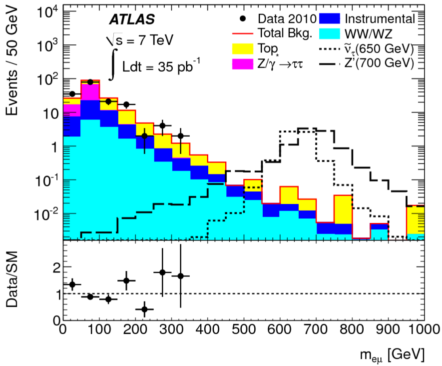
Phenomenological MSSM framework (same as before)

$e^\pm\mu^\mp$ resonance - selections

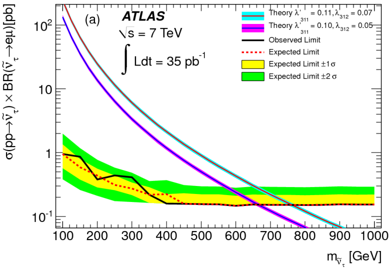
- Search for new heavy resonance decaying to $e^\pm\mu^\mp$
- Motivated by
  - RPV SUSY where $\tilde{\nu} \to e^\pm\mu^\mp$
  - Additional gauge symmetry featuring lepton flavor violation, e.g. $Z' \to e^\pm\mu^\mp$

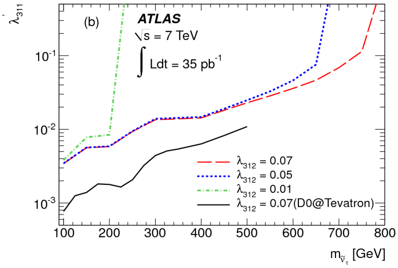


- Selections
  - Single-lepton trigger (e or $\mu \Rightarrow \epsilon = 100\%$)
  - Exactly 1 e and 1 μ with opposite charge and $p_{\mathrm{T}} > 20$ GeV



$e^{\pm}\mu^{\mp}$ resonance - results





Upper limits on $\sigma(pp \to \tilde{\nu}_\tau) \times \mathcal{B}(\tilde{\nu}_\tau \to e\mu)$ and resulting $m_{\tilde{\nu}_\tau}$ limits for two RPV SUSY scenarios.

Excludes $m_{\tilde{\nu}_\tau} < 750$ GeV if $\lambda'_{311} = 0.11$ and $\lambda_{312} = 0.07$

Limits in $m_{\tilde{\nu}_\tau}$-λ'_{311} space for various λ_{312} values.

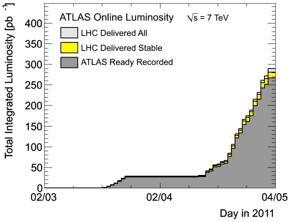
$\sigma_{Z' \to e\mu} < 0.175$ (0.183) pb^{-1} for $m_{Z'} = 700$ GeV (1 TeV) in LFV models at 95% C.L.

Summary & conclusions

- The ATLAS detector is working very well and recording excellent data efficiently
- SUSY-inspired search analyses in final states with two or more leptons were carried out with 2010 dataset of ∼34 pb^{-1}:
  - $2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ (same/opposite sign): arXiv
  - $2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ (flavor subtraction): arXiv (accepted by EPJC Letter)
  - $\geq 3\ell$+MET ("multilepton"): CONF note
  - $e\mu$ resonance: arXiv

  ⇒ Already matching current Tevatron limits in many channels which shows that detector works well and is quite well understood
- 2011 already looks like an exciting year for SUSY and other new physics!

ATLAS has already recorded ∼250 pb^{-1} in 2011!



Back-up slides

Details on the phenomenological MSSM signal grids

Two grids PhenoGrid2:
$m_{3^{\rm rd}{\rm gen}} = 2000$ GeV, $m_{\tilde{\ell}_R} = m_{\tilde{\ell}_L}$, $m_{\tilde{q}_R} = m_{\tilde{q}_L}$, $M = min\{m_{\tilde{q}}, m_{\tilde{g}}\}$

"PhenoGrid2a"

Compressed particle spectrum ⇒ soft lepton spectra

$m_{\tilde{\chi}_2^0} = M - 50$ GeV
$m_{\tilde{\chi}_1^0} = M - 150$ GeV
$m_{\tilde{\ell}_L} = M - 100$ GeV

"PhenoGrid2b"

More favorable scenario with larger mass differences ⇒ harder lepton $p_{\rm T}$ etc

$m_{\tilde{\chi}_2^0} = M - 100$ GeV
$m_{\tilde{\chi}_1^0} = M - 100$ GeV
$m_{\tilde{\ell}_L} = \frac{M}{2}$ GeV

Details on lepton identification & isolation criteria

General:

- Electron reconstruction:
  - "medium": requirements on track quality and lateral shower shape in calorimeter ⇒ used for signal region in multilepton and $e\mu$ resonance searches
  - "tight": in addition to the above, cuts are imposed on E/p and high-threshold hits along the track in the transition radiation tracker ⇒ used for signal region in SS/OS and flavor subtraction dilepton searches
- Muon reconstruction:
  - Combined: matched tracks in ID+MS ⇒ used for signal region in all analyses
  - Segment-tagged: ID track matched with at least one track segment in the MS ⇒ used by dilepton and multilepton searches, in addition to the combined muons

Isolation requirements are slightly different across analyses

- Dilepton SS/OS, flavor subtraction and multilepton analyses
  - e: $\frac{\sum_{\Delta R<0.2} E_{\mathrm{T}}^{\mathrm{calo}}}{p_{\mathrm{T}}^{e}} < 0.15$, μ: $\sum_{\Delta R<0.2} p_{\mathrm{T}}^{\mathrm{track}} < 1.8$ GeV
- $e\mu$ resonance search:
  - e: $\frac{\sum_{\Delta R<0.2} E_{\mathrm{T}}^{\mathrm{calo}}}{E_{\mathrm{T}}^{e}} < 0.1$, μ: $\frac{\sum_{\Delta R<0.2} p_{\mathrm{T}}^{\mathrm{track}}}{p_{\mathrm{T}}^{\mu}} < 0.1$

More on statistical methods

$2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ SS/OS & multilepton searches used a profile likelihood ratio method

- Likelihood function

$$L(n|s, b, \boldsymbol{\theta}) = P_S \times C_{\mathrm{syst.}} \tag{7}$$

where n events are observed with a background expectation of b, s is the signal to be tested and $\boldsymbol{\theta}$ represents the uncertainties. P_S is the Poisson probability and $C_{\mathrm{syst.}}$ constrains the systematics, including correlations.

- Exlcusion p-values though pseudo-experiments on likelihood ratio test statistic:

$$\Lambda(s) = -2(\ln L(n|s, \hat{\hat{b}}, \hat{\hat{\boldsymbol{\theta}}})) - \ln L(n|\hat{s}, \hat{b}, \hat{\boldsymbol{\theta}})) \tag{8}$$

where $\hat{s}$, $\hat{b}$ and $\hat{\boldsymbol{\theta}}$ maximize L, and $\hat{\hat{b}}$ and $\hat{\hat{\boldsymbol{\theta}}}$ maximize L for a given s.