Search for new physics in multi-lepton final states with the ATLAS and CMS detectors

On behalf of the ATLAS and CMS collaborations
Searches for new physics with multileptons

- Many interesting BSM physics phenomena can be searched for in multilepton final state
  - Observation of neutrino oscillation makes the following exciting:
    - Lepton flavour violation (LFV) decays of $Z$ ($Z \rightarrow e\mu$)
      - New physics like massive Dirac or Majorana neutrinos or R-parity SUSY
    - Lepton flavour violating decays of new heavy resonances
      - Resonant $\nu_\tau$ LSP production in RPV SUSY
      - LFV gauge boson ($Z'/a'$) exist and generate transitions between families
  - Compositeness in the lepton sector
  - Type III seesaw models
  - New phenomena with multi-photon
Lepton-flavor-violation in Z decays

- Final state of $e\mu$ consistent with Z decays in $M_{e\mu}$ spectrum
- oppositely charged $e$, $\mu$
- Dominant background: $Z \rightarrow \tau\tau$
- CMS: Multi-lepton background: data-driven technique
- ATLAS: background estimated by fit to data excluding the Z region, extrapolate
- Upper limits:
  - CMS: $7.3 \times 10^{-7}$
  - ATLAS: $7.5 \times 10^{-7}$

Everything Consistent with the SM

At 95% CL
Lepton-flavour-violating decays of heavy resonances

- CMS: $e\mu$, ATLAS: $e\mu, e\tau$ or $\mu\tau$
- Final state of $ll'$ in broad range spectrum of $M_{ll'}$
- Oppositely charged $e$, $\mu$
- ATLAS: collinear neutrino approximation used to reconstruct $m_{ll'}$ in the final state of $\tau_{\text{had}}$
  - $\tau_{\text{had}}$ coming from decay of heavy resonance
  - $\nu$ and jets are collinear. 4-p vector of $\nu$ can be reconstructed
  - Significantly improves the mass resolution

CMS: PAS EXO-13-002
Results and limits

$\bar{\nu}_\tau \rightarrow e\mu$

$M_{\nu\tau} > 2.0$ TeV

Z' $\rightarrow e\mu$

$M_{Z'} > 2.5$ TeV

LFV neutral gauge boson

RPV coupling parameters

ATLAS:

$\Lambda_{311}' = 0.11$ and $\Lambda_{132} = 0.07$

CMS:

$\Lambda_{311}' = 0.01$ and $\Lambda_{132} = 0.01$

For different parameters, CMS has:

$\Lambda_{311}' = 0.1$ and $\Lambda_{132} = 0.05$

$M_{\nu\tau} > 2.11$ TeV

ATLAS Run II

QBH

n=6, $M_{th} > 3.6$ TeV

$\Lambda_{132}$: coupling of $\nu_\tau$ with $e\mu$

$\Lambda_{311}'$: coupling of $\nu_\tau$ with $d$ quarks

$\Lambda_{132}$: coupling of $\nu_\tau$ with $u$ quarks

SSM

n=6; $M_{th} > 3.6$ TeV

At 95% CL

CMS Preliminary

$\sigma \times BR (fb)$

19.7 fb$^{-1}$ (8 TeV)

68% expected

95% expected

$\lambda_{132} = 0.01$
Non-LFV Multi-lepton searches
Search for excited leptons

- Look for single production of $\ell^*$
  - ATLAS: $pp \rightarrow \ell^* \ell \rightarrow \ell \ell \gamma$
  - CMS: $pp \rightarrow \ell^* \ell \rightarrow \ell \ell V \ell$ ($V=Z, \gamma$)
    - Depending on the decay mode, final states can be:
      - $\ell \ell \gamma$ ($\ell = e, \mu$)
      - $\ell Z$ (For the first time at LHC from CMS!)
    - $Z \rightarrow \ell' \ell$ ($\ell' = e, \mu$) - A similar kind of decay topology is probed by ATLAS in the context of type III seesaw and vector-like leptons
  - $Z \rightarrow \text{dijet}$

- $pp \rightarrow \ell^* \ell \rightarrow \ell \ell Z$ in CMS: Z boson is boosted
  - Leptons from Z decay are collinear
  - Relaxed isolation is applied

- Two leptons in the final state,
  - Two possible combinations: $M_{\ell V}^{\text{Min}}$ and $M_{\ell V}^{\text{Max}}$

ATLAS: NJP 15 (2013) 093011

CMS: EXO-14-015

EPS-HEP Conference, Vienna
Results and Limits

- ATLAS: applies cut on $M_{\ell\gamma}$ for the search
- CMS: Apply a 2-D cut in the invariant mass plane of $M_{\ell V}^{\text{min}}$ and $M_{\ell V}^{\text{max}}$ - improves the sensitivity
- ATLAS: $M_{\ell^*}<2.2$ TeV excluded
- CMS:
  - $f=f'$ in $\ell\gamma$ final state: $M_{\ell^*}<2.45(2.48)$ TeV for $e(\mu)$
  - $f=-f'$ in $\ell Z$: $M_{\ell^*}<2.35(2.38)$ TeV for $e(\mu)$

At 95% CL
Heavy-lepton partners of neutrinos (type III seesaw)

Can explain the neutrino masses and their smallness

- Look for triplet state: $\Sigma^0, \Sigma^{+/−}$
- In the Final state of:
  - CMS: 3 isolated leptons and MET (diag. A and B)
  - ATLAS: 2 isolated leptons and at least 2 jets and MET (diag. A)
- Parameters of the theory: $V_e, V_\mu, V_\tau$: mixing angles between the SM and triplet state

CMS PAS: EXO-14-001
ATLAS: arxiv:1506.01839

ATLAS: 4l final state with 5.8 fb$^{-1}$ at 8 TeV:
ATLAS-CONF-2013-019
Heavy lepton partners of neutrinos (type III seesaw)

- **ATLAS** divides its analysis into OS and SS leptons (2 lepton final state)
- **CMS** categorizes in 12 categories:
  - 6 with total + and 6 with total - charge (e.g.: $\mu^+\mu^-\mu^+$, $e^+e^+e^-$ etc)
- Dalitz background:
  - In CMS, asymmetric photon conversion is a source of background: $Z\gamma \rightarrow \text{llll}$
    - One of the leptons from photon conversion takes most of the momentum – thus other goes undetected (low $p_T$)
    - Rejection by vetoing $M_{lll}$ in the $Z$ window
CMS excludes masses ($M_{\Sigma^{+/-}}$) below 280 GeV with $V_e=V_\mu=V_\tau = 10^{-6}$

Assuming only $\tau$-e mixing, the mass limit 320 GeV

ATLAS excludes masses ($M_{L/N}$) below 335 GeV for $V_\tau = 0; V_e/V_\mu = 0.87$

$L^{+/-} = \Sigma^{+/-}$ and $N = \Sigma^0$

At 95% CL
New phenomena with multi-photon

Brand new!

ATLAS: EXOT-2013-24: to be published

Five times stronger than the previous results from LEP!

At 95% CL

<table>
<thead>
<tr>
<th>Inclusive signal region</th>
<th>$80 \text{ GeV} &lt; m_{3\gamma} &lt; 100 \text{ GeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total SM exp.</td>
<td>$1370 \pm 140$</td>
</tr>
<tr>
<td>Observed</td>
<td>$1290$</td>
</tr>
</tbody>
</table>

Obs. (exp.) 95% C.L. upper limit

<table>
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<tr>
<th>$N_{\text{sig}}$</th>
<th>$240 \left(273^{+83}_{-66}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BR(Z \rightarrow 3\gamma)$</td>
<td>$2.2 \left(2.0\right) \times 10^{-6}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\sigma_{\text{fid}} \times A \ [\text{fb}]$</th>
<th>$H \rightarrow aa \rightarrow 4\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$300 \text{ GeV} &lt; m_H &lt; 900 \text{ GeV}$</td>
<td>$m_a = 100 \text{ GeV}$</td>
</tr>
<tr>
<td>$18 \left(21^{+6}_{-3}\right)$</td>
<td>$m_a = 100 \text{ GeV}$</td>
</tr>
</tbody>
</table>

$Z' \rightarrow a + \gamma \rightarrow 3\gamma$

$200 \text{ GeV} < m_{Z'} < 1 \text{ TeV}$

$19 \left(22^{+6}_{-3}\right)$
Summary

• Many new searches for BSM physics have been searched for in the final state of multileptons/photons
  – Most recent have been presented today
  – More can be found here:
    – https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
    – https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

• Limits on LFV decays to Z, heavy resonances, type III seesaw mechanism, excited leptons, multi-photons have been put

• Exciting times ahead for the search of new physics with the new energy frontier at the LHC
....and who knows tomorrow may turn out to be yet another day for celebration...
backup
Window to the hidden sector

- Presence of a dark sector
  - Dark vector boson ($Z_d$) with the following parameters in the theory:
    - $\varepsilon$: coupling strength between $Z_d$ and SM particles
    - $\delta$: coupling strength between $Z_d$ and SM $Z$ boson
    - $M_{Z_d}$: mass of $Z_d$
- $H \rightarrow ZZ_d \rightarrow 4l$
  - $H \rightarrow ZZ_d \rightarrow 4l$: covers the parameter space of $\varepsilon$ and $M_{Z_d}$ or $\delta$ and $M_{Z_d}$
- Final states of 4e, 4$\mu$, 2e2$\mu$ are considered

CMS: arXiv:1506.00424: Look for hidden sectors via $\gamma_d$ as well in the multi-lepton final state

ATLAS: arXiv:1505.07645

For $15 < Z_d < 35$ GeV,
Limits on BR($H \rightarrow ZZ_d \rightarrow 4l$): $(1-9) \times 10^{-5}$
Heavy lepton resonances decaying to a $Z$ boson and a lepton

- Results are interpreted as vector-like leptons and type-III seesaw
- Limits on vector like: 129-176 GeV(114-168 GeV)
- Limits on typeIII seesaw: 100-430 GeV(100-468 GeV)

ATLAS: arXiv:1506.01291
Heavy Majorana neutrinoes

- Looks for a pair of same sign high-\(p_T\) leptons and high \(p_T\) jets
- Limits are set in the context of:
  - Minimal extension of the SM
    - Limit on mixing between SM neutrinoes and Majorana neutrinoes: couplings below \(|V_{\mu N}|^2 = 0.0028; |V_{eN}|^2 = 0.029\) are excluded
  - Left-right symmetric extension of the SM
    - Heavy gauge boson masses below 400 GeV are excluded

ATLAS: arXiv:1506.06020
Final state of 3 or more charged leptons

- Search for events with at least 3 leptons, 2 of them at least - e's or μ's, 3rd may be τ had

- Limits put in the context of:
  - Doubly charged Higgs boson
    - For decay to eτ or μτ, mass limit is 400 GeV
  - Excited leptons
    - For Λ=M*,
      - $M_{e^*}$ and $M_{μ^*} < 3$ TeV
      - $M_{τ^*} < 2.5$ TeV
      - $M_{ν^*} < 1.6$ TeV

ATLAS: arXiv:1411.2921
Anomalous same-sign lepton pairs and a pair of doubly charged Higgs bosons

- Search for same sign dileptons: $e^+e^+$, $\mu^+\mu^+$, $e^+\mu^+$

Limits on the mass:
- $H_L - 465-550$ GeV
- $H_R - 370-435$ GeV

ATLAS: arXiv:1412.0237

EPS-HEP Conference, Vienna
Excited leptons
Type III seesaw - ATLAS

TABLE I. Event yields for opposite-sign (OS) and same-sign (SS) selection for predicted backgrounds, data, and type-III seesaw lepton pair-production with masses of 150 and 300 GeV. The reported errors include both the statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th></th>
<th>OS</th>
<th>SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake Leptons</td>
<td>1.4 ± 0.9</td>
<td>0.67 ± 0.42</td>
</tr>
<tr>
<td>Z+jets</td>
<td>2.4 ± 1.2</td>
<td>0.06 ± 0.23</td>
</tr>
<tr>
<td>WW/WZ/ZZ</td>
<td>9.2 ± 2.9</td>
<td>1.95 ± 0.58</td>
</tr>
<tr>
<td>$t\bar{t}$ (+W/Z) and single top</td>
<td>17.9 ± 6.9</td>
<td>0.47 ± 0.25</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>31.0 ± 7.7</td>
<td>3.15 ± 0.80</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td><strong>Signal $m_{L/N} = 150$ GeV</strong></td>
<td>9.5 ± 1.6</td>
<td>20.3 ± 2.3</td>
</tr>
<tr>
<td><strong>Signal $m_{L/N} = 300$ GeV</strong></td>
<td>12.2 ± 0.6</td>
<td>5.7 ± 0.5</td>
</tr>
</tbody>
</table>
CMS: LFV decays of heavy resonances (extra dimension)
LVF - Z

- Z decays
  - BR of Z->emu < 4.10^-60 via one loop decays with flavour-oscillating neutrinoes in the SM (QUES: is it really SM??)
  - New physics (eg, massive Dirac or Majorana neutrinoes) can change the BR to 10^-9)
  - Direct probe of new physics

Figure 1: The leading jet $p_T$ for events where a well-identified electron and muon are selected, the trigger requirement is met and that satisfy 60 < m_{e\mu} < 120 GeV. The signal is drawn on the bottom (not stacked). The background uncertainty band includes only uncertainties from statistical precision and systematic effects on the normalization.
LVF in Z decays: Backgrounds and Selection

- Backgrounds: $Z \rightarrow \tau\tau$, leptonic decays of $WW$, $ttbar$, $tW$, $WZ$, $ZZ$, mis-identified leptons from $W+jets$ and $Z+jets$
- $Z$: oppositely charged $\mu$ and $e$
- Events vetoed: third lepton passing loose criteria (rejects multi-lepton backgrounds e.g., $WZ$ or $ZZ$)
- $60 \ (70) < M_{\mu\mu} < 120 \ (110)$ in CMS(ATLAS)
- Top background (eg, $tW$, $tt$) rejection: $P_{T}\text{jet} < 40$
- Reject $WW$, transverse mass $< 60$
- $P_{T}$ of the $Z$ candidate $< 10$ GEV
Table 2: Predicted background yields with systematic uncertainties and observed data yields for all event categories. The values for three signal mass points are listed. For the EWK prompt and fake background sources, the statistical uncertainties are given in parenthesis.

<table>
<thead>
<tr>
<th>Category</th>
<th>EWK prompt</th>
<th>Fake</th>
<th>Total background</th>
<th>Data</th>
<th>Signal mass $M_\Sigma$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
</tr>
<tr>
<td>$\mu^+ \mu^+ \mu^-$</td>
<td>4.7±1.2 (0.4)</td>
<td>0.4±0.5 (0.4)</td>
<td>5.0±1.3</td>
<td>9</td>
<td>4.3±0.3</td>
</tr>
<tr>
<td>$e^+e^+e^-$</td>
<td>2.9±0.8 (0.3)</td>
<td>1.4±1.1 (0.8)</td>
<td>4.3±1.4</td>
<td>6</td>
<td>2.8±0.3</td>
</tr>
<tr>
<td>$\mu^+ \mu^+ e^-$</td>
<td>0.6±0.2 (0.1)</td>
<td>2.1±1.3 (0.7)</td>
<td>2.7±1.3</td>
<td>1</td>
<td>6.7±0.4</td>
</tr>
<tr>
<td>$\mu^+ e^+ \mu^-$</td>
<td>7.1±1.8 (0.6)</td>
<td>3.5±1.9 (0.7)</td>
<td>10.6±2.6</td>
<td>8</td>
<td>9.8±0.6</td>
</tr>
<tr>
<td>$e^+e^+\mu^-$</td>
<td>0.7±0.2 (0.1)</td>
<td>2.8±1.5 (0.6)</td>
<td>3.6±1.6</td>
<td>1</td>
<td>5.9±0.5</td>
</tr>
<tr>
<td>$\mu^+e^+e^-$</td>
<td>4.8±1.2 (0.4)</td>
<td>1.0±0.8 (0.6)</td>
<td>5.7±1.4</td>
<td>6</td>
<td>8.7±0.7</td>
</tr>
<tr>
<td><strong>Total sign +</strong></td>
<td>20.7±2.6 (0.9)</td>
<td>11.2±3.1 (1.6)</td>
<td>31.9±4.0</td>
<td>31</td>
<td>38.2±1.2</td>
</tr>
<tr>
<td>$\mu^- \mu^- \mu^+$</td>
<td>2.4±0.6 (0.3)</td>
<td>0.2±0.5 (0.5)</td>
<td>2.6±0.8</td>
<td>2</td>
<td>2.1±0.2</td>
</tr>
<tr>
<td>$e^-e^-e^+$</td>
<td>2.4±0.7 (0.3)</td>
<td>2.7±1.6 (0.9)</td>
<td>5.1±1.8</td>
<td>5</td>
<td>1.4±0.1</td>
</tr>
<tr>
<td>$\mu^- \mu^- e^+$</td>
<td>0.5±0.2 (0.1)</td>
<td>1.6±1.0 (0.6)</td>
<td>2.1±1.0</td>
<td>2</td>
<td>3.4±0.2</td>
</tr>
<tr>
<td>$\mu^- e^- \mu^+$</td>
<td>3.4±0.9 (0.4)</td>
<td>2.1±1.2 (0.7)</td>
<td>5.5±1.5</td>
<td>2</td>
<td>5.0±0.4</td>
</tr>
<tr>
<td>$e^-e^-\mu^+$</td>
<td>0.6±0.2 (0.1)</td>
<td>2.3±1.3 (0.7)</td>
<td>2.9±1.4</td>
<td>1</td>
<td>2.8±0.2</td>
</tr>
<tr>
<td>$\mu^- e^- e^+$</td>
<td>3.4±0.8 (0.4)</td>
<td>2.0±1.2 (0.7)</td>
<td>5.4±1.5</td>
<td>4</td>
<td>4.5±0.4</td>
</tr>
<tr>
<td><strong>Total sign -</strong></td>
<td>12.6±1.5 (0.7)</td>
<td>10.9±2.9 (1.6)</td>
<td>23.5±3.3</td>
<td>16</td>
<td>19.2±0.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>33.3±3.9 (1.2)</td>
<td>22.1±5.2 (1.7)</td>
<td>55.4±6.5</td>
<td>47</td>
<td>57.5±1.4</td>
</tr>
</tbody>
</table>
Multi-photon search - ATLAS
- Possible combination of same flavour, opposite charge leptons are made
- \(m_{12}\): pair closest to Z mass, \(m_{34}\): other pair
- Search is performed in \(m_{34}\) mass spectrum
  - Template fit of \(m_{34}\) is used for local access using signal and background templates from the MC

For \(15 < Z_d < 35\) GeV,
\[
\text{Limits on } \varepsilon : (1.5-8.7) \times 10^{-4}
\]
**H→Z_dZ_d→4l: Results and Limits**

- Possible combination of same flavour, opposite charge leptons are made
- Pairs which have minimum $\Delta m = |m_{12} - m_{34}|$ are chosen
- Require:
  - $115 < m_4l < 130$
  - Veto $Z, J/\psi, \gamma$
  - Loose signal region: $m_{12} < m_H/2$ and $m_{34} < m_H/2$
  - Tight signal: $|M_d - m_{12}| < \delta m$

For $15 < Z_d < 60$ GeV,
- Limits on $\text{BR}(H→ZZ_d→4l)$: $(2-3) \times 10^{-5}$
- Limits on $\kappa$: $(1-10) \times 10^{-4}$
New light gauge bosons in Higgs boson decays to 4-μ final states

- Looks in the final state of 4 muons
- Models considered: NMSSM and Dark SUSY
- Require two pairs of dimuons
  - coming from a common vertex OR
  - \( m_{\mu\mu} < 5 \) GeV
  - Near in dR (<0.01)
- Require the invariant mass of two dimuons to be compatible with each other within the detector resolution
- To maintain model independence - no restriction on the 4μ invariant mass
- Dominated backgrounds are bb~ and J/psi

CMS: arXiv:1506.00424
Estimation of the main background

- bb~
  - Modeled as a 2-D template $B_{bb~}(m1,m2)$ in invariant mass plane of the two dimuons
  - Construct the template as: $B_{17+8}(m1) \times B_{8+8}(m2)$
  - B17x8(m1): estimated from bb~ events rich sample:
    - One dimuon (with one muon $p_T > 17$ GeV) and one orphan (ungrouped) muon (with $p_T > 8$ GeV)
  - B8x8(m2): estimated from bb~ events rich sample:
    - One dimuon (with both muons $p_T > 8$ GeV) and one orphan (ungrouped) muon (with $p_T > 17$ GeV)
  - Both templates fitted with Crystall ball and Bernstein polynomials

- J/ψ pair: using simulation
Results

- After unblinding the signal region, one event was observed in the signal region \((m_1 \sim m_2)\)
- Limit is valid for new light boson masses in the range: \(0.25 < m_a < 3.55\) and \(m_h > 86\) GeV