High-mass resonances searches with leptons

Noam Tal Hod, on behalf of ATLAS & CMS
Outline

- Introduction

- Focus on $Z'$, $W'$, Heavy neutrinos and Multilepton searches
  - ATLAS $Z'\rightarrow\ell\ell$ search, 139 fb$^{-1}$ [arXiv:1903.06248]
  - CMS $Z'\rightarrow\ell\ell$ search, 36 fb$^{-1}$ [JHEP 06 (2018) 120, JHEP 04 (2019) 114]
  - ATLAS $W'\rightarrow\ell\nu$ search, 139 fb$^{-1}$ [soon]
  - ATLAS $W_R\rightarrow\ell N_R\rightarrow\ell\ell qq$ search, 80 fb$^{-1}$ [arXiv:1904.12679]
  - CMS Multilepton search 137 fb$^{-1}$ [CMS-PAS-EXO-19-002]

- Outlook
Motivation

- Some well known SM extensions featuring new heavy resonances
- Also well known new types of non-resonant interactions
- Coupling to leptons provide the cleanest signatures for searches
  - selection *usually* straightforward
- Not many fresh models for “standard” resonances
  - several relatively new models motivated by the flavour-anomalies
- Recent models suggest completely new signatures, e.g. the clockwork theory [JHEP 1806 (2018) 009]
What’s new experimentally?

Yes, much more data plus some incremental improvements, but what’s besides that?

- increased luminosity is great, but also poses some problems for searches!
  - Keep the “high-stat end” in tune
  - FullSim MC has to grow significantly
    - storage, processing, modelling…
  - Can we work around that?

need at least \(N_{MC} \geq 100 \times N_{data}\) to keep the stat error ratio below 10% → difficult at low masses

Limit on \(m(Z')\) at ~3.8 TeV from both ATLAS & CMS
ATLAS $Z'\rightarrow\ell\ell$ search with 139 fb$^{-1}$

- Bkg model: fit $m_{\ell\ell}$ spectra in data
  - search from 250 GeV up to 6 TeV
  - MC is still used - see backup

- Generic signal shapes
  - Breit-Wigner$\otimes$Resolution

- Full response description
  - efficiency and resolution vs $m_{\ell\ell}^{\text{true}}$
  - allows easy reinterpretations

- Limits placed on the fiducial $\sigma\times\mathcal{B}$
  - for various widths
  - applicable to spin-0/1/2 signals
  - converted for a set of benchmarks (E6, HVT, SSM,...)

\[ \mathcal{F} = Z_0(m_{\ell\ell}) \cdot \left(1 - x^c\right)^b \cdot x \sum p_n \log^n(x) \]
\[ x = m_{\ell\ell}/\sqrt{s}, \quad n = 0,...,3 \]
Most massive $\ell^+\ell^-$ event ever recorded!

- $m_{ee} = 4.06$ TeV
- Leading electron
  - $E_T = 2.01$ TeV
  - $\eta = 0.47$
  - $\phi = -0.78$
- Subleading electron
  - $E_T = 1.92$ TeV
  - $\eta = -0.03$
  - $\phi = 2.37$
ATLAS $Z'\rightarrow\ell\ell$ search with 139 fb$^{-1}$

plus several more interpretations

but more uniquely than in the past:

Noam Tal Hod, WIS
CMS $\ell\ell$ search with 36 fb$^{-1}$

- Based on MC
- Resonant
  - expect full Run2 result to be out soon
- Non-resonant

$$\frac{d\sigma_{X\rightarrow\ell\ell}}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} + \eta_X I(m_{\ell\ell}) + \eta_X^2 S(m_{\ell\ell})$$

$$\eta_X = -\frac{\eta_{ij}}{\Lambda_{ij}^2}$$

**Limits:**

$\Lambda_{LL}>20$ TeV (destructive)

$\Lambda_{RR}>32$ TeV (constructive)

and more!

(ADD etc)
The ATLAS $W' \rightarrow \ell \nu$ search with 139 fb$^{-1}$

- The low-m$_T$ region re-included (was 300, now 150 GeV)
- Added single-bin (cross section) and generic ($\Gamma/M=1-15\%$) limits
- MC used for all bkgs except for fake electrons contributions
  - ttbar and diboson smoothed and extrapolated
- $E_T^{\text{miss}}$: $|\Sigma_{\text{vec}}p_T(\text{signal leptons + photons + jets})|+(\text{soft term})$
- Large uncertainties in the bkg at high m$_T$ have little impact (tiny stat...)

Reduce disagreement at low mass due to:
- jet energy resolution
- $E_T^{\text{miss}}$ trk soft term

Noam Tal Hod, WIS  May 20 2019
**ATLAS $W' \rightarrow \ell \nu$ search with 139 fb$^{-1}$**

$m_{W'} > 6$ (5.8) TeV, dominated by the electron channel

- Limits on $\sigma_{\text{vis}} = N_{\text{sig}}/L$
- different $m_{T}^{\text{min}}$ thresholds
- different $A \times \varepsilon$ (already in $N_{\text{sig}}$)
- provide full binned info

**Observed limits at 95% CL**

- $m_{\ell \nu} > 0.3 m_{W'}$
- $\Gamma / M = 3.5 \%$
- $m_{\ell \nu} > 0.85 m_{W'}$
- $\Gamma / M = 1-15\%$

**Expected limits**

- $\sigma_{\text{vis}} = N_{\text{sig}}/L$
- different $m_{T}^{\text{min}}$ thresholds
- different $A \times \varepsilon$ (already in $N_{\text{sig}}$)
- provide full binned info
Framework of L-R symmetric models
- SM-singlet heavy neutrinos $N_R$

Focus on $m(N_R)/m(W_R) \leq 0.1$
- $N_R$ can be highly boosted
  - quarks merge $\Rightarrow$ large-R jets
  - electrons: $m(N_R) = m(J)$
  - muons: $p(N_R) = p(J) + p(\mu_2)$

SR: $m_{WR} > 2$ TeV, same-flavour leptons
- dominant bkg is ttbar

Bkg MC is used for
- optimise selection
- electron-in-jet performance
- estimate $Z$+jets contribution
Z+jets: fit the MC prediction → $\mathcal{F}_{Z+\text{jets}}$
- larger than ttbar at high m(WR)

Ttbar: data fit in the CR, m(WR)<2 TeV
- $\mathcal{F} = \mathcal{F}_{\text{data,CR}} + \mathcal{F}_{Z+\text{jets}}$ (fixed from MC)
- validate in the e$\mu$ VR (Z+jets negligible)

Extrapolate to the SR: m(WR)>2 TeV
- uncertainty on bkg yield: 25%
- Single-bin counting experiment in the SR

<table>
<thead>
<tr>
<th>Electron Channel</th>
<th>Muon Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected background</td>
<td>2.8$^{+0.5}_{-0.7}$</td>
</tr>
<tr>
<td>Observed events</td>
<td>8</td>
</tr>
<tr>
<td>Significance</td>
<td>2.4$\sigma$</td>
</tr>
<tr>
<td>p-value</td>
<td>0.0082</td>
</tr>
</tbody>
</table>

...small tension

$\mathcal{F}_{\text{data,CR}} = Ae^{-Bu}/u^C$ \hspace{0.5cm} $u = m_{WR}/\sqrt{s}$

$\mathcal{F}_{Z+\text{jets}} = A'(1-u)^B(1+u)^Cu$
ATLAS $W_R \rightarrow \ell N_R \rightarrow \ell \ell qq$ with 80 fb$^{-1}$

- Excluded region extends to $m(W_R)$ of $\sim 5$ TeV for both channels, for $m(N_R)$ of 0.4-0.5 TeV
- Much more sensitive wrt the resolved channel at small $N_R$ masses

![Graph of signal selection efficiency for ATLAS Simulation](image)

- Electron channel
- Muon channel
- Observed 95% CL
- Expected 95% CL
- Observed resolved 95% CL
- Expected 1σ Band
- Expected 2σ Band
- Not covered
- Excluded

![Graph of tension](image)
CMS Multileptons with 137 fb⁻¹

- Exactly 3 (3L) or 4 and more (4L) leptons
- Type-III seesaw pairs of heavy fermions
  - non-resonant tails in \( m_T \) or \( L_T + p_T^{\text{miss}} \)
- Light scalar top-associated production (ttφ)
  - resonant in dilepton mass (first direct search!)
    - 15-75 GeV and 108-340 GeV (not onia/Z/φ→tt)
- Bkgs: Diboson and ttZ (MC) and Z/ttbar+jets (data)
Heavy fermions excluded below 880 GeV (case of lepton flavour democratic decay)

$\mathcal{B}(\phi \rightarrow \ell \ell)$ excluded above 0.04 for scalar (0.03 pseudoscalar) mass in 108-340 GeV, for $g_t^2 \sim 1$. 

Noam Tal Hod, WIS
A few recent cutting-edge direct searches with leptons

- some refreshments in long-standing strategies
- no significant evidence of such physics yet
  - new/stronger exclusions from both experiments

However,

- what we usually exclude is a class of very strong signals
- recall that we haven’t observed the $H \rightarrow \mu\mu$ signal yet
- weakly coupled resonances could still be anywhere above the $Z$

- We need more luminosity and more energy!
THANK YOU
BACKUP
ATLAS Z' selection

Event Selection
- At least one $pp$ interaction vertex is reconstructed
- Primary vertex: highest $\sum p_T^2$ using tracks with $p_T > 0.5$ GeV

Electrons
- $E_T > 30$ GeV
- $|\eta| < 1.37$ or $|\eta| > 1.52$
- *medium* ID (93% efficient for $E_T > 80$ GeV)

Muons
- $p_T > 30$ GeV
- $|\eta| < 2.5$
- *high-pt ID*: three hits required in MS, some veto areas (69% $\eta$ averaged efficiency at 1 TeV)
- *good muon selection*: $q/p$ uncertainty passes $p_T$-dependent threshold
- $|z_0 \sin(\theta)| < 0.5$ mm constraint on the longitudinal impact parameter
- $|d_0/\sigma(d_0)| < 5(3)$ for $e(\mu)$ constraint on the traverse impact parameter
- Both $e$ and $\mu$ pass a 99% efficient isolation requirement

Event selection
- Must have two same-flavor leptons
- If additional leptons, pick same-flavor pair with largest $E_T$ ($p_T$) for $ee$ ($\mu\mu$)
- If two different flavors are found, $ee$ is used because of the better resolution
- For dimuon pairs, an opposite charge requirement is applied
ATLAS Z' Fiducial region

- Done to reduce model-dependencies from off-shell effects

- Requirements at particle level (for resonance X)
  - $|\eta(\ell)|<2.5$
  - $p_T(\ell)>30$ GeV
  - $m_{\ell\ell}(\text{tru})>(m_X-2\Gamma_X)$
Table 2: The relative impact of ±1σ variation of systematic uncertainties on the signal yield in percent for zero (10%) relative width signals at the pole masses of 300 GeV and 5 TeV for dielectron and dimuon channels. A signal is injected at the cross-section limit.

<table>
<thead>
<tr>
<th>Uncertainty source for $m_X$ [GeV]</th>
<th>Dielectron (300)</th>
<th>Dielectron (5000)</th>
<th>Dimuon (300)</th>
<th>Dimuon (5000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spurious signal</td>
<td>±12.5 (12.0)</td>
<td>±0.1 (1.0)</td>
<td>±11.7 (11.0)</td>
<td>±2.1 (2.2)</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>±1.6 (1.6)</td>
<td>±5.6 (5.6)</td>
<td>±1.8 (1.8)</td>
<td>$^{+25}<em>{-20}$ ($^{+25}</em>{-20}$)</td>
</tr>
<tr>
<td>Isolation</td>
<td>±0.3 (0.3)</td>
<td>±1.1 (1.1)</td>
<td>±0.4 (0.4)</td>
<td>±0.4 (0.5)</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±1.7 (1.7)</td>
<td>±1.7 (1.7)</td>
<td>±1.7 (1.7)</td>
<td>±1.7 (1.7)</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>$^{-1.7}<em>{-4.0}$ ($^{+1.0}</em>{-1.8}$)</td>
<td>$^{+0.1}_{-0.4}$ ($^{±0.8}$)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Electron energy resolution</td>
<td>$^{+7.9}<em>{-8.3}$ ($^{+1.1}</em>{-0.9}$)</td>
<td>$^{+0.4}_{-0.9}$ ($^{±0.1}$)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Muon ID resolution</td>
<td>-</td>
<td>-</td>
<td>$^{+0.8}<em>{-2.3}$ ($^{+0.3}</em>{-0.8}$)</td>
<td>$^{+0.6}<em>{-0.4}$ ($^{+0.5}</em>{-0.3}$)</td>
</tr>
<tr>
<td>Muon MS resolution</td>
<td>-</td>
<td>-</td>
<td>$^{+2.8}<em>{-3.8}$ ($^{+1.0}</em>{-1.3}$)</td>
<td>±2.4 (2.1)</td>
</tr>
<tr>
<td>‘Good muon’ requirement</td>
<td>-</td>
<td>-</td>
<td>±0.6 (0.6)</td>
<td>$^{+55}<em>{-35}$ ($^{+55}</em>{-35}$)</td>
</tr>
</tbody>
</table>
Non-huge MC samples still used to
- explore fit functions
- study bkg compositions
- evaluate efficiency & resolution
- derive spurious signal uncertainty
  - for each $\Gamma_X$ assumptions in: 0%, 0.5%, ..., 10%

Main backgrounds are DY and ttbar
- produced from large-stat generator level
- smeared by the $m_{\ell\ell}$ resolution
- corrected by $m_{\ell\ell}$-dependent $A \times \epsilon$
CMS’s Z’ search

- Cross section can, in the narrow-width approx’, be expressed as $c_u \omega_u + c_d \omega_d$
- $c_u$ ($c_d$) contains information about the model-dependent $Z'$ couplings to the up-type (down-type) quarks, while $\omega_u$ ($\omega_d$) depends on the respective PDFs
- The parameterisation of the linear mixing of the relevant $U'(1)$ generators produces a contour in the $c_d$-$c_u$ plane that represents each class of models
## CMS’s CI uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Electrons $m_{ee} &gt; 2$ TeV</th>
<th>$m_{ee} &gt; 4$ TeV</th>
<th>$m_{\mu\mu} &gt; 2$ TeV</th>
<th>$m_{\mu\mu} &gt; 4$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron trigger + selection efficiency BB (BE)</td>
<td>6 (8)%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron energy scale BB (BE)</td>
<td>12.0 (6.7)%</td>
<td>21.7 (11.0)%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon trigger efficiency BB (BE)</td>
<td></td>
<td></td>
<td>0.3 (0.7)%</td>
<td></td>
</tr>
<tr>
<td>Muon ID efficiency BB (BE)</td>
<td></td>
<td></td>
<td>0.8 (4.6)%</td>
<td>1.7 (7.6)%</td>
</tr>
<tr>
<td>Muon $p_T$ resolution BB (BE)</td>
<td></td>
<td></td>
<td>0.8 (1.4)%</td>
<td>1.5 (2.3)%</td>
</tr>
<tr>
<td>Muon $p_T$ scale BB (BE)</td>
<td></td>
<td></td>
<td>0.8 (2.8)%</td>
<td>4.1 (12.1)%</td>
</tr>
<tr>
<td>$t\bar{t}$/diboson cross section</td>
<td></td>
<td>7%</td>
<td></td>
<td>7%</td>
</tr>
<tr>
<td>Z boson peak normalization</td>
<td></td>
<td>1%</td>
<td></td>
<td>5%</td>
</tr>
<tr>
<td>PDF</td>
<td>5.7%</td>
<td>17.1%</td>
<td>5.7%</td>
<td>17.1%</td>
</tr>
<tr>
<td>Multijet BB (BE)</td>
<td>0.1 (1.3)%</td>
<td>0.1 (0.1)%</td>
<td>&lt;0.1 (4.8)%</td>
<td>&lt;0.1 (&lt;0.1)%</td>
</tr>
<tr>
<td>Pileup reweighting BB (BE)</td>
<td>0.5 (0.7)%</td>
<td>0.4 (0.7)%</td>
<td>0.2 (0.1)%</td>
<td>0.2 (0.2)%</td>
</tr>
<tr>
<td>MC statistics BB (BE)</td>
<td>1.0 (1.8)%</td>
<td>0.7 (1.7)%</td>
<td>1.1 (1.3)%</td>
<td>1.0 (2.0)%</td>
</tr>
</tbody>
</table>

**Table 1.** Systematic uncertainties in the predicted SM yields for the electron and the muon channels, for two dilepton mass thresholds. Where noted, uncertainties are provided separately for events where both leptons are in the barrel region (BB), or where at least one of the leptons is in the endcap region (BE). Uncertainties that are mass-dependent affect both the event yield and the shape of the invariant mass distribution. The systematic uncertainties in the signal yields are largely the same as for the background, with a few exceptions as discussed in the text.
ATLAS W' search

ATLAS Simulation Preliminary

$\sqrt{s} = 13$ TeV

Acceptance $\times$ Efficiency

$W' \rightarrow e\nu$

$W' \rightarrow \mu\nu$
ATLAS $N_R$ search

Table 2: Object selection criteria. The significance of the transverse impact parameter is defined as the transverse impact parameter $d_0$ divided by its uncertainty, $\sigma_{d_0}$, of tracks relative to the primary vertex with the highest sum of track $p_T$. The longitudinal impact parameter $z_0$ is multiplied by $\sin \theta$, where $\theta$ is the polar angle of the track.

<table>
<thead>
<tr>
<th></th>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lepton:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T$</td>
<td>&gt; 26 GeV</td>
<td>&gt; 28 GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;1.37$ or $1.52&lt;</td>
</tr>
<tr>
<td>Leading lepton quality</td>
<td>Medium [61], isolated [61]</td>
<td>Medium [62], isolated [62]</td>
</tr>
<tr>
<td>Subleading lepton quality</td>
<td>Medium, no isolation</td>
<td>Medium, no isolation</td>
</tr>
<tr>
<td>Transverse impact parameter significance</td>
<td>$</td>
<td>d_0</td>
</tr>
<tr>
<td>Longitudinal impact parameter</td>
<td>$</td>
<td>z_0</td>
</tr>
<tr>
<td><strong>Trimmed large-$R$ jet:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T$</td>
<td></td>
<td>&gt; 200 GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>Mass</td>
<td>&gt; 50 GeV</td>
<td>None</td>
</tr>
</tbody>
</table>
Large-R jet trimming

- Decays of boosted massive particles (t,Z,W) appear merged in the detector
- Average angular separation between the decay products is $\Delta R \sim 2m/p_T$
- Different grooming algorithms, input variables, tagging approaches etc.
- Jet grooming (e.g. trimming) is used to remove soft contaminations from PU, UE and ISR
- Trimming: Jets built with the anti-kt algorithm using $R \sim 1$, trimmed using $R \sim 0.2$ subjets, removing those whose $p_T$ fraction is e.g. <5% of the jet $p_T$
ATLAS heavy neutrinos

Table 4: Relative systematic uncertainties of the signal yield in the signal region, in percentage for each source. The ranges indicate the different signal samples. The systematic uncertainties with sub-percent contributions are not shown.

<table>
<thead>
<tr>
<th>Component</th>
<th>Electron channel [%]</th>
<th>Muon channel [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton identification</td>
<td>4–20</td>
<td>4–8</td>
</tr>
<tr>
<td>Lepton isolation</td>
<td>4–5</td>
<td>1.0–1.5</td>
</tr>
<tr>
<td>Lepton reconstruction</td>
<td>4–5</td>
<td>1–4</td>
</tr>
<tr>
<td>Lepton trigger</td>
<td>4–5</td>
<td>0.5</td>
</tr>
<tr>
<td>Pile-up</td>
<td>&lt; 0.5</td>
<td>2–3</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Theory</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

- Ttbar fit uncert.: variations of the fit range→largest change in the SR yield
- Z+jets fit uncert.: same as ttbar + fit alternative Z+jets MC samples after varying the scale and using alternative PDF sets (all in quadrature)
- The uncertainty of the background yield in the SR is 25% for both channels
- Fits statistical uncertainties: use pseudo-experiments while varying the input data points within their statistical uncertainties
Figure 1: Leading order Feynman diagrams for the type-III seesaw (left) and $t\bar{t}\phi$ (right) signal models, depicting example production and decay modes in pp collisions.
Table 1: Multilepton signal region definitions for the signal models. All events containing a same-flavor lepton pair with mass below 12 GeV, and 3L events containing an OSSF lepton pair with mass below 76 GeV when the trilepton mass is within a Z boson mass window (91 ± 15 GeV) are vetoed.

<table>
<thead>
<tr>
<th>Label</th>
<th>$N_\ell$</th>
<th>$N_{\text{OSSF}}$</th>
<th>$M_{\text{OSSF}}$</th>
<th>$N_b$</th>
<th>$p_T^{\text{miss}}$</th>
<th>Variable</th>
<th>Binning scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal model: type-III seesaw</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3L below-Z</td>
<td>3</td>
<td>1</td>
<td>&lt; 76 GeV</td>
<td>–</td>
<td>–</td>
<td>$L_T + p_T^{\text{miss}}$</td>
<td>0 – 1200 GeV</td>
</tr>
<tr>
<td>3L on-Z</td>
<td>3</td>
<td>1</td>
<td>76 – 106 GeV</td>
<td>–</td>
<td>&gt; 100 GeV</td>
<td>$M_T$</td>
<td>0 – 700 GeV</td>
</tr>
<tr>
<td>3L above-Z</td>
<td>3</td>
<td>1</td>
<td>&gt; 106 GeV</td>
<td>–</td>
<td>–</td>
<td>$L_T + p_T^{\text{miss}}$</td>
<td>0 – 1600 GeV</td>
</tr>
<tr>
<td>3L OSSF0</td>
<td>3</td>
<td>0</td>
<td></td>
<td>–</td>
<td>–</td>
<td>$L_T + p_T^{\text{miss}}$</td>
<td>0 – 1200 GeV</td>
</tr>
<tr>
<td>4L OSSF1</td>
<td>≥4</td>
<td>1</td>
<td></td>
<td>–</td>
<td>–</td>
<td>$L_T + p_T^{\text{miss}}$</td>
<td>0 – 1000 GeV</td>
</tr>
<tr>
<td>4L OSSF2</td>
<td>≥4</td>
<td>2</td>
<td></td>
<td>–</td>
<td>&gt; 100 GeV if double on-Z</td>
<td>$L_T + p_T^{\text{miss}}$</td>
<td>0 – 1200 GeV</td>
</tr>
<tr>
<td><strong>Signal model: $t\bar{t}\phi$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3L($\ell\ell$)* 0B</td>
<td>3</td>
<td>1</td>
<td>off-Z</td>
<td>0</td>
<td>–</td>
<td>$M_{\text{OSSF}}^{20}$</td>
<td>12 – 77 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$M_{\text{OSSF}}^{300}$</td>
<td>106 – 356 GeV</td>
</tr>
<tr>
<td>3L($\ell\ell$)* 1B</td>
<td>3</td>
<td>1</td>
<td>off-Z ≥1</td>
<td>–</td>
<td>–</td>
<td>$M_{\text{OSSF}}^{20}$</td>
<td>12 – 77 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$M_{\text{OSSF}}^{300}$</td>
<td>106 – 356 GeV</td>
</tr>
<tr>
<td>4L($\ell\ell$)* 0B</td>
<td>≥4</td>
<td>≥1</td>
<td>off-Z</td>
<td>0</td>
<td>–</td>
<td>$M_{\text{OSSF}}^{20}$</td>
<td>12 – 77 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$M_{\text{OSSF}}^{300}$</td>
<td>106 – 356 GeV</td>
</tr>
<tr>
<td>4L($\ell\ell$)* 1B</td>
<td>≥4</td>
<td>≥1</td>
<td>off-Z ≥1</td>
<td>–</td>
<td>–</td>
<td>$M_{\text{OSSF}}^{20}$</td>
<td>12 – 77 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$M_{\text{OSSF}}^{300}$</td>
<td>106 – 356 GeV</td>
</tr>
</tbody>
</table>

$| S_T (\text{GeV}) |
\begin{align*}
0 – 400 & 13 bins & 13 bins & 5 bins \\
400 – 800 & 10 bins & 10 bins & 10 bins \\
> 800 & 10 bins & 10 bins & 10 bins \\
\end{align*}

* $\ell = e$ or $\mu$
# CMS Multileptons

Table 2: Sources of systematic uncertainties, affected background and signal processes, relative variation on the affected processes, and correlation model across years in signal regions.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>Signal/Background process</th>
<th>Variation (%)</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>Signal/Rare/Non-Zγ conversion</td>
<td>2.3 – 2.5</td>
<td>No</td>
</tr>
<tr>
<td>Lepton reco, ID and iso. efficiency</td>
<td>Signal/Background*</td>
<td>4 – 5</td>
<td>No</td>
</tr>
<tr>
<td>Lepton displacement efficiency (only in 3L)</td>
<td>Signal/Background*</td>
<td>3 – 5</td>
<td>Yes</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>Signal/Background*</td>
<td>&lt; 3</td>
<td>No</td>
</tr>
<tr>
<td>B tag efficiency</td>
<td>Signal/Background*</td>
<td>&lt; 5</td>
<td>No</td>
</tr>
<tr>
<td>Minbias cross section (pileup)</td>
<td>Signal/Background*</td>
<td>&lt; 3</td>
<td>Yes</td>
</tr>
<tr>
<td>Factorization/renormalization scale &amp; PDF</td>
<td>Signal/Background*</td>
<td>&lt; 10</td>
<td>Yes</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>Signal/Background*</td>
<td>&lt; 5</td>
<td>Yes</td>
</tr>
<tr>
<td>Unclustered energy scale</td>
<td>Signal/Background*</td>
<td>&lt; 5</td>
<td>Yes</td>
</tr>
<tr>
<td>Muon energy scale and resolution</td>
<td>Signal/Background*</td>
<td>&lt; 5</td>
<td>Yes</td>
</tr>
<tr>
<td>Electron energy scale and resolution</td>
<td>Signal/Background*</td>
<td>&lt; 2</td>
<td>Yes</td>
</tr>
<tr>
<td>WZ normalization (0/1/2/≥3 jets)</td>
<td>WZ</td>
<td>5 – 10</td>
<td>Yes</td>
</tr>
<tr>
<td>ZZ normalization (0/1/≥2 jets)</td>
<td>ZZ</td>
<td>5 – 10</td>
<td>Yes</td>
</tr>
<tr>
<td>ttZ normalization</td>
<td>ttZ</td>
<td>15 – 20</td>
<td>Yes</td>
</tr>
<tr>
<td>Conversion normalization</td>
<td>Conversion</td>
<td>20 – 50</td>
<td>Yes</td>
</tr>
<tr>
<td>Rare normalization</td>
<td>Rare</td>
<td>50</td>
<td>Yes</td>
</tr>
<tr>
<td>Lepton misidentification rates</td>
<td>Misidentified lepton</td>
<td>30 – 40</td>
<td>Yes</td>
</tr>
<tr>
<td>Electron charge misidentification</td>
<td>WZ/ZZ†</td>
<td>&lt; 20</td>
<td>No</td>
</tr>
</tbody>
</table>

*WZ, ZZ, ttZ, rare, and conversion background processes.
†Only in 3L OSSF0 and 4L OSSF1 signal regions.
Table 3: Acceptance times efficiency values in 3 and 4 lepton channels for the signal models at various mass hypotheses.

<table>
<thead>
<tr>
<th>Signal model</th>
<th>Acceptance $\times$ efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Type-III seesaw</td>
<td></td>
</tr>
<tr>
<td>$\Sigma$ mass (GeV)</td>
<td>100  200  300  400  550  700  850  1000  1250  1500</td>
</tr>
<tr>
<td>Flavor democratic</td>
<td>0.32  1.82  2.63  3.02  3.29  3.34  3.29  3.21  2.99  2.82</td>
</tr>
<tr>
<td>$t\bar{t}\phi$</td>
<td></td>
</tr>
<tr>
<td>$\phi$ mass (GeV)</td>
<td>15   20   25   30   40   50   60   70   75   108  125  150  200  250  300</td>
</tr>
<tr>
<td>Scalar $\phi(\to ee)$</td>
<td>0.85  1.29  1.67  2.02  2.74  3.44  4.25  5.16  4.95  5.53  8.32  9.00 10.3 11.1 11.5</td>
</tr>
<tr>
<td>Scalar $\phi(\to \mu\mu)$</td>
<td>1.54  2.16  2.81  3.35  4.38  5.29  6.40  7.69  7.56  8.74  11.6  12.3  14.0 14.8 15.3</td>
</tr>
<tr>
<td>Pseudoscalar $\phi(\to ee)$</td>
<td>0.96  1.81  2.69  3.45  4.88  5.82  6.62  7.35  6.83  6.8  9.77  10.4 11.0 11.4 11.9</td>
</tr>
<tr>
<td>Pseudoscalar $\phi(\to \mu\mu)$</td>
<td>1.69  2.95  4.24  5.38  7.14  8.46  9.73  10.4  9.93  10.3  13.4  14.0 14.9 15.2 15.9</td>
</tr>
</tbody>
</table>
Clockwork theory

- [JHEP 1806 (2018) 009]
- Multiple copies of gravity
- Multiple massless gravitons

Clockwork Fierz-Pauli:
\[ \mathcal{L} = -\frac{m^2}{2} \sum_{j=0}^{N-1} \left( [h_{j}^{\mu\nu} - q h_{j+1}^{\mu\nu}]^2 - [\eta_{\mu\nu} (h_{j}^{\mu\nu} - q h_{j+1}^{\mu\nu})]^2 \right) \]

Massless graviton from gauge symmetry:
\[ h_{j}^{\mu\nu} \rightarrow h_{j}^{\mu\nu} + \frac{1}{q^2} (\partial^\mu A^\nu + \partial^\nu A^\mu) \]

![Fourier transform](image1)

![FFT ee (1000 toys)](image2)

![One toy _s+b_ ee](image3)

![One toy _s+b_ Fit ee](image4)

![Signal only (analytic)](image5)