Searches for New Phenomena at the LHC

Lars Sonnenschein
on behalf of the CMS & ATLAS collaborations
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Outline

Introduction

Searches for TeV scale gravity
- Black holes (CMS)
- TeV scale gravity signatures (ATLAS)
- Extra Dimensions in $\gamma\gamma$ (CMS)
- ED in $\gamma\gamma + \ell\ell$ (ATLAS)
- Large ED in $\mu\mu + ee + \gamma\gamma$ (CMS)
- Dark Matter + LED in $\gamma + E_T^{\text{miss}}$ (CMS)
- LED/Unpart. in Mono-Jet + $E_T^{\text{miss}}$ (CMS)
- RS gravitons in jet + $E_T^{\text{miss}}$ (CMS)

Searches in lepton production
- $W' \rightarrow \ell\nu$ ($\ell = e, \mu$) (CMS)
- Multileptons (CMS)
- Excited leptons (ATLAS)
- Contact Interactions in dilepton events (ATLAS)

Searches in lepton + jet production
- 1st generation Lepto Quarks (ATLAS)
- 2nd generation Lepto Quarks (ATLAS)
- Heavy bottom quarks to $Zb$ (ATLAS)
- Heavy bottom like quark (CMS)
- Heavy neutrinos (ATLAS)

Searches in jet production
- Search in dijet angular distribution (CMS)
- Search for heavy vector-like quarks (ATLAS)

Searches for long-lived charged particles
- Heavy Stable Charged Particles (CMS)
- Light Higgs $\rightarrow$ long-lived $\pi_v\pi_v$ (ATLAS)

Conclusions
Introduction

Searches for physics beyond the Standard Model

- Based on LHC 2011 data \((1.1 - 4.9 \text{ fb}^{-1})\) with \(\sqrt{s} = 7 \text{ TeV}\)
- Some of important theories tested
  - TeV scale gravity
  - Quark/lepton compositeness/contact interactions
  - New heavy vector bosons & other exotic signatures
- Only new results are presented (post HCP 2011)
- All public results (preliminary, published or submitted/accepted for publication) are available at:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
Searches for TeV scale gravity

- Black holes (CMS)
- TeV scale gravity signatures (ATLAS)
- Extra Dimensions in $\gamma\gamma$ (CMS)
- ED in $\gamma\gamma + \ell\ell$ (ATLAS)
- Large ED in $\mu\mu + ee + \gamma\gamma$ (CMS)
- Dark Matter + LED in $\gamma + E_T^{\text{miss}}$ (CMS)
- LED/Unpart. in Mono-Jet + $E_T^{\text{miss}}$ (CMS)
- RS gravitons in jet + $E_T^{\text{miss}}$ (CMS)
Search for microscopic black holes

Black Hole candidate signature/selection

- Energetic multi-particles ($\sim 75\%$ jets, $\sim 25\%$ $W, Z, \gamma, \ell, H$)
- $S_T = \Sigma \text{jets(anti-}k_T, R=0.5) + \gamma's + \ell'\text{s} + E_T^{\text{miss}}$ discriminating variable insensitive to Black Hole evaporation details
- Requiring $S_T > S_T^{\text{min}}$ in bins of $N$ objects

$CL_S$ (modified frequentist) exclusion limits at 95% C.L.

- Model independent limits, counting experiment: $S_T > S_T^{\text{min}}$, for $3 \leq N \leq 8$
- Minimum QBH mass as function of $M_D$ for $n$ extra dimensions
- Further limits on minimum string-ball mass and semi-classical BH mass (approximation breakdown for $m_{BH}^{\text{min}} \simeq 3 - 5 M_D$)
Search for TeV-scale gravity signatures in leptons + jets

Electron channel: scalar $p_T$ sum

Signal filtering
- $\geq 3$ obj. $\in \ell, j$
- $\sum p_T > 700\ldots1500$ GeV
- $p_T(\ell_{1st}) > 100$ GeV
- Combining $e + \mu$ channels

Charybdis model: Rotating BH, low multiplicity remnant. Reliable modelling for $M_{TH} > kM_D$; $k > 1$

$CL_s$ exclusion limits at 95% C.L.
- on $M_D(M_S)$ vs. $M_{TH}$ (2-dim) for diff. models
- on $\sigma \times A$ of 16.7 fb for $\sum p_T > 1.5$ TeV

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Searches for New Phenomena at the LHC
Search for extra dimensions in diphoton mass spectrum


$$\mathcal{L} = 2.2 \text{ fb}^{-1}$$

Update of previous CMS measurement JHEP 5 85 (2011), hep-ex 1103.4279

ADD: $$M_D^{n+2} = \frac{M_{Pl}^2}{(8\pi)^n L^n}$$

RS: $$\frac{M_{Pl}^2}{8\pi} = \frac{M_5^3}{k}(1 - e^{-2\pi k r_c})$$

$$\sigma(G \rightarrow \gamma\gamma)/\sigma(G \rightarrow f\bar{f}) = 2$$ (spin)

95% C.L. limits on $$M_S(\text{TeV})$$ in ADD models

<table>
<thead>
<tr>
<th>K factor</th>
<th>GRW</th>
<th>Hewett pos.</th>
<th>Hewett neg.</th>
<th>n$_{ED}$ = 2</th>
<th>n$_{ED}$ = 3</th>
<th>n$_{ED}$ = 4</th>
<th>n$_{ED}$ = 5</th>
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<td>1.0</td>
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<tr>
<td>1.6</td>
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<td>2.84</td>
<td>2.41</td>
<td>3.68</td>
<td>3.79</td>
<td>3.18</td>
<td>2.88</td>
<td>2.68</td>
<td>2.53</td>
</tr>
</tbody>
</table>

CL$_S$ exclusion limits at 95% C.L.

- String mass scale (UV cut-off) $$M_S = 2.3 - 3.8 \text{ TeV}$$ (ADD models) depending on $$n_{ED}$$ (HLZ convention)
- Resonant graviton $$M_1 = 0.86 - 1.84 \text{ TeV}$$ (RS1 model) depending on normalised coupling strength $$\tilde{k} = k/M_{Pl}$$

Randall-Sundrum model limits

- String mass scale (UV cut-off) $$M_S = 2.3 - 3.8 \text{ TeV}$$ (ADD models) depending on $$n_{ED}$$ (HLZ convention)
- Resonant graviton $$M_1 = 0.86 - 1.84 \text{ TeV}$$ (RS1 model) depending on normalised coupling strength $$\tilde{k} = k/M_{Pl}$$
Search for Extra Dimensions ($\gamma\gamma$ and $\ell\ell$ comb.)

Diphoton modelling (backgrounds)

- Diphoton production: inv. mass and diff. cross section from DIPHOX (NLO)
- $\gamma$+ jet, multijet bkg. from data ($m_{\gamma\gamma}$ fit)
- $m_{\gamma\gamma}$ background shape and normalisation systematics: $\simeq 2\%$ at $m_{\gamma\gamma} = 140$ GeV to $\simeq 20\%$ for $\gtrsim 2$ TeV

Bayesian exclusion limits at 95% C.L.

- ADD: $2.27 < M_S < 3.53$ TeV depending on $N$(dim) and model
- Randall-Sundrum: $0.79 < m_{G_{RS}} < 1.85$ TeV for $0.01 < k/M_{Pl} < 0.1$
- Comb. with prev. $\ell\ell$ results: $0.8 < m_{G_{RS}} < 1.95$ TeV for $0.01 < k/M_{Pl} < 0.1$
Search for Large Extra Dimensions in $\mu\mu$ and $ee$ events


$\mathcal{L}_{\mu\mu}(ee) = 2.3 (2.1) \text{ fb}^{-1}$

Signal filtering
- Central leptons: Both $\mu$'s (at least one $e$)
- Signal region: $M_{\ell\ell} > 1.1 \text{ TeV}$

$CL_s$ exclusion limits at 95% C.L.
- ADD signal NLO K-factor = 1.3 for $\ell\ell$ (1.6 for $\gamma\gamma$)
- Signal cross section $\sigma_s = 1.2 \text{ fb}$ for $\mu\mu$ channel (1.6 fb for $ee$ channel)
- Combined limit: $\sigma_s(\mu\mu + ee) = 1.4 \text{ fb}$
- Combination with $\gamma\gamma$ channel provides most stringent ADD limits to date ($M_{\text{max}} = \Lambda_T(\text{GRW}), M_S(\text{HLZ})$)

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<table>
<thead>
<tr>
<th>ADD K-factor</th>
<th>$\Lambda_T$ [TeV] (GRW)</th>
<th>$M_s$ [TeV] (HLZ)</th>
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</thead>
<tbody>
<tr>
<td>$\mu\mu$, $ee$, and $\gamma\gamma$</td>
<td>1.3 ($\mu\mu$ and $ee$), 1.6 ($\gamma\gamma$)</td>
<td>3.3</td>
</tr>
</tbody>
</table>

$\mu\mu$, ee, and $\gamma\gamma$

| $\mu\mu$, ee, and $\gamma\gamma$ | 1.3 ($\mu\mu$ and $ee$), 1.6 ($\gamma\gamma$) | 3.3 | 4.1 | 3.9 | 3.3 | 3.0 | 2.8 | 2.6 |
Models and phenomenology

- ADD: $q\bar{q} \rightarrow \gamma G \rightarrow \gamma + \not{E}_T$
- Dark Matter: $q\bar{b} \rightarrow \gamma D \bar{D} \rightarrow \gamma + \not{E}_T$
  Contact interaction scale $\Lambda (m_{\text{mediator}})$
  Describing spin (in-)dependent interactions through (vector) axial-vector coupling
  ⇒ limits on WIMP-nucleon elastic cross section

$\mathcal{L} = 4.67 \text{ fb}^{-1}$

$CL_S$ exclusion limits at 95% C.L.
(and at 90% C.L. for DM literature comparison)

- ADD 95% C.L. limit on multi-dim. Planck mass at $M_{XP} = 1.59 - 1.66 \text{ TeV}$ for $n = 3 - 6$ dim. (NLO)
- 90% C.L. WIMP masses $m_{\text{WIMP}} \lesssim 3.5 \text{ GeV}$ excluded for cross sections $> 16.8 \text{ fb}$
  For spin-dependent scattering: 90% C.L. limits on cross section of $16.1 - 17.6 \text{ fb}$
  surpassing previous measurements
Searches for Dark Matter, LED’s and Unparticles in monojet events

CMS PAPER EXO-11-059  $L = 4.7 \text{ fb}^{-1}$

**Theoretical models (effective theories)**

Point-like interactions below certain mass scale
- ADD: $pp \rightarrow G + j(\text{ISR}) \rightarrow E_T^{\text{miss}} + j$
- Unparticle: $pp \rightarrow U + j(\text{ISR}) \rightarrow E_T^{\text{miss}} + j$
- DM: $pp \rightarrow \chi(\text{Dirac fermion}) + j(\text{ISR}) \rightarrow E_T^{\text{miss}} + j$

**$CL_S$ exclusion limits at 95% C.L.**

- $M_D = 4.45, 3.45, 2.94, 2.65, 2.46 \text{ TeV}$ for number of ED = 2, 3, 4, 5, 6
- Unparticle mass scale
  $\Lambda_U = 28.5, 7.5, 3.55, 2.50, 1.48, 1.16 \text{ TeV}$
  for scale dimensions $d_U = 1.4, 1.5, 1.6, 1.7, 1.8, 1.9$
- Limits on dark matter-nucleon scattering cross section (at 90% C.L.)
  - Best dark matter limits for $m_\chi < 3.5 \text{ GeV}$ (spin-independent)
  - Most stringent constraints over entire range $1 < m_\chi < 1000 \text{ GeV}$ (spin-dependent)
Search for RS gravitons in jet + $E_T^{miss}$ channel

CMS PAS EXO-11-061

$\mathcal{L} = 4.7$ fb$^{-1}$

RS graviton $G^*$: first resonance of KK modes spin-2 resonance

$G^* \rightarrow ZZ \rightarrow q\bar{q}\nu\bar{\nu}$ channel

- Very boosted $Z$ bosons
  $\Rightarrow$ collimated $q\bar{q}$ single jet + $E_T^{miss}$

$CL_S$ exclusion limits at 95% C.L.

- $\sigma \times BR$ limits in range [0.047, 0.021] pb for $m_{G^*}$ between 1000 and 1500 GeV
- Relaxing perturbative regime: $k/M_{Pl} < 0.1$
  following Kelley, Randall, Shuve (JHEP 1102 (2011) 014)
  - Width of $G^*$ becomes large for high values of $k/M_{Pl}$
  - Stable signal selection efficiency for $0.005 < k/M_{Pl} < 0.3$
Searches in lepton production

- \( W' \rightarrow \ell \nu (\ell = e, \mu) \) (CMS)
- Multileptons (CMS)
- Excited leptons (ATLAS)
- Contact Interactions in dilepton events (ATLAS)
Search for $W' \rightarrow \ell \nu$ ($\ell = e, \mu$)

CMS PAPER EXO-11-024

$\mathcal{L} = 4.7 \text{ fb}^{-1}$

Models and interpretations

- $W - W'$ interferences considered (left-handed $W'$)
- UED: $W'_{KK} (n = 2, 4, ..)$ (coupling to SM fermions)

Lepton channels $\ell = e, \mu (+ E_{\text{miss}})$

- $W$ boson transverse mass reconstruction
  
  \[ M_T = \sqrt{2 \cdot \ell_T \cdot E_{\text{miss}} \cdot (1 - \cos \Delta \phi_{\ell, \nu})} \]

Bayesian exclusion limits at 95% C.L.

- Higher order EW corrections (not plotted) at high masses reduce interference effects
- Limit on $m_{W'}$ (right-handed): 2.5 TeV, on $m_{W'}$ (left-handed): 2.63 TeV [2.43 TeV] for constructive [destructive] $W - W'$ interference
- Universal Extra Dimension re-interpretation:
  - Limits in terms of ED Radius $R$ and Dirac mass term $\mu$
  - No sensitivity to $n \geq 4$ modes (yet)

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Searches for New Phenomena at the LHC
Search for anomalous production of multilepton events

CMS PAPER EXO-11-045

$\mathcal{L} = 4.7 \text{ fb}^{-1}$

R-parity: $R_P = (-1)^{3B+L+2s}$, SM particles: $R_P = +1$

Leptons: $\ell = e, \mu, \tau \rightarrow e, \mu \&$ hadronic $\tau$ (1-prong)

Supersymmetric RPV scenarios

- $W_{RP} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$
- Decay length constraints: $L(\lambda_{ijk}) \lesssim 100 \mu$m, $L(\lambda'_{ijk})$: prompt
- Only one coupling simultaneously $\neq 0 \Rightarrow$ consistent with proton lifetime:
  - L-RPV: $\lambda_{ijk} \neq 0$, $\lambda'_{ijk} = \lambda''_{ijk} = 0$
  - H-RPV: $\lambda_{ijk} = \lambda'_{ijk} = 0$, $\lambda''_{ijk} \neq 0$

$\mathcal{CL}_S$ exclusion limits at 95% C.L.

- Limits on slepton co-NLSP scenario, RPV coupling $\lambda_{e\mu\tau} \neq 0$ and H-RPV scenarios ($\lambda''_{ijk} \neq 0$)
- Exceeding significantly limits of previous (RPV $\lambda_{e\mu\tau}$ scenario) search

Update of previous CMS measurement

Excited leptons $\ell^*$ via four-fermion interactions

$$\mathcal{L}_{\text{contact}} = \frac{g_\ast^2}{2\Lambda^2} j^\mu j_\mu; \quad q\bar{q} \rightarrow \ell^*\bar{\ell}, q\bar{q} \rightarrow \ell^*\bar{\ell}$$

Bayesian 95% C.L. exclusion limits

- Optimised signal region: $m_{\ell\ell} = m_{\ell^*} + 150$ GeV, $m_{\ell\ell} > 110$ GeV
- For $m_{\ell^*} > 0.9$ TeV observed limit on $\sigma \times BR$ is 1.0 fb (1.9 fb) for $e^*$ ($\mu^*$)
- For $\Lambda = m_{\ell^*}$ observed limit on $m_{\ell^*}$ is 2.0 TeV (1.9 TeV) for $e^*$ ($\mu^*$)
- Most stringent bounds to date for $m_{\ell^*} \geq 200$ GeV
Search for Contact Interactions in dilepton events

\[ \mathcal{L}_{ee(\mu\mu)} = 1.08 (1.21) \text{ fb}^{-1} \]

Modelling of backgrounds

- Multi jets from data, others from MC

Likelihood method

- Product of Poisson probabilities for each mass bin

Bayesian exclusion limits

- Marginalised likelihood (nuisance parameters integrated out)
- Prior probability flat in \(1/\Lambda^2\) (\(\sim \mathcal{L}_{\text{int.}}\))
- 95% C.L. limits:
  - \(\Lambda^+ > 9.4 \text{ TeV} \) (ee, constructive interference)
  - \(\Lambda^- > 10.1 \text{ TeV} \) (ee, destructive interference)
  - \(\Lambda^+ > 7.0 \text{ TeV} \) (\(\mu\mu\), constructive interference)
  - \(\Lambda^- > 8.0 \text{ TeV} \) (\(\mu\mu\), destructive interference)

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Searches for New Phenomena at the LHC
Searches in lepton + jet production

- 1st generation Lepto Quarks (ATLAS)
- 2nd generation Lepto Quarks (ATLAS)
- Heavy bottom quarks to $Zb$ (ATLAS)
- Heavy bottom like quark (CMS)
- Heavy neutrinos (ATLAS)
Search for 1st generation scalar leptoquarks

Electron channels

\[ pp \rightarrow LQ \bar{LQ} \rightarrow ej ej, \; ej \nu j \]

Production

- FCNC constraints \implies assuming only same generation LQ, SM particle couplings
- \( gg \) production dominates for \( m_{LQ} \lesssim 1 \text{ TeV} \)
- \( q\bar{q} \) production dominates for \( m_{LQ} \gtrsim 1 \text{ TeV} \)

Modelling of backgrounds

- Multi jets from data (control regions)
- \( Z/W^+ \) jets, top, di-boson from MC

**CL\( _S \) exclusion limits (Gaussian nuisance parameters)**

- Full LLR distribution considered via Poisson log-likelihood ratio test statistic
- 95% C.L. limit: \( m_{LQ} > 660 \text{ GeV} \) for \( BR = 1.0 \)
- 95% C.L. limit: \( m_{LQ} > 607 \text{ GeV} \) for \( BR = 0.5 \)

\[ \mathcal{L} = 1.03 \text{ fb}^{-1} \]
Search for 2nd generation scalar leptoquarks

**ATLAS CDS 1389822**

Muon channels

\[ pp \rightarrow LQ \bar{LQ} \rightarrow \mu j \mu j, \mu j \nu j \]

**Background discrimination**

- Scalar transverse momentum sum
  \[ S_T(\mu\mujj) = p_T(j_1) + p_T(j_2) + E_T(\mu_1) + E_T(\mu_2) \]
  \[ S_T(\mu\nujj) = p_T(j_1) + p_T(j_2) + E_T(\mu) + E_T^{\text{miss}} \]

- Likelihood ratio inputs:
  \[ m_{\mu\mu}, S_T, \overline{m}_{LQ} (\mu\mujj \text{ channel}) \]
  \[ S_T, m_T, m_T^{LQ}, m_{LQ} (\mu\nujj \text{ channel}) \]

- Likelihood ratio variable \( LLR = \log(L_{\text{Sig}}/L_{\text{Bkg}}) \)

**CL_s exclusion limits (Gaussian nuisance parameters)**

- Full LLR distribution considered via Poisson log-likelihood ratio test statistic
- 95\% C.L. limit: \( m_{LQ} > 685 \text{ GeV} \) for \( \beta = 1.0 \)
- 95\% C.L. limit: \( m_{LQ} > 594 \text{ GeV} \) for \( \beta = 0.5 \)

\[ \mathcal{L} = 1.03 \text{ fb}^{-1} \]
Search for heavy quark pairs with $b' \rightarrow Zb$ decay

$p p \rightarrow b' \bar{b'} \rightarrow bZ + X$, $Z \rightarrow e^+ e^-$ (ee + j channel)

- Complementary to $b' \rightarrow tW$ searches
- Standard scenario: $\beta = BR(b' \rightarrow Zb) = 1$
- Vector Like Singlet (VLS) scenario:
  $\beta = BR(b' \rightarrow Zb) = 0.9(0.5)$
  for $m_{b'} = 200(700)$ GeV

**Signal filtering**

- $b$-tagging: Likelihood based on 3D IP and Secondary VTX information
- ALPGEN vs. SHERPA $Z + b$ jet production differences ⇒ scaling to data

**95% CLs exclusion limits**

- $m_{b'} = 400$ GeV for $BR(b' \rightarrow Zb) = 100\%$
- $m_{b'} = 358$ GeV for Vector-Like Singlet $b'$  
  (only 3rd SM generation mixing)
Search for a heavy bottom like quark

CMS PAPER EXO-11-036

\[ \mathcal{L} = 4.6 \text{ fb}^{-1} \]

Like-sign di- \((\ell^\pm \ell^\pm)\) and tri-lepton \((\ell^\pm \ell^\pm \ell)\) channels

- Decay chain (assuming \(m_{b'} > m_t + m_W\)):
  \[ b'\bar{b}' \rightarrow tW \bar{t}W^+ \rightarrow bW^+ \bar{b}W^- W^+ \]
- Backgrounds: \(t\bar{t}(+W/Z),\) single top, di-boson, multi-jets (data driven)
- \(b\)-tagging \((IP\) significance based\)
- \(S_T = \Sigma \text{jets}(\text{anti-}k_T, R=0.5) + \gamma's + \ell's + E_{T}^{\text{miss}}\)

Bayesian exclusion limits at 95\% C.L.

- Assuming 100\% \(b' \rightarrow tW\)
- \(\sigma_{\text{NLO}}(pp \rightarrow b'\bar{b}')\) from theory
- Excluding: \(m_{b'}\) up to 600 GeV

Limit at 95\% CL: \(M_{b'} > 600 \text{ GeV}/c^2\)

CMS 2011 Preliminary 4.6 fb\(^{-1}\) \(\sqrt{s} = 7 \text{ TeV}\)

\[ \sigma(pp \rightarrow b\bar{b}) \text{ [pb]} \]

\[ \text{Events / 200 GeV} \]

Backgrounds:
- data
- \(tt\)
- Single-top
- \(W \rightarrow l\nu\)
- \(Z \rightarrow l\nu\)
- di-boson

\(\geq 1b\)-jet

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Searches for New Phenomena at the LHC
Search for heavy $\nu$'s and right handed $W$ bosons

\[\mathcal{L} = 2.1 \text{ fb}^{-1}\]

$\bar{q}q' (\rightarrow W_R) \rightarrow N\ell, \quad N (\rightarrow W_R^* \ell) \rightarrow jj\ell$

2 $\ell + 2$ jets final states

- Dirac (OS $\ell^\pm \ell'^\mp$ only) + Majorana (SS + OS) heavy neutrinos $N$ (effective theory HNEO)
- LRSM ($W_R, Z'$ bosons)

Channels

<table>
<thead>
<tr>
<th>Channels</th>
<th>$\langle \sigma A / \epsilon \rangle_{\text{obs}}^{95} \text{ [fb]}$</th>
<th>$\langle \sigma A / \epsilon \rangle_{\text{exp}}^{95} \text{ [fb]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^\pm e'^\mp$</td>
<td>28.3</td>
<td>30.7</td>
</tr>
<tr>
<td>$\mu^\pm \mu'^\mp$</td>
<td>25.1</td>
<td>36.7</td>
</tr>
<tr>
<td>$e^\pm \mu'^\mp$</td>
<td>50.9</td>
<td>36.4</td>
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<tr>
<td>$e^\pm e'^\pm$</td>
<td>34.8</td>
<td>27.4</td>
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<tr>
<td>$\mu^\pm \mu'^\pm$</td>
<td>6.1</td>
<td>4.6</td>
</tr>
<tr>
<td>$e^\pm \mu^\pm$</td>
<td>25.4</td>
<td>16.2</td>
</tr>
</tbody>
</table>

95\% exclusion limits

- Excluding $m_{W_R}$ up to 1.8 (2.3) TeV for $\Delta m(W_R, N) > 0.3(0.9)$ TeV (no- and maximal-mixing)
- Excluding $\Lambda/\sqrt{\alpha}$ from $\approx 2.5$ to $\approx 0.7$ TeV for $m_N$ from 0.1 to 2.7 TeV
- Most stringent limits to date

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Searches for New Phenomena at the LHC
Searches in jet production

- Search in dijet angular distribution (CMS)
- Search for heavy vector-like quarks (ATLAS)
**Search for new physics in dijet angular distribution**

**CMS PAPER EXO-11-017**

- Sensitive to spin of exchanged particle
- No strong dependence on PDF's
- Probing quark compositeness

**Inclusive dijet production**

- \( N_{\text{jet}} \geq 2 \) (anti-\( k_T \), R=0.5)
- \( \chi_{\text{dijet}} := \exp(|y_1 - y_2|) \frac{m \to 0}{1 + |\cos \theta^*|} \)
- \( M_{jj} > 0.4 \) TeV (9 inv. mass ranges)

**Correction and comparison to theory**

- Correction/unfolding for \( \chi_{\text{dijet}} \) and \( M_{jj} \) migrations
- Normalised dijet angular distributions insensitive to many systematics (JES, \( p_T \) resolution)
- Comparison to NLO theory including non-perturbative corrections for hadronisation + MPI

**CLs exclusion limits at 95% C.L.**

- Different (color- and isospin-singlet) models: + = constructive, - = destructive interference between QCD and Contact Interactions


**d\sigma/d\chi_{\text{dijet}}** is flat for Rutherford scattering
Search for heavy vector-like quarks

\[ \text{hep-ex 1112.5755, submitted to Phys. Lett. B} \]

\[ pp \rightarrow Qq \rightarrow Wqq', W \rightarrow \ell \nu \]

\[ pp \rightarrow Qq \rightarrow Zqq', Z \rightarrow \ell \ell \]

**Template fits**

- Signal yield from binned ML method
- Templates: VLQ candidate mass distribution

**CL$_5$ exclusion limits**

- 95% C.L. upper limit: 900 GeV for the CC channel
- 95% C.L. upper limit: 760 GeV for the NC channel
- Assuming coupling $\tilde{\kappa}_{qQ} = 1$ and 100% BR(VLQ $\rightarrow$ W/Z + jet)

\[ \mathcal{L} = 1.04 \text{ fb}^{-1} \]
Searches for long-lived charged particles

- Heavy Stable Charged Particles (CMS)
- Light Higgs $\rightarrow$ long-lived $\pi_v\pi_v$ (ATLAS)
Long-lived (Heavy Stable) Charged Particles

- $\beta \equiv v/c < 0.9$ for $m_{HSCP} \gtrsim 100$ GeV
- Large rate of energy loss $dE/dx$ (tracker)
- Long time of flight (TOF) [in muon detectors]
- Selecting high $p_T$ muon and $E_T^{miss}$ events

Various models: Stable $R$-hadrons at hadronisation

**CL$_S$ exclusion limits at 95% C.L.**

- $\tilde{g}\tilde{g}$ pairs to $R$-gluonballs with 0.1 (0.5) probability:
  - $m_R = 1091$ (1038) GeV (tracker-only); $m_R = 1076$ (1024) GeV (tracker + TOF)
- Stop mass: $m_{\tilde{t}_1} = 709$ (734) GeV with tracker-only (tracker + TOF)
- Charge suppressed: $m_{\tilde{g}} = 923$ GeV for $f_R = 0.01$ and $m_{\tilde{g}} = 623$ GeV for $\tilde{t}_1$ scenario
- GMSB $\tilde{\tau}_1\tilde{\tau}_1$ pairs: $m_{\tau_1} = 306$ (221) GeV for $\tilde{g}$ ($\tilde{t}_1$) scenarios
- $m_{\tilde{K}} = 481$ (599) [746] GeV for $m_{\tilde{\rho}} = 800$ (1200) [1600] GeV using tracker + TOF selection
Search for light Higgs boson decaying to long-lived weakly-interacting particles

ATL-COM-PHYS-2011-956, preliminary

$\mathcal{L} = 1.94 \text{ fb}^{-1}$

$h^0 \rightarrow \pi_V \pi_V$ (RPV) MSSM, inelastic Dark Matter, Hidden Valley

$\pi_V \rightarrow$ heavy fermion ($b, c, \tau$), $\rightarrow \mu$

Signature: 2 weakly interacting long-lived particles decaying in muon spectrometer

<table>
<thead>
<tr>
<th>$m_{h^0}$ (GeV)</th>
<th>$m_{\pi_V}$ (GeV)</th>
<th>Excluded Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>20</td>
<td>$0.50 \text{ m} &lt; c\tau &lt; 22.45 \text{ m}$</td>
</tr>
<tr>
<td>120</td>
<td>40</td>
<td>$1.50 \text{ m} &lt; c\tau &lt; 27.20 \text{ m}$</td>
</tr>
<tr>
<td>140</td>
<td>20</td>
<td>$0.45 \text{ m} &lt; c\tau &lt; 17.25 \text{ m}$</td>
</tr>
<tr>
<td>140</td>
<td>40</td>
<td>$1.10 \text{ m} &lt; c\tau &lt; 29.75 \text{ m}$</td>
</tr>
</tbody>
</table>

$\int \mathcal{L} \text{dt} = 1.94 \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$

Lars Sonnenschein, RWTH Aachen, III. Phys. Inst. A

Searches for New Phenomena at the LHC
Conclusions

- LHC and detectors performing excellently
- CMS and ATLAS are searching for evidence of new physics beyond the SM in many channels
- No signals of new physics observed in LHC data yet
- More LHC data at higher energy this year (expected in 2012: up to $\sim 20 \text{ fb}^{-1} @ 8 \text{ TeV}$)
Extra dimensions

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Searches for New Phenomena at the LHC

Compact. scale 1/R (SPS8)

Graviton mass

Graviton mass

KK gluon mass

Compact. scale 1/R (SPS8)

Mass scale [TeV]

10^{-1} 1 10 10^2

* Only a selection of the available mass limits on new states or phenomena shown

By courtesy of ATLAS Exotica convenor Henri Bachacou

\[ \int L dt = (0.04 - 5.0) \text{ fb}^{-1} \]

\[ \sqrt{s} = 7 \text{ TeV} \]
Backup slides
CMS detector and pseudorapidity coverage

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Searches for New Phenomena at the LHC
Detector and reconstructed object resolutions

Object energy and momentum resolutions

- **anit-**$k_T$ ($R = 0.5$) energy resolution:
  \[ \frac{\Delta E}{E} = 100\% / \sqrt{E} \, [\text{GeV}] \oplus 5\% \]

- e + unconverted \(\gamma\)'s: \(p_T > 100\) GeV: \(\frac{\Delta E}{E} \lesssim 0.5\%\)
  For 2011 data, \(E_T > 35(40)\) GeV: barrel(endcap) \(\frac{\Delta E}{E} = 1\%(3\%)\)

- global muon \(p_T\) res.: \(1 - 10\%\) up to 1 TeV

Calorimeter transverse energy resolutions

- ECAL ($|\eta| < 3$): \(\sim 2\% / \sqrt{E_T}\)
- HCAL ($|\eta| < 5$): \(\sim 100\% / \sqrt{E_T}\)

Inner tracker resolutions

- transverse momentum: \(\text{res}(p_T) = 1, 2, 5\% @ p_T = 10, 100, 500\) GeV
- impact parameter: \(\text{res}(IP) = 15\ \mu\text{m}\)
Search for resonances with dijet angular ratio

CMS-EXO-11-026, preliminary  \( \mathcal{L} = 2.2 \text{ fb}^{-1} \)


**Resonance search**

- Central \( |\Delta \eta| < 1.3 \) vs. forward \( 1.3 < |\Delta \eta| < 3.0 \) dijet events as function of inv. dijet mass (anti-\( k_T \) (R=0.7))
- Ratio cancels many systematic effects

**Excited quark model**

\[ q^* \rightarrow qg \rightarrow 2 \text{ jets} \]

![Graph showing dijet events as a function of inv. dijet mass](image)

**CL\( S \) exclusion limits at 95% C.L.**

- Excited quark mass limit: \( m_{q^*} = 3.2 \text{ TeV} \)
- Improving on previous CMS result and existing ATLAS result
Search for 4th generation down-type quark


1 lepton + 8 jets channel (assuming $m_{b'} > m_t + m_W$)

- Decay chain: $b' \bar{b}' \rightarrow tW^{-}\bar{t}W^{+} \rightarrow bW^{+}W^{-}\bar{b}W^{-}W^{+} \rightarrow \ell\nu + 8$ jets
- Tagging close $W \rightarrow q\bar{q}$ jets: $\Delta R \approx 2m_W/p_T^{W}$
- Backgrounds: $t\bar{t}$ + jets, $W$ + jets, multi-jets
- 9 exclusive bins: $N_{W\rightarrow 2j} = 0, 1, \geq 2$, $N_{jets} = 6, 7, \geq 8$ (anti-$k_T$ (R=0.4))

$\mathcal{L} = 1.04$ fb$^{-1}$

$\int L \, dt = 1.04$ fb$^{-1}$

ATLAS

$\sqrt{s} = 7$ TeV

$\sigma_{b\bar{b} \rightarrow tW}$

CL$_S$ exclusion limits at 95% C.L.

- Assuming 100% $b' \rightarrow tW$
- $\sigma_{\text{NNLO}}(pp \rightarrow b'\bar{b}')$ from theory (Hathor)
- Excluding: $m_{b'}$ up to 480 GeV

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Searches for New Phenomena at the LHC 37
Search for resonant $t\bar{t}$ production in $e+\text{jets}$

CMS PAS EXO-11-092

$\mathcal{L} = 4.33$ fb$^{-1}$

BSM heavy resonance to $t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (q\bar{q}b)(e^-\bar{\nu}b)$ or charge conjugated

Event selection and reconstruction

- $e + \geq 2$ jets + $E_T^{\text{miss}}$
- Minimise $\Delta R_{\text{sum}} = \Delta R(b_l, t_l) + \Delta R(\nu, t_l) + \Delta R(l, t_l)$ (expected to be small for signal)

Modelling

- Multi-jets from data (fitting $E_T^{\text{miss}}$ distribution)
- Maximum likelihood fit to multi-jet and MC (single top, $W$, $Z+\text{jets}$) background templates
Search for resonant $t\bar{t}$ production in $e^+\text{jets}$

**CLs exclusion limits at 95% C.L.**

- Limits on $Z' \rightarrow t\bar{t}$ cross section as function of $t\bar{t}$ invariant mass
- Likelihood ratio used as test statistic
- Limit of 2.51 pb for a $Z'$ resonance with mass of 1 TeV (width 1%)
- Limit of 0.62 pb for a $Z'$ resonance with mass of 2 TeV (width 1%)
Search for heavy top-like quark pairs in dilepton channel

CMS PAPER EXO-11-050

\( L = 4.7 \text{ fb}^{-1} \)

\[ pp \rightarrow t^\prime \overline{t}' \rightarrow (W^+b)(W^-\overline{b}) \rightarrow (\ell^+\nu b)(\ell^-\overline{\nu}\overline{b}) \]
assuming \( m_{t'} < m_{b'} + m_W \) (← EW precision data)

Event selection
- \( \geq 2 \ell \)'s, oppositely charged
- Exactly 2 \( b \)-tagged jets
- \( E_T^{\text{miss}} \) (from \( W \rightarrow \ell\nu \) decays)
- inv. mass \( M_{\ell b} \) discriminant

Modelling
- Misidentified leptons and \( b \) jets from data
- \( t\overline{t} \) + other backgrounds from simulation

\( CL_S \) exclusion limits at 95% C.L.
- Limits on \( t' \overline{t}' \) cross section as function of \( t' \) invariant mass
- Expected limit at \( m_{t'} = 542 \text{ GeV} \)
- Observed limit at \( m_{t'} = 552 \text{ GeV} \)
Effective 4-fermion interaction ($M \gg \Lambda(EWSB)$)

**Same sign dilepton + jets (anti-$k_T$ ($R=0.4$)) + $E_T^{\text{miss}}$**

- Heavy flavour jet tagging ($\sigma_{IP}$ based)
- For $pp \to b'\bar{b}'$ assuming $m_{b'} > m_t + m_W$
- 3 signal regions:
  - $H_T > 350$ GeV (high mass $Z'$ exchange)
  - Only positive charged lepton pair ($pp \to tt$ favored over $pp \to \bar{t}t$)
  - $H_T > 350$ GeV, $m_{\ell\ell} > 100$ GeV (low mass $Z'$ exchange)
Search for same-sign $tt$ and $b'b'$ pair production

\[ \int L \, dt = 1.04 \, fb^{-1} \sqrt{s} = 7 \, TeV \]

**ATLAS**

- Expected limit at 95% CL
- Observed limit at 95% CL
- Expected limit $\pm 1 \sigma$
- Expected limit $\pm 2 \sigma$
- Theory NNLO

---

**CLs exclusion limits at 95% C.L.**

- $\sigma_{NNLO}(pp \rightarrow tt)$ from theory
- $tt$ production cross section limit: $1.4 - 2.0$ pb depending on mediator mass
- Excluding: $m_{b'}$ up to 450 GeV (assuming 100% $b' \rightarrow Wt$)
- Tevatron $A_{FB}$ anomaly interpretation challenged
Heavy quark pair production ($Q\bar{Q}$)

hep-ex 1202.3389, submitted to Phys. Rev. D

$L = 1.04 \text{ fb}^{-1}$

**Benchmark model**

4th generation $u$-type quarks in dilepton channel
$Q\bar{Q} \rightarrow \ell^+ \nu q \ell^- \bar{\nu} \bar{q}$, $\ell = e, \mu$

**Signal filtering and modelling**

- Exploiting larger $W$ boost from heavy $Q$ compared to $t$ quark
  Boost makes undetected $\nu$ approximately collinear to $\ell^\pm$
- $\geq 2$ jets (anti-$k_T$ (R=0.4)), 2 oppositely charged isolated leptons, $E_T^{\text{miss}}$
- Initial dilepton selection to validate and model $Z/\gamma^*$ background and object ID and reconstruction
- Matrix method for data driven fake lepton estimate
Heavy quark pair production ($Q\bar{Q}$)

**CLs 95% C.L. exclusion limits**

- Signal mass $m_{\text{Collinear}}$ to be probed dependent selection
- Binned maximum-likelihood ratio to fit $m_{\text{Collinear}}$ distributions to data
- Assuming $BR(Q \rightarrow Wq) = 100\%$, exclusion limit is $m_Q = 350$ GeV
- Valid for 4th generation quarks of up-type and also down-type (charge=-4/3)
Heavy quark pair production ($Q \rightarrow Wb$)

Benchmark model

4th generation $u$-type quarks in $\ell+\text{jets}$ channel

$t'\bar{t}' \rightarrow W^+bW^-\bar{b} \rightarrow \ell \nu bq - \bar{q}'\bar{b}, \quad \ell = e, \mu$

Signal filtering

- Assuming $BR(t' \rightarrow Wb) = 100\%$
- Multi-jet (anti-$k_T$ (R=0.4)) background suppressed by $E_T^{\text{miss}}$ requirement
- $b$-tagging: multi-variate technique (based on displaced tracks, vertices)
- Likelihood fit to rec. heavy quark mass $m_{\text{reco}}$ for events with $\geq 4$ jets
- Separate evaluation (significances) of $\ell+3\text{jets}$ and $\ell+\geq 4\text{jets}$ channels

$\mathcal{L} = 1.04 \text{ fb}^{-1}$
Heavy quark pair production \((Q \rightarrow Wb)\)

- **CL\(_S\) 95% C.L. exclusion limits**
  - Using Log Likelihood Ratio test-statistic to set limits on \(t'\bar{t}'\) production cross section
  - Assuming \(BR(t' \rightarrow Wb) = 100\%\), exclusion limit on mass \(m_{t'} = 404\text{ GeV}\)
  - Most stringent limit to date
  - Directly applicable to down-type vector-like quark (charge=-4/3) \(\rightarrow W + b\)

\[
\int Ldt = 1.04\text{ fb}^{-1} \\
\sqrt{s} = 7\text{ TeV}
\]
Constraints on anomalous $\mu^+\mu^+$ and $tt$ production

ATLAS-CONF-2011-139, preliminary

$\bar{u}u \rightarrow \bar{t}t$ suppressed at $pp$ collider

Production mechanism: FCNC via $Z'$

Modelling

- non-prompt $\mu$ background from data
- Prompt $\mu$ bkg. from MC (dibosons)
- Fiducial acceptance from PROTOS LO MC

Bayesian exclusion limits on anomalous $\mu^+\mu^-$ production

- $\sigma \times \text{BR} \times A = 8.7$ fb for $m(\mu^+\mu^+) > 200$ GeV at 95% C.L.
- $\sigma(t_R t_R) = 4.1 - 2.9$ pb for $100$ GeV $< m(Z') < 1$ TeV
- Stringent limits challenging Tevatron FCNC $A_{FB}$ interpretation

$L = 1.6$ fb$^{-1}$
Search for anomalous prompt $\mu^\pm \mu^\pm$ production

Inclusive $\mu^\pm \mu^\pm$ production

Various new physics signal models:
- $pp \rightarrow H^\pm H^\pm$
- $pp \rightarrow W_R \rightarrow N_R \ell \rightarrow W \ell \ell$
- $pp \rightarrow d_4 \bar{d}_4 \rightarrow tW\bar{t}W \rightarrow bWW\bar{b}WW$

Muon background rejection
- $m(\mu\mu) > 15$ GeV
  Suppression of low mass $J/\psi, \Upsilon$ res.
- $IP_T < 0.2$ mm, $IP_{||} < 5.0$ mm
  Rejection of cosmic rays
- $|IP_T|/\sigma(IP_T) < 3.0$
  Rejection of semi-leptonic $b,c$-decays

Models of prompt/non-prompt dimuon background
- Prompt $\mu\mu$ dominated by diboson pairs (from MC)
- Non-prompt $\mu$’s from data (loose/tight matrix method)

$\mathcal{L} = 1.6$ fb$^{-1}$

$\int \mathcal{L} dt = 1.6$ fb$^{-1}$

$\sqrt{s} = 7$ TeV

Data 2011

Non-prompt $\mu$

Prompt $\mu$

Muon pairs / 25 GeV

$\sigma$(IP$_T$) [GeV]

$\sigma$(IP$_T$) [GeV]
Search for anomalous prompt $\mu^\pm\mu^\pm$ production

Model independent limits on cross section

Bayesian exclusion limits on anomalous prompt like-sign $\mu\mu$ production

- 95% C.L. upper limits range from 304 fb for $m_{\mu\mu} > 15$ GeV to 5.0 fb for $m_{\mu\mu} > 300$ GeV
Search for new phenomena in ≥ 3 charged lepton events

ATLAS-CONF-2011-158, preliminary

\[ \mathcal{L} = 1.02 \text{ fb}^{-1} \]

New physics models
- Doubly charged Higgs
- SUSY
- Extra gauge bosons (\(W', Z'\))
- Seasaw mediators
- Leptoquarks
- Technicolor particles
- Heavy charged leptons
- Excited neutrinos

Complementary to dedicated like-sign di-muon analysis ATLAS-CONF-127

Modelling of ≥ 3 isol. lepton bkg.
- Di-boson and \(t\bar{t} + W/Z\) from MC
- Fakes, \(\mu\)'s from \(b, c\)-jets, \(\gamma\) conversion, \(K, \pi\) decay in flight: data driven

Multi-lepton (\(\ell = e, \mu\)) bkg. rejection
- At least 3 isolated charged leptons
- Rejection of identified \(Z \rightarrow \ell\ell\) decays
  - Exploited as control sample
Search for new phenomena in $\geq 3$ charged lepton events

- $p_T(\ell) > 20$ GeV (signal selection)
- SM expectation $p$-value $= 27\%$

- $p_T(\ell) > 30$ GeV (tighter signal selection)
- SM expectation $p$-value $= 33\%$

$CL_S$ exclusion limits (syst. entered via profile likelihood)

- 95% C.L. upper limits: 38 (14) fb for (tighter) signal selection
- 95% C.L. upper limits: 41 (34) fb for 200 (300) GeV on excited neutrino pair production
Search for resonances in $\gamma + \text{jet}$ events


$L = 2.11 \text{ fb}^{-1}$

### New physics models

- General resonant Gaussian $m(\gamma j)$ signal
- Excited quark $q^*$
  - Setting compositeness scale to $m(q^*)$
  - Assuming $SU(3), SU(2), SU(1)$ coupling multipliers $f_s = f = f' = 1$
  - $BR(u^* \rightarrow ug) = 0.85$, $BR(u^* \rightarrow u\gamma) = 0.02$
  - $BR(d^* \rightarrow dg) = 0.85$, $BR(d^* \rightarrow d\gamma) = 0.005$

### Likelihood method

- Fitting background distribution $f(x \equiv m_{\gamma j}/\sqrt{s}) = p_1(1 - x)p_2x^{-p_3} - p_4 \ln x$
- neg. log-likelihood test statistic $p$-value $= 23$
- Seeking resonances with BUMPHEunter algorithm

### Modelling of $\gamma + \text{jet}$ (anti-$k_T$ (R=0.6))

- Bkg. shape from NLO JETPHOX MC
- Instrumental background negligible

### ATLAS

$\sqrt{s} = 7 \text{ TeV}$
$\int L dt = 2.11 \text{ fb}^{-1}$
- Data
- Fit
- $q^*(0.5 \text{ TeV})$
- $q^*(1.0 \text{ TeV})$
- $q^*(2.0 \text{ TeV})$

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Searches for New Phenomena at the LHC 52
Search for resonances in $\gamma + \text{jet}$ events

95% CL Limit on $\sigma \times BR \times A \times \epsilon$ [pb]

- $\sqrt{s} = 7$ TeV
- $\int L \, dt = 2.11$ fb$^{-1}$
- $\sigma / m_G$
- PYTHIA $q^*$ prediction
- ATLAS
- 95% CL upper limits: Observed $\pm 1\sigma$, Expected $\pm 2\sigma$

Bayesian exclusion limits at 95% C.L.

- For Gaussian shape resonances at 2 TeV: $\sigma \times BR \times A \times \epsilon$ near 5 fb
- $m(q^* \rightarrow \gamma j)$ excluded up to 2.46 TeV