Search for Non-Resonant New Phenomena with the CMS Experiment

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The CMS Detector

3.8T Superconducting Solenoid

Lead tungstate E/M Calorimeter (ECAL)

Hermetic ($|\eta|<5.2$) Hadron Calorimeter (HCAL) [scintillators & brass]

All Silicon Tracker (Pixels and Microstrips)

Redundant Muon System (RPCs, Drift Tubes, Cathode Strip Chambers)
Highlights from 2010 analyses
Search for Pair Production of First-Generation Scalar Leptoquarks Using Events Containing Two Electrons And Two Jets Produced in pp Collisions at $\sqrt{s} = 7$ TeV


Search for Pair Production of Second-Generation Scalar Leptoquarks in pp Collisions at $\sqrt{s} = 7$ TeV


Search for First Generation Scalar Leptoquarks in the evjj Channel in pp Collisions at $\sqrt{s} = 7$ TeV

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Search for Large Extra Dimensions in Dimuon Events in pp Collisions at $\sqrt{s} = 7$ TeV

Physics Analysis Summary EXO-10-020

Search for Large Extra Dimensions in the Diphoton Final State at the Large Hadron Collider

arXiv:1103.4279, accepted by JHEP
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Search for New Physics in Highly Boosted Z0 Decays to Dimuons in pp Collisions at $\sqrt{s}=7$ TeV

Physics Analysis Summary EXO-10-025

Model Unspecific Search for New Physics in pp Collisions at $\sqrt{s} = 7$ TeV

Physics Analysis Summary EXO-10-021
Search for Pair Production of First-Generation Scalar Leptoquarks Using Events Containing Two Electrons And Two Jets Produced in pp Collisions at $\sqrt{s} = 7$ TeV


Search for Pair Production of Second-Generation Scalar Leptoquarks in pp Collisions at $\sqrt{s} = 7$ TeV


Search for First Generation Scalar Leptoquarks in the $\text{c}\bar{\text{v}}\text{v}$$\text{i}$ Channel in pp Collisions at $\sqrt{s} = 7$ TeV

• 2010 analyses made public before EPS 2011
• No evidence for New Physics

Search for Large Extra Dimensions in the Diphoton Final State at the Large Hadron Collider

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Physics Analysis Summary EXO-10-025

Model Unspecific Search for New Physics in pp Collisions at $\sqrt{s} = 7$ TeV

Physics Analysis Summary EXO-10-021
$W'$ searches with 2011 data
$W'$: Overview

• Many beyond-the-SM theories predict new vector bosons: $W'$ and $Z'$
  – GUT, SUSY, ED, Little Higgs, Technicolor, etc
  – “Natural” new particles to predict: any extension of SM gauge group introduces new vector bosons
$W'$: Overview

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  - GUT, SUSY, ED, Little Higgs, Technicolor, etc
  - “Natural” new particles to predict: any extension of SM gauge group introduces new vector bosons

$W'$ Signatures

- Leptonic: $e + \nu$, $\mu + \nu$, $\tau + \nu$
- Bosonic: $WZ$, $W\gamma$
- Hadronic: $qq'$, $t\bar{b}$, $\ell N_\ell$ ($N_\ell \rightarrow qq'\ell'$)
$W'$: Overview

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- Large $W'$ mass opens up new channels
- Channels that are favored/suppressed: model-dependent
$W'$: Overview

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Significantly larger integrated luminosity than published 2010 analyses

- $W'$ Signatures
  - Leptonic: $e + \nu, \mu + \nu, \tau + \nu$
  - Bosonic: $WZ, W\gamma$
  - Hadronic: $qq', t\bar{t}, \ell N_\ell (N_\ell \rightarrow qq'\ell')$

Considered by CMS for the first time

Results presented here for the first time outside CMS
\( W' \rightarrow \ell \nu \)
Search for $W'$ decaying to electron/muon and neutrino

- $W'$: carbon copy of $W$ (same couplings to fermions)
- Neutrino is light & stable
  - Important in context of L-R symmetric model
- No mixing between $W'$ and other bosons ($W, Z, Z'$)
- $WZ$ channel also suppressed
$W' \rightarrow \ell \nu$: Analysis outline

Very similar event selection & analysis cuts for $e, \mu$ channels

- Trigger:
  - Highest $p_T/E_T$ unprescaled single lepton trigger
  - Plus $M_T$ condition for electron channel
- Only one (good quality) isolated high-$p_T/E_T$ lepton
- Plus: “nothing else” in the event, i.e. lepton $p_T$ and $M_E_T$ are similar in magnitude and back-to-back in $x\ y$ plane
Very similar event selection & analysis cuts for $e, \mu$ channels

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**Typical signal efficiencies**

- $> 80\%$ in both electron & muon channels
- Fairly independent of $W'$ mass
$W' \rightarrow \ell \nu \ (\ell = e, \mu)$ signature

Spectacular signature:

• One very energetic lepton in event ("straight track")
• Plus, "nothing else" in the event
$W' \rightarrow \ell \nu$ ($\ell = e, \mu$) signature

Spectacular signature:
- One very energetic lepton in event ("straight track")
- Plus, “nothing else” in the event

Muon channel: Event with $M_T = 778$ GeV
$W' \rightarrow \ell \nu$ ($\ell = e, \mu$) signature

Spectacular signature:
• One very energetic lepton in event (“straight track”)
• Plus, “nothing else” in the event

Electron channel: Event with $M_T = 922$ GeV
\[ W' \rightarrow \ell \; N_\ell \; , \; N_\ell \rightarrow qq' \ell' \]
$W' \rightarrow \ell N_\ell (qq'\ell')$ model

Search for $W'$ decaying to heavy neutrino plus lepton

• Coupling to right-handed (heavy) neutrino

• L-R symmetric model: restores parity at higher energies by introducing new heavy charged bosons
  – Parity violation explained by $W, W'$ mass difference

• Massive neutrinos: “see-saw” mechanism
$W' \rightarrow \ell N_\ell (qq' \ell')$ model

Search for $W'$ decaying to heavy neutrino plus lepton

- No L-R mixing: heavy neutrino decays via $W_R'$
- Cross-section: depends on $W_R'$, $N_\ell$ masses (assuming $W_L'$ couplings)
- Final state: two (same-flavor) leptons plus two jets
$W' \rightarrow \ell N_\ell (qq' \ell')$ signature

Muon channel: Event with $M_{\mu\mu} = 331$ GeV, $M_{\mu\mu jj} = 881$ GeV
$W' \rightarrow \ell N_\ell (qq' \ell')$ signature

Electron channel: Event with $M_{ee} = 264$ GeV, $M_{eejj} = 1009$ GeV

Run: 163374
LS: 54
Event: 29135486
Very similar event selection & analysis cuts for $e, \mu$ channels

- Single-lepton triggers
- Two (good quality) isolated leptons
- Two anti-$k_T$ ($\Delta R = 0.5$) jets
- Ensure no jet-lepton overlaps
- Remove Z/Drell-Yan by applying $M_{\ell\ell}$ cut
\[ W' \rightarrow \ell N_\ell (qq'\ell') \]: Analysis outline

Very similar event selection & analysis cuts for \( e, \mu \) channels

- Single-lepton triggers
- Two (good quality) isolated leptons
- Two anti-\( k_T \) (\( \Delta R = 0.5 \)) jets
- Ensure no jet-lepton overlaps
- Remove Z/Drell-Yan by applying \( M_{\ell\ell} \) cut

Typical signal efficiencies

- 70-75% in \( eejj \) channel
- 75-80% in \( \mu\mu jj \) channel
- Assuming \( m(N_\ell) > m(W_R')/2 \)
Background estimations
Background estimation

- $W' \rightarrow \ell \nu$: sideband fit of $M_T$ spectrum
  - Find “signal-free” region of $M_T$ spectrum (off-peak $W$)
  - Fit and use parameters to model background shape
  - Extrapolate function to “region of interest” ($M_T$ tail)
  - Estimate background in signal region w/o relying on MC

- $W' \rightarrow \ell \ N_\ell$: combination of data- and MC-based estimates
  - Major backgrounds: top and $Z +$jets
    - Use MC shapes, normalize to data
  - Other backgrounds:
    - QCD: determine from data
    - $W +$jets, dibosons: use MC prediction
(Transverse*) Mass distributions

\( M_T = \sqrt{2 \cdot (p_T^\mu \cdot c) \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta \phi_{\mu,\nu})} \)
$e + MET$ transverse mass

2011 analysis: 1.03 fb$^{-1}$

Figure 2: Transverse mass distribution (left) and cumulative distribution (right) for the electron channel.

No excess (compared to bgd expectations) observed in data
μ + MET transverse mass

2011 analysis: 1.13 fb⁻¹

Figure 3: Transverse mass distribution (left) and cumulative distribution (right) for the muon channel.

No excess (compared to bgd expectations) observed in data
No excess (compared to bgd expectations) observed in data
\( \mu \mu jj \) invariant mass

2010 analysis:
36 pb\(^{-1}\)

2011 analysis:
204 pb\(^{-1}\)

No excess (compared to bgd expectations) observed in data
Systematic Uncertainties
Systematic uncertainties

Long list of systematic uncertainties considered (see backup)

Major systematics summarized here

- $W' \rightarrow \ell \nu$
  - PDF/$k$-factor uncertainties
  - Muon $p_T$ resolution for very energetic muons
  - Uncertainties related to background determination

- $W' \rightarrow \ell N_\ell$
  - Jet-energy scale
  - PDF/$k$-factor uncertainties
  - Initial & final state radiation
Statistical analysis & Exclusion limits
Setting Exclusion Limits

• Look for excess of events at tail of mass distributions
• No signal observed

😊

• Simple “event-counting” experiments
  – What is the number of expected signal events?
  – What is the number of expected background events?
  – What is the number of observed events in the data?

• Limit setting
  – Bayesian method with flat prior for signal cross section
  – $W' \rightarrow \ell \nu$: using “sliding” search window
  – $W' \rightarrow \ell N_\ell$: using fixed search window
Exclusion limit: $e/\mu + ME_T$

- Fully correlated luminosity uncertainty
- Fully uncorrelated background uncertainty

Combined limit in SSM:
Expected: $m(W') > 2.20$ TeV
Observed: $m(W') > 2.27$ TeV

Significant improvement over 2010 result (1.58 TeV)
Exclusion limits: $W_R'$, $N_\ell$ mass plane

- Reconstruction, ID uncertainties between 2010, 2011: uncorrelated
- All other uncertainties: correlated

- Lower bound on $m(W_R')$ extends up to 1.7 TeV
- Significant improvement over TeVatron limit (780 GeV)
Summary
This just in
Search for pair production of a fourth-generation $t'$ quark in the lepton-plus-jets channel with the CMS experiment

$t't' \rightarrow WbW\bar{b} \rightarrow \ell v b q\bar{q}b$
Search for pair production of a fourth-generation $t'$ quark in the lepton-plus-jets channel with the CMS experiment

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Search for pair production of a fourth-generation $t'$ quark in the lepton-plus-jets channel with the CMS experiment

$$t't' \rightarrow WbWb \rightarrow \ell v b q\bar{q}b$$

A search is presented for the pair production of a fourth-generation $t'$ quark and its antiparticle in proton-proton collisions at $\sqrt{s} = 7$ TeV provided by the Large Hadron Collider. The data were collected by the CMS detector during the 2011 collider run. The $t'$ quark is assumed to decay exclusively to a $W$ boson and a $b$ quark. The search is carried out using events with a single isolated electron or muon, large missing transverse momentum, and at least four jets with large transverse momenta, one of which must be identified as originating from the fragmentation of a $b$ quark. The data analyzed correspond to an integrated luminosity of 573 pb$^{-1}$ for the electron channel and 821 pb$^{-1}$ for the muon channel. No significant excess over standard model expectations is observed. Assuming strong pair production of $t'$ quarks, a lower limit is set on the $t'$ quark mass of 450 GeV at 95% confidence level.
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$$t't' \rightarrow WbWb \rightarrow \ell\nu bq\overline{q}b$$

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https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
Summary
Summary

• Search for $W'$ in $\ell + ME_T$ final state carried out with 1.1 fb$^{-1}$ of 2011 data
• Search for right-handed $W'$ (in $\ell\ell jj$ final state) carried out with 240 pb$^{-1}$ of 2010-11 data

• No excess above SM background expectations is observed in data distributions

• A lower bound has been set on the $W'$ mass, assuming SM-like couplings and no interference with other bosons:
  - $m(W') > 2.27$ TeV \quad $\ell + MET$
  - $m(W_R') > 1.70$ TeV (for $m_{N_\ell} \sim 500$ GeV) \quad $\ell\ell jj$

• Significant improvement over 2010 limits
• A lower bound has been set on the $W'$ mass, assuming SM-like couplings and no interference with other bosons:
  - $m(W') > 2.27 \text{ TeV} \quad \ell + \text{MET}$
  - $m(W_R') > 1.70 \text{ TeV} \quad (\text{for } m_{N\ell} \sim 500 \text{ GeV}) \quad \ell\ell jj$

• Significant improvement over 2010 limits
Backup
Total weight 14000 t
Overall diameter 15 m
Overall length 21.6 m

- **ECAL**: 76k scintillating PbWO$_4$ crystals
- **HCAL**: Plastic scintillator/Brass sandwich
- **4T Solenoid**
- **IRON YOKE**
- **Muons & Tracker**:
  - Pixels (100x150 µm$^2$)
    - ~ 1 m$^2$ 66M channels
  - Silicon Microstrips
    - ~ 210 m$^2$ 9.6M channels
- **MUON BARREL**:
  - Drift Tubes (DT) and Resistive Plate Chambers (RPC)
- **Muon End-Caps**
  - Cathode Strip Ch. (CSC)
  - Resistive Plate Ch. (RPC)

- **Pixels**
- **Tracker**
- **ECAL**
- **HCAL**
- **Muons**
- **Solenoid coil**
$W' \rightarrow \ell \nu$ search results in 2010

<table>
<thead>
<tr>
<th>Limits</th>
<th>Electron (TeV)</th>
<th>Muon (TeV)</th>
<th>Combined (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF (5.3 fb$^{-1}$, 2 TeV)</td>
<td>1.12</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>CDF (107 pb$^{-1}$, 1.8 TeV)</td>
<td></td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>CMS (36 pb$^{-1}$, 7 TeV)</td>
<td>1.36</td>
<td>1.40</td>
<td>1.58</td>
</tr>
<tr>
<td>Atlas (36 pb$^{-1}$, 7 TeV)</td>
<td>1.37</td>
<td>1.29</td>
<td>1.49</td>
</tr>
</tbody>
</table>

**NNLO $k$-factor for $W'$ production**

- Signal samples generated with PYTHIA6 in LO
- Determination of NNLO $k$-factors for each $W'$ mass point using FEWZ 2.0 (see: http://gate.hep.anl.gov/fpetriello/FEWZ.html)
- Calculated LO cross-section for CTEQ6L1 (used for generation) and NNLO cross-section for MSTW2008 PDF-sets for masses 600-2500 GeV in steps of 100 GeV
- Analysis uses $\text{NNLO} = \text{LO} \times k$-factor

\[
K_{\text{Factor}}^{\text{NNLO}} = \frac{\sigma_{\text{FEWZ}}(\text{NNLO; MSTW2008})}{\sigma_{\text{FEWZ}}(\text{LO; CTEQ6L1})}
\]
PDF uncertainties

Three different PDF sets (PDF4LHC recommendation, end of 2010)

\[ \Delta F_{\text{tot}} = \frac{1}{2} \left( \max_i \left( F_i^i + (\Delta F_{\text{PDF}+\alpha_s}^i)_+ \right) - \min_i \left( F_i^i - (\Delta F_{\text{PDF}+\alpha_s}^i)_- \right) \right) \]
Background estimation

- $W' \rightarrow \ell \nu$: sideband fit of $M_T$ spectrum
  - Find “signal-free” region of $M_T$ spectrum (off-peak $W$)
  - Fit and use parameters to model background shape
  - Extrapolate function to “region of interest” ($M_T$ tail)
  - Estimate background in signal region w/o relying on MC

**Tested several fitting functions**

Function 1:

$$\frac{a}{(x+b)^c}$$

Function 2:

$$\frac{a}{(x^2+b \cdot x+c)^d}$$

Function 3:

$$\frac{a(1+x)^b}{(x^{c+d \cdot \log x})}$$

Example: muon channel
Background estimation

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  - Find “signal-free” region of $M_T$ spectrum (off-peak $W$)
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  - Estimate background in signal region w/o relying on MC

- Variations of sideband width and different functions give slightly different predictions for background at large $M_T$: systematic uncertainty
- Impact of fit parameters uncertainty on extrapolation: statistical uncertainty
- MC-Data difference: minor effect (including Sudakov corrections, a $\sim 15$-20% effect)

Example: muon channel

Function 2:

$$\frac{a}{(x^2 + b \cdot x + c)^d}$$

Function 3:

$$\frac{a(1+x)^b}{(x^c + d \cdot \log x)}$$
Systematic uncertainties: $\ell + M E_T$

### Signal

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Value</th>
<th>Impact on signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6 %</td>
<td>6 %</td>
</tr>
<tr>
<td>Muon $p_T$ resolution and Momentum scale</td>
<td>0.14 TeV$^{-1}$ (pT)</td>
<td>10 %</td>
</tr>
<tr>
<td></td>
<td>0.4% (scale)</td>
<td></td>
</tr>
<tr>
<td>MET resolution, hadronic component</td>
<td>10 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Muon trigger efficiency</td>
<td>3 %</td>
<td>3 %</td>
</tr>
<tr>
<td>Combined electron efficiency (trigger, ID and reconstruction)</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>1% EE, 3% EC</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

### Background

Taking into account uncertainties due to fit parameter errors in extrapolation, sensitivity of fit on range of sideband, choice of fitting function and discrepancy between MC and sideband fit prediction
# Systematic uncertainties: $\ell\ell jj$

## Electron Channel

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Signal</th>
<th>$\ttbar$</th>
<th>Z+jets</th>
<th>QCD</th>
<th>Other bkgd</th>
<th>All bkgd</th>
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</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>$\pm 2-20%$</td>
<td>$\pm 11%$</td>
<td>$\pm 5%$</td>
<td>$-$</td>
<td>$\pm 12%$</td>
<td>$\pm 7%$</td>
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<tr>
<td>Electron Energy Scale</td>
<td>$\pm 1-3%$</td>
<td>$\pm 4%$</td>
<td>$\pm 3%$</td>
<td>$-$</td>
<td>$\pm 9%$</td>
<td>$\pm 4%$</td>
</tr>
<tr>
<td>Electron Reco/ID/Iso</td>
<td>$\pm 10%$</td>
<td>$\pm 10%$</td>
<td>$\pm 10%$</td>
<td>$-$</td>
<td>$\pm 10%$</td>
<td>$\pm 10%$</td>
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<tr>
<td>Normalization</td>
<td>$\pm 6%$</td>
<td>$\pm 12%$</td>
<td>$\pm 7%$</td>
<td>$-$</td>
<td>$\pm 6%$</td>
<td>$\pm 8%$</td>
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<tr>
<td>Simulation Statistics</td>
<td>$\pm 1-7%$</td>
<td>$\pm 5%$</td>
<td>$\pm 4%$</td>
<td>$-$</td>
<td>$\pm 7%$</td>
<td>$\pm 5%$</td>
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<tr>
<td>Theoretical</td>
<td>$\pm 5%$</td>
<td>$\pm 13%$</td>
<td>$\pm 19%$</td>
<td>$-$</td>
<td>$\pm 13%$</td>
<td>$\pm 14%$</td>
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<tr>
<td>QCD estimate</td>
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<td>$-$</td>
<td>$\pm 18%$</td>
<td>$-$</td>
<td>$\pm 3%$</td>
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<tr>
<td><strong>Total</strong></td>
<td>$\pm 12-25%$</td>
<td>$\pm 24%$</td>
<td>$\pm 23%$</td>
<td>$\pm 18%$</td>
<td>$\pm 25%$</td>
<td>$\pm 23%$</td>
</tr>
</tbody>
</table>

## Muon Channel

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>Signal</th>
<th>$\ttbar$</th>
<th>Z+jets</th>
<th>QCD</th>
<th>Other bkgd</th>
<th>All bkgd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>$\pm 0.5-20%$</td>
<td>$\pm 4%$</td>
<td>$\pm 7%$</td>
<td>$-$</td>
<td>$\pm 10%$</td>
<td>$\pm 5%$</td>
</tr>
<tr>
<td>Muon Energy Scale</td>
<td>$\pm 0-3%$</td>
<td>$\pm 5%$</td>
<td>$\pm 3%$</td>
<td>$-$</td>
<td>$\pm 4%$</td>
<td>$\pm 4%$</td>
</tr>
<tr>
<td>Muon Reco/ID/Iso</td>
<td>$\pm 6-10%$</td>
<td>$\pm 1%$</td>
<td>$\pm 0.5%$</td>
<td>$-$</td>
<td>$\pm 0.5%$</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>$\pm 0.3%$</td>
<td>$\pm 0.3%$</td>
<td>$\pm 0.3%$</td>
<td>$-$</td>
<td>$\pm 0.3%$</td>
<td>$\pm 0.3%$</td>
</tr>
<tr>
<td>Normalization</td>
<td>$\pm 6%$</td>
<td>$\pm 12%$</td>
<td>$\pm 8%$</td>
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<td>$\pm 6%$</td>
<td>$\pm 8%$</td>
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<td>$\pm 1-7%$</td>
<td>$\pm 4%$</td>
<td>$\pm 3%$</td>
<td>$-$</td>
<td>$\pm 9%$</td>
<td>$\pm 3%$</td>
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<td>Theoretical</td>
<td>$\pm 5%$</td>
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<td>$\pm 19%$</td>
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<td>$\pm 14%$</td>
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<tr>
<td>QCD estimate</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$\pm 25%$</td>
<td>$-$</td>
<td>$\pm 0.1%$</td>
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<tr>
<td><strong>Total</strong></td>
<td>$\pm 10-25%$</td>
<td>$\pm 19%$</td>
<td>$\pm 22%$</td>
<td>$\pm 25%$</td>
<td>$\pm 22%$</td>
<td>$\pm 17%$</td>
</tr>
</tbody>
</table>
Exclusion limits: $e/\mu + ME_T$

**Electron channel**

<table>
<thead>
<tr>
<th>$W'$ mass (GeV)</th>
<th>$M_T$ (GeV)</th>
<th>$N_{\text{sig}}$ (Events)</th>
<th>$N_{\text{bkg}}$ (Events)</th>
<th>$N_{\text{data}}$ (Events)</th>
<th>$\sigma_{\text{theor}}$ (pb)</th>
<th>Exp. Limit (pb)</th>
<th>Obs. Limit (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>1000</td>
<td>53.838 ± 3.707</td>
<td>2.227 ± 1.124</td>
<td>1</td>
<td>0.144</td>
<td>0.014</td>
<td>0.011</td>
</tr>
<tr>
<td>1600</td>
<td>1000</td>
<td>23.681 ± 1.630</td>
<td>1.438 ± 0.798</td>
<td>1</td>
<td>0.063</td>
<td>0.013</td>
<td>0.011</td>
</tr>
<tr>
<td>1800</td>
<td>1000</td>
<td>12.021 ± 0.735</td>
<td>1.438 ± 0.798</td>
<td>1</td>
<td>0.029</td>
<td>0.011</td>
<td>0.010</td>
</tr>
<tr>
<td>2100</td>
<td>1100</td>
<td>3.764 ± 0.242</td>
<td>1.438 ± 0.798</td>
<td>1</td>
<td>0.009</td>
<td>0.012</td>
<td>0.010</td>
</tr>
<tr>
<td>2400</td>
<td>1100</td>
<td>1.193 ± 0.087</td>
<td>1.438 ± 0.798</td>
<td>1</td>
<td>0.003</td>
<td>0.013</td>
<td>0.012</td>
</tr>
</tbody>
</table>

**Muon channel**

<table>
<thead>
<tr>
<th>$W'$ mass (GeV)</th>
<th>$M_T$ (GeV)</th>
<th>$N_{\text{sig}}$ (Events)</th>
<th>$N_{\text{bkg}}$ (Events)</th>
<th>$N_{\text{data}}$ (Events)</th>
<th>$\sigma_{\text{theor}}$ (pb)</th>
<th>Exp. Limit (pb)</th>
<th>Obs. Limit (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400</td>
<td>1000</td>
<td>68.665 ± 7.320</td>
<td>2.014 ± 1.402</td>
<td>0</td>
<td>0.144</td>
<td>0.011</td>
<td>0.006</td>
</tr>
<tr>
<td>1600</td>
<td>1050</td>
<td>31.932 ± 3.403</td>
<td>1.621 ± 1.182</td>
<td>0</td>
<td>0.063</td>
<td>0.010</td>
<td>0.006</td>
</tr>
<tr>
<td>1800</td>
<td>1100</td>
<td>14.455 ± 1.540</td>
<td>1.316 ± 1.002</td>
<td>0</td>
<td>0.029</td>
<td>0.009</td>
<td>0.006</td>
</tr>
<tr>
<td>2100</td>
<td>1100</td>
<td>4.435 ± 0.473</td>
<td>1.316 ± 1.002</td>
<td>0</td>
<td>0.009</td>
<td>0.010</td>
<td>0.007</td>
</tr>
<tr>
<td>2400</td>
<td>1100</td>
<td>1.249 ± 0.133</td>
<td>1.316 ± 1.002</td>
<td>0</td>
<td>0.003</td>
<td>0.013</td>
<td>0.008</td>
</tr>
</tbody>
</table>
Exclusion limits: $eejj$

$m(W_R') = 0.9$ TeV

$m(W_R') = 1.5$ TeV

$m(N_{\ell}) = 0.5$ TeV
Exclusion limits: $\mu\mu jj$

$$m(W_R') = 0.9 \text{ TeV}$$

$$m(W_R') = 1.5 \text{ TeV}$$

$$m(N_\ell) = 0.6 \text{ TeV}$$

Muon Channel (2010, 36 pb$^{-1}$)

<table>
<thead>
<tr>
<th>Data</th>
<th>Signal</th>
<th>$(\epsilon \times A)$ (%)</th>
<th>Tot. BG</th>
<th>$tt$</th>
<th>$Z$+jets</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>56</td>
<td>1.6 ± 0.4</td>
<td>0.9</td>
<td>0.6</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Muon Channel (2011, 204 pb$^{-1}$)

<table>
<thead>
<tr>
<th>Data</th>
<th>Signal</th>
<th>$(\epsilon \times A)$ (%)</th>
<th>Tot. BG</th>
<th>$tt$</th>
<th>$Z$+jets</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>52</td>
<td>55</td>
<td>9.9 ± 2.2</td>
<td>5.5</td>
<td>4.0</td>
<td>0.4</td>
</tr>
</tbody>
</table>