Study of Electroweak Physics in the $l^\pm \nu l^\pm \nu jj$ Final State with the ATLAS Detector

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PhD Thesis Defense
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June 3, 2019
Outline

- Introduction
  - Standard Model and electroweak physics
  - The LHC and the ATLAS detector
- Thesis research topics
- Analysis overview
- Same sign WW electroweak production
- WWW production
- Summary
Introduction
The Standard Model of particle physics

- A theoretical framework to describe the elementary particles and their interactions
  - Describe strong and electroweak interactions based on symmetry groups $SU(3) \times SU(2) \times U(1)$
    - Strong interactions: $SU(3)$
    - Electroweak interactions: $SU(2) \times U(1)$
  - Electroweak interactions play the crucial role in the Standard Model
The Large Hadron Collider at CERN

- 26.7 km ring, proton-proton collisions at $\sqrt{s} = 7/8/13$ TeV
- Peak luminosity $10^{34}$ cm$^{-2}$s$^{-1}$
- Provide the great potential to study the electroweak physics
Electroweak physics at the LHC

- **W/Z boson decays**
  - Precision measurements of W mass, weak mixing angle...

- **Di-boson production**
  - Involves triple gauge couplings (TGC)
  - Search for new physics: anomalous TGC (aTGC) ...

- **Triple-boson production**
  - Involves quartic gauge couplings (QGC)
  - Search for new physics: anomalous QGC (aQGC) ...

- **Electroweak production of vector boson: VBS, VBF**
  - Involves QGC
  - Sensitive to the electroweak symmetry breaking mechanism and new interactions

✓ Constitute important background to many new physics searches and studies
The ATLAS detector

Muon spectrometer (|\eta|<2.7)
Trigger, identification and measurement of muon

Inter detector (|\eta|<2.5, B=2T)
Precise tracking and vertex, e/\pi separation
Si pixels; Si microstrips; Transition Radiation detector

Hadronic calorimeter (|\eta|<4.9)
Trigger, identification and measurement of jet and MET

Electromagnetic calorimeter (|\eta|<3.2)
e/\gamma trigger, identification and measurement
ATLAS performance and dataset

ATLAS Run-2 Detector Status (from May 2018)

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>92 M</td>
<td>97.8%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
<td>98.7%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>97.2%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>100%</td>
</tr>
<tr>
<td>Tile Calorimeter</td>
<td>5200</td>
<td>99.9%</td>
</tr>
<tr>
<td>Hadronic End-Cap LAr Calorimeter</td>
<td>5600</td>
<td>99.6%</td>
</tr>
<tr>
<td>Forward LAr Calorimeter</td>
<td>3500</td>
<td>99.7%</td>
</tr>
<tr>
<td>LV1 Calo Trigger</td>
<td>7180</td>
<td>99.9%</td>
</tr>
<tr>
<td>LV1 Mth RPT Trigger</td>
<td>383 k</td>
<td>99.8%</td>
</tr>
<tr>
<td>LV1 Mth TGC Trigger</td>
<td>320 k</td>
<td>99.6%</td>
</tr>
<tr>
<td>MDT Muon Diff Tubes</td>
<td>387 k</td>
<td>99.7%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>98.7%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>383 k</td>
<td>94.4%</td>
</tr>
<tr>
<td>TGC End-Cap Muon Chambers</td>
<td>320 k</td>
<td>99.5%</td>
</tr>
<tr>
<td>ALFA</td>
<td>10 k</td>
<td>99.9%</td>
</tr>
<tr>
<td>AFN</td>
<td>430 k</td>
<td>93.8%</td>
</tr>
</tbody>
</table>

Detector status

- High operating efficiency

Reconstruction efficiency for muon

- High reconstruction efficiency

Integrated Luminosity

- High statistics
Thesis research topics
Electroweak physics with $l^\pm \nu l^\pm \nu jj$ final state

- **Same sign WW electroweak production**
  - VBS is one of its main production mechanisms
  - sensitive to the electroweak symmetry breaking mechanism
  - search for new physics: aTGC/aQGC and new interactions

- **WWW production**
  - test the SM non-Abelian gauge structure
  - search for new physics: aTGC/aQGC and new interactions

- **Research goals**
  - Observe the same sign WW electroweak process
  - Probe the WWW production process

$pp \rightarrow W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$

$pp \rightarrow W^\pm W^\pm W^\mp \rightarrow l^\pm \nu l^\pm \nu jj$
Previous studies

- Same sign WW electroweak production
  - ATLAS: 8TeV, 20.3 fb$^{-1}$, significance of 3.6σ
  - CMS: 8TeV, 19.4 fb$^{-1}$, significance of 2.0σ
    - 13TeV, 35.9 fb$^{-1}$, significance of 5.5σ

- WWW production
  - ATLAS: 8TeV, 20.3 fb$^{-1}$, significance of 0.96σ

✓ Measurements are limited by statistics in 8 TeV data
✓ Higher energy and more statistics with 13 TeV data, significant improvements are expected
Analysis overview
Signal selections

Develop signal selections according to signal signatures

- Same sign WW VBS signatures
  - two isolated leptons (=e, µ) with same electric charge
  - missing transverse energy
  - two forward jets

- WWW signatures
  - two isolated leptons (e, µ) with same electric charge
  - missing transverse energy
  - two jets from W decay
Background sources and estimations

- **Charge flip background**
  - $t\bar{t}$, $W^{\pm}W^{\mp}$, $Z/\gamma^*$
  - The charge of one of the leptons is wrongly assigned
  - not well modelled in MC, data driven

- **Non-prompt background**
  - $W+$jet, $t\bar{t}$, single top
  - Jet is mis-reconstructed as lepton or lepton from hadron decay
  - not well modelled in MC, data driven

- **$V\gamma$+jets background**
  - The photon is mis-identified as an electron
  - not well modelled in MC, data driven

- **WZ+jets background**
  - One of the leptons is not reconstructed or identified
  - MC estimate

- **Other SM Processes background**
  - $t\bar{t}V$, $ZW$, $ZZ$, $ZZ$
  - MC estimate
Systematic uncertainties and cross section extraction

- **Systematic uncertainties:**
  - Experimental uncertainties
    - Object reconstruction uncertainties (muon, electron, jet, MET)
    - Data driven background estimation uncertainties
  - Theoretical uncertainties
    - Uncertainties with respect to nominal choice of parameters of the MC event generation

- **Cross section extraction:**
  - Profile likelihood fit method
    - Shape analysis to enhance sensitivity
    - Include CR/VR to constrain backgrounds

\[
L(\mu, \theta) = Pois_{SR} \times Pois_{CR/VR} \times Gaus(\theta)
\]
Same sign WW electroweak production
Introduction

- **Motivation**
  - Vector boson scattering includes triple, quartic, and Higgs couplings
    - Study the electroweak symmetry breaking mechanism
    - Search for new physics: aTGC/aQGC and new interactions

- **Search for same sign WW electroweak production with final state:**
  \( W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm vjj \)
  - High EW/QCD cross section ratio

<table>
<thead>
<tr>
<th>Process</th>
<th>( VVjj\text{-EW} )</th>
<th>( VVjj\text{-QCD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W^\pm W^\pm )</td>
<td>19.5 fb</td>
<td>18.8 fb</td>
</tr>
<tr>
<td>( W^\pm W^{\mp} )</td>
<td>91.3 fb</td>
<td>3030 fb</td>
</tr>
</tbody>
</table>

Cross sections for electroweak and QCD-mediated production
### Data/MC samples and Object selections

- **Data sample**
  - $L = 36.1 \text{ fb}^{-1}$ (recorded in 2015 and 2016 at $\sqrt{s} = 13$ TeV)

- **MC samples**
  - Signal: Sherpa at next-to-leading order (NLO) accuracy in QCD
  - Background:
    - diboson and triboson (VV,VVV) : Sherpa
    - $t\bar{t} + V$ : MadGraph
    - $V\gamma$ : Sherpa

- **Object selections**

<table>
<thead>
<tr>
<th>Nominal Muon</th>
<th>Nominal Electron</th>
<th>Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>$Tight_{LH}$</td>
<td>$p_T &gt; 25 \text{ GeV, }</td>
</tr>
<tr>
<td>$p_T &gt; 27 \text{ GeV}$</td>
<td>Author = 1</td>
<td>$p_T &gt; 30 \text{ GeV, }</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$</td>
<td>z_0 \times \sin \theta</td>
<td>&lt; 0.5 \text{ mm}$</td>
</tr>
<tr>
<td>$\frac{d_{\eta}}{\sigma_{d_{\eta}}} &lt; 3$</td>
<td>$\frac{d_{\eta}}{\sigma_{d_{\eta}}} &lt; 5$</td>
<td>$b$-tagging with 85% efficiency</td>
</tr>
</tbody>
</table>

- **Object selections**
Event selections

- exactly two signal leptons with $p_T > 27$ GeV
- same electrical charge
- with $|\eta| < 2.5$ for muons and
- with $|\eta| < 2.47$ excluding $1.37 \leq |\eta| \leq 1.52$ for electrons
- with $|\eta| < 1.37$ in the $ee$ channel
- $m_{ll} \geq 20$ GeV
- 3$^{rd}$ lepton veto
- $|m_{ee} - m_Z| > 15$ GeV in the $ee$-channel
- $E_T^{miss} \geq 30$ GeV
- at least two jets
- satisfying $p_T > 65(35)$ GeV
- $b$-jet veto using the 85% efficiency working point
- $m_{jj} \geq 500$ GeV
- $|\Delta y_{jj}| > 2$

- Reduce charge-flip background
- Reduce low mass Drell-Yan process
- Get rid of WZ process
- Reduce $Z \rightarrow ee$ background
- Get rid of background from top process
- Separate signal from the QCD
Charge flip background estimation (1)

- Two sources of charge mis-identification:
  - Conversion of bremsstrahlung photon (dominated)
  - Wrong tracks reconstruction

- Estimation:
  - $\epsilon$, charge mis-identification rate is estimated with $Z \rightarrow ee$
  - Scale each opposite-sign event with a weight

$$N_{bkg}^{\text{charge-flip}} = N_{OC}^{\text{data}} \cdot \text{weight}$$

$$\text{weight} = \frac{\epsilon_1(1 - \epsilon_2) + \epsilon_2(1 - \epsilon_1)}{(1 - \epsilon_1)(1 - \epsilon_2) + \epsilon_1 \epsilon_2}$$
Electron energy corrections:
- Reconstructed electrons that suffer charge mis-identification tend to have lower reconstructed energy
- Calculate energy scale and resolution for opposite-sign events to match same-sign $m_{ll}$ distribution

Systematic uncertainties:
- Variation of $Z \rightarrow ee$ event selections
  - Vary $Z$ mass window selection
  - Switch on and off the background subtraction
  - Require one/two electron to fire the trigger
- Closure test in MC
- Switching on and off the energy loss correction
Non-prompt background estimation (1)

- Two sources of non-prompt lepton:
  - Lepton from semi-leptonic decay of B hadron
  - Lepton resulting from B hadron decay and mis-identification tend to have loose quality, referred to as "Loose lepton"

- Estimation:
  - Estimate fake factor in dijet events enriched with non-prompt lepton
  - Weight nominal + loose events with the fake factor

\[
N_{bkg}^{fake} = N_{nominal+loose} \cdot fake\ factor
\]

\[
fake\ factor = \frac{N_{nominal}}{N_{loose}}
\]

Fake factor for muon

Fake factor for electron
Parameterization of fake factor:

- Fake factor measured using dijet samples would eventually be applied to the nominal+loose events.
- Original parameterization was with $p_T$.
- Fake factor has dependence on jet kinematic:
  - For a jet producing a lepton, jet $p_T = \text{lepton } p_T + \text{momentum deposited around the lepton}$.
  - Jet kinematic in dijet event and nominal + loose event are different.
  - Fake factor in di-jet event is not the same as fake factor in nominal+loose event.

Subleading lepton $p_T$ in a validation region.
Non-prompt background estimation (3)

- Parameterize fake factor with $p_T + p_T^{\text{varcone30}}$
  - Jet kinematic which fake to lepton is not accessible
  - As close to jet kinematic as possible

$$fake\,\text{factor} = \frac{N_{\text{nominal}}(p_T + p_T^{\text{varcone30}})}{N_{\text{loose}}(p_T + p_T^{\text{varcone30}})} \rightarrow \frac{N_{\text{nominal}}(p_T)}{N_{\text{loose}}(p_T + p_T^{\text{varcone30}})}$$

Distributions of $p_T^{\text{varcone30}}$ for nominal and loose leptons

Parameterization with $p_T$

Parameterization with $p_T + p_T^{\text{varcone30}}$
Non-prompt background estimation (4)

- Systematic uncertainties:
  - Variation of di-jet event selections:
    - Tagging jet $p_T$, $m_T + E_{T,\text{track}}^\text{mis}$, $\Delta \Phi(j, l)$
    - Prompt lepton subtraction: vary normalization correction by $\sim 10\%$
    - Jet flavor composition: without requiring the tagging jet to be a $b$-jet
    - Residual dependence on the jet $p_T$ spectrum: test with tag-jet $p_T$ reweighting

- Validate the method in a validation region
  - defined with the same selections as the signal region but $N_{b\text{-jet}} = 1$
WZ+jets background estimation

- WZ is the dominant background
- Dedicated control region to normalize WZ+jets background
  - an opposite-sign same-flavour dilepton pair
  - a third lepton with $p_T > 15$ GeV
  - $m_{lll} > 106$ GeV to reduce the Z+jets and Zγ contamination
  - $N_{b-\text{jet}} = 0$
  - $N_{\text{jet}} \geq 2$
  - $m_{jj} > 200$ GeV
  - $\Delta Y_{jj} > 2.0$

Distribution of leading lepton $p_T$ in control region

<table>
<thead>
<tr>
<th>$W^\pm Z$</th>
<th>Other Bkgs</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>197.09 ± 68.92</td>
<td>24.23 ± 4.24</td>
<td>201 ± 14.17</td>
</tr>
</tbody>
</table>

Event yields in control region
Vγ+jets background estimation

- Study the modelling of photon conversions in Zγ control region
  - an opposite-sign di-muon pair with leading(sub-leading) muon $p_T > 27(20)$ GeV
  - an additional electron assumed to originate from a converted photon with $p_T > 27$ GeV
  - $75 < m_{\mu\mu\gamma} < 100$ GeV
  - $E_T^{miss} < 30$ GeV

Distribution of subleading muon $p_T$ in control region

<table>
<thead>
<tr>
<th></th>
<th>Total bkg</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$35.76 \pm 3.71$</td>
<td>$57.00 \pm 7.55$</td>
</tr>
</tbody>
</table>

Event yields in control region

SF $= 1.77 \pm 0.36$
Systematic uncertainty (1)

- **Experimental uncertainties**
  - Object reconstruction
    - Muon
    - Electron
    - Jet
    - MET
    - Pileup and Luminosity
  - Data driven background estimation uncertainties
    - Charge flip uncertainty
    - Non-prompt uncertainty
    - Photon mis-identified uncertainty

- Largest sources of experimental uncertainty is
  - Uncertainty from jet

<table>
<thead>
<tr>
<th></th>
<th>ee % Yield</th>
<th>$e\mu$ % Yield</th>
<th>$\mu\mu$ % Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet-related Uncertainties</td>
<td>2.28</td>
<td>2.22</td>
<td>2.28</td>
</tr>
<tr>
<td>$b$-tagging efficiency</td>
<td>1.81</td>
<td>1.76</td>
<td>1.74</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.48</td>
<td>0.97</td>
<td>2.42</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.02</td>
<td>0.08</td>
<td>0.47</td>
</tr>
<tr>
<td>Lepton reconstruction and identification</td>
<td>1.45</td>
<td>1.14</td>
<td>1.83</td>
</tr>
<tr>
<td>MET reconstruction</td>
<td>0.26</td>
<td>0.17</td>
<td>0.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ee % Yield</th>
<th>$e\mu$ % Yield</th>
<th>$\mu\mu$ % Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet-related Uncertainties</td>
<td>9.58</td>
<td>5.03</td>
<td>8.45</td>
</tr>
<tr>
<td>$b$-tagging efficiency</td>
<td>2.49</td>
<td>2.23</td>
<td>2.40</td>
</tr>
<tr>
<td>Pile-up</td>
<td>2.99</td>
<td>3.49</td>
<td>3.33</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.03</td>
<td>0.09</td>
<td>0.43</td>
</tr>
<tr>
<td>Lepton reconstruction and identification</td>
<td>1.52</td>
<td>1.24</td>
<td>3.07</td>
</tr>
<tr>
<td>MET reconstruction</td>
<td>0.93</td>
<td>0.79</td>
<td>1.63</td>
</tr>
</tbody>
</table>
Systematic uncertainty (2)

- Theoretical uncertainties
  - Scale uncertainty
  - PDF uncertainty
  - $\alpha_s$ uncertainty
  - Parton shower
  - Interference between $W^\pm W^\pm jj$ EW and QCD
    - estimated with MadGraph at LO
  - NLO EW correction

![Graph showing uncertainty from NLO EW correction for signal shape]
Event yields in signal region

- Event yields in the signal region
  - backgrounds from $V\gamma$ and electron charge mis-identification are combined in the “$e/\gamma$ conversion” category
  - all source of systematic uncertainties are included

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^+$</th>
<th>$e^-e^-$</th>
<th>$e^+\mu^+$</th>
<th>$e^-\mu^-$</th>
<th>$\mu^+\mu^+$</th>
<th>$\mu^-\mu^-$</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WZ$</td>
<td>$1.7 \pm 0.6$</td>
<td>$1.2 \pm 0.4$</td>
<td>$13 \pm 4$</td>
<td>$8.1 \pm 2.5$</td>
<td>$5.0 \pm 1.6$</td>
<td>$3.3 \pm 1.1$</td>
<td>$32 \pm 9$</td>
</tr>
<tr>
<td>Non-prompt</td>
<td>$4.1 \pm 2.4$</td>
<td>$2.3 \pm 1.8$</td>
<td>$9 \pm 6$</td>
<td>$6 \pm 4$</td>
<td>$0.57 \pm 0.16$</td>
<td>$0.67 \pm 0.26$</td>
<td>$23 \pm 12$</td>
</tr>
<tr>
<td>$e/\gamma$</td>
<td>$1.74 \pm 0.31$</td>
<td>$1.8 \pm 0.4$</td>
<td>$6.1 \pm 2.4$</td>
<td>$3.7 \pm 1.0$</td>
<td>-</td>
<td>-</td>
<td>$13.4 \pm 3.5$</td>
</tr>
<tr>
<td>Other prompt</td>
<td>$0.17 \pm 0.06$</td>
<td>$0.14 \pm 0.05$</td>
<td>$0.90 \pm 0.24$</td>
<td>$0.60 \pm 0.25$</td>
<td>$0.36 \pm 0.12$</td>
<td>$0.19 \pm 0.07$</td>
<td>$2.4 \pm 0.5$</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$</td>
<td>$0.38 \pm 0.13$</td>
<td>$0.16 \pm 0.06$</td>
<td>$3.0 \pm 1.0$</td>
<td>$1.2 \pm 0.4$</td>
<td>$1.8 \pm 0.6$</td>
<td>$0.76 \pm 0.26$</td>
<td>$7.3 \pm 2.5$</td>
</tr>
<tr>
<td>Expected background</td>
<td>$8.1 \pm 2.4$</td>
<td>$5.6 \pm 1.9$</td>
<td>$32 \pm 7$</td>
<td>$20 \pm 5$</td>
<td>$7.7 \pm 1.7$</td>
<td>$4.9 \pm 1.1$</td>
<td>$78 \pm 15$</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$</td>
<td>$3.80 \pm 0.30$</td>
<td>$1.49 \pm 0.13$</td>
<td>$16.5 \pm 1.2$</td>
<td>$6.5 \pm 0.5$</td>
<td>$9.1 \pm 0.7$</td>
<td>$3.50 \pm 0.29$</td>
<td>$40.9 \pm 2.9$</td>
</tr>
<tr>
<td>Data</td>
<td>$10$</td>
<td>$4$</td>
<td>$44$</td>
<td>$28$</td>
<td>$25$</td>
<td>$11$</td>
<td>$122$</td>
</tr>
</tbody>
</table>
Three regions are included in the likelihood fit:

- **Signal region**: 4 $m_{jj}$ bins: [500 GeV, 700 GeV, 1000 GeV, 1500 GeV, 3000 GeV], 6 channels
- **Low $m_{jj}$ validation region**: 1 $m_{jj}$ bin: [200 GeV, 500 GeV], 6 channels
- **WZ control region**: 1 $m_{jj}$ bin: [200 GeV, 3000 GeV], 1 channel
  - Channels: $e^+e^+, e^-e^-; e^+\mu^-, e^-\mu^-; \mu^+\mu^+, \mu^-\mu^-.$

$W^\pm W^\pm jj$ EW is observed with a significance of **6.9 $\sigma$** (Expected 4.6 $\sigma$)
Cross section extraction (2)

- Fiducial region is defined to pass truth level cuts which follow closely the selections applied in the analysis.

- The observed fiducial cross section being:
  \[ \sigma_{\text{meas.}}^{\text{fid.}} = 2.91^{+0.51}_{-0.47} \text{(stat.)}^{+0.28}_{-0.29} \text{(syst.) fb} \]

- Compared to a theoretical fiducial cross-section:
  \[ \sigma_{\text{pred.}}^{\text{fid.}} = 2.01^{+0.33}_{-0.23} \text{(syst.) fb} \]

Comparison of the measured fiducial cross section with the theoretical and predicted cross section with Sherpa.
WWW production
Introduction

- **Motivation**
  - Gauge bosons self-interact with each other
    - Test the SM non-Abelian gauge structure
    - Search for new physics: aTGC/aQGC and new interactions

- **Search for WWW with two final states:**
  - $W^+ W^- W^+ \rightarrow l^\pm \nu l^\pm \nu jj$
    - Significantly reduces background from the SM processes including Drell-Yan, diboson, and $t \bar{t}$
    - High branching ratio
    - The channel I participated in, and will focus on this channel

  - $W^\pm W^\pm W^\mp \rightarrow l^\pm \nu l^\pm \nu l^\mp \nu$
    - Studied by other colleagues
Data/MC samples and Object selections

- **Data samples**
  - $L = 79.8 \text{ fb}^{-1}$ (recorded in 2015, 2016 and 2017 at $\sqrt{s} = 13 \text{ TeV}$)

- **MC samples**
  - Signal: Sherpa at next-to-leading order (NLO) accuracy in QCD
  - Background:
    - diboson and triboson (VV, VVV) : Sherpa
    - $t\bar{t} + V$ : MadGraph
    - $V\gamma$ : Sherpa

- **Object selections**

<table>
<thead>
<tr>
<th>Nominal Muon</th>
<th>Nominal Electron</th>
<th>Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Medium</strong></td>
<td><strong>Tight LH</strong></td>
<td></td>
</tr>
<tr>
<td>$p_T &gt; 20 \text{ GeV}$</td>
<td>$p_T &gt; 20 \text{ GeV}$</td>
<td>$p_T &gt; 20 \text{ GeV},</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$</td>
<td>z_0 \times \sin \theta</td>
<td>&lt; 0.5 \text{ mm}$</td>
</tr>
<tr>
<td>$\frac{d_{ta}}{\sigma_{ta}} &lt; 3$</td>
<td>$\frac{d_{ta}}{\sigma_{ta}} &lt; 5$</td>
<td></td>
</tr>
<tr>
<td>Isolation Gradient</td>
<td>Author = 1</td>
<td></td>
</tr>
<tr>
<td>Prompt Lepton Tagger $&lt; -0.5$</td>
<td>Isolation FixCutLoose</td>
<td></td>
</tr>
</tbody>
</table>

*Author: 1*
**Event selections**

### \( \ell^{\pm}\ell^{\pm}jj \) Signal Region

<table>
<thead>
<tr>
<th>Channel</th>
<th>2 same-sign leptons with ( p_T &gt; 20 ) 27 GeV</th>
<th>3rd lepton veto</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^\pm e^\pm ) channel</td>
<td>( \geq 2 ) jets with ( p_T &gt; 20 ) 30 GeV and (</td>
<td>\eta</td>
</tr>
<tr>
<td>( e^\pm \mu^\pm ) channel</td>
<td>( 40 &lt; m_{\ell\ell} &lt; 80 ) GeV</td>
<td>( 40 &lt; m_{\ell\ell} &lt; 400 ) GeV</td>
</tr>
<tr>
<td>( \mu^\pm \mu^\pm ) channel</td>
<td>( 100 &lt; m_{\ell\ell} &lt; 400 ) GeV</td>
<td>( \Delta\eta_{jj} &lt; 1.5 )</td>
</tr>
<tr>
<td></td>
<td>( m_{jj} &lt; 300 ) GeV</td>
<td>( E_T^{miss} &gt; 55 ) GeV</td>
</tr>
</tbody>
</table>

- Get rid of WZ process
- Get rid of background from top process
- Z veto in ee channel to suppress charge flip background
- Mll<400 to remove WZ process
- Veto VBS events
- Get rid of residual Z bosons
Charge flip background estimation

- The method is the same as VBS analysis
- Charge mis-identification rate is estimated with $Z \rightarrow ee$ events
- Validate the method in a validation region
  - Dilepton invariant mass is required to be inside the $Z$ mass window
  - Other cuts are the same as the signal region

Distribution of leading lepton $p_T$, subleading lepton $p_T$ and $m_{ll}$ in ee channel in validation region
Non-prompt background estimation

- The method is the same as VBS analysis
- But fake factor is estimated in $t\bar{t}$ control region
  - defined with the same as the signal region selection but $N_{b\text{-jet}} = 1$
  - Non-prompt component is nearly identical with signal region
- The inclusive fake factors are estimated
  - Muon fake factor is: 0.035 ± 0.005; Electron fake factor is: 0.017 ± 0.010

Distribution of leading lepton $p_T$ in ee, $e\mu$ and $\mu\mu$ channel in $t\bar{t}$ control region
Electrons resulting from photon conversions tend to have no B-Layer hits, referred to as “NoBL electrons”.

$V\gamma$ background is estimated with data driven method:

- $\epsilon$, photon mis-ID rate is measured using a $Z\gamma$ control region in $\mu^+\mu^-e^\pm$ channel
- Weight nominal+NoBL events with the rate

$$N_{bkg}^{V\gamma} = N_{\text{nominal+NoBL}} \cdot \epsilon$$

$$\epsilon = \frac{N_{\text{nominal}}}{N_{\text{NoBL}}}$$

Estimated $V\gamma$ background in $Z\gamma$ control region
Validate the overall estimated background in a validation region

- $M_{jj} < 50$ GeV or $120 < M_{jj} < 300$ GeV
- Other cuts are the same as the signal region
Events yields

- Event yields in the full $m_{jj}$ region
  - backgrounds from $V\gamma$ and electron charge mis-identification are combined in the “$\gamma$ conversion” category.
  - statistical and systematic uncertainties are shown

<table>
<thead>
<tr>
<th></th>
<th>$e^\pm e^\pm jj$</th>
<th>$e^\pm \mu^\pm jj$</th>
<th>$\mu^\pm e^\pm jj$</th>
<th>$\mu^\pm \mu^\pm jj$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWW</td>
<td>10.57 ± 3.28</td>
<td>27.9424 ± 8.62</td>
<td>24.92 ± 7.68</td>
<td>32.00 ± 9.84</td>
</tr>
<tr>
<td>WZ</td>
<td>37.65 ± 2.25</td>
<td>121.693 ± 5.81</td>
<td>96.70 ± 4.98</td>
<td>120.10 ± 6.16</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.46 ± 0.051</td>
<td>5.13 ± 0.25</td>
<td>3.45 ± 0.18</td>
<td>4.13 ± 0.24</td>
</tr>
<tr>
<td>Non-prompt</td>
<td>6.15 ± 2.98</td>
<td>35.40 ± 4.95</td>
<td>17.41 ± 8.70</td>
<td>37.14 ± 6.61</td>
</tr>
<tr>
<td>$\gamma$ conv.</td>
<td>21.00 ± 1.95</td>
<td>35.13 ± 3.12</td>
<td>76.44 ± 6.73</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>Others</td>
<td>11.31 ± 0.96</td>
<td>22.33 ± 1.59</td>
<td>17.26 ± 1.23</td>
<td>21.45 ± 1.47</td>
</tr>
<tr>
<td>data</td>
<td>87</td>
<td>239</td>
<td>235</td>
<td>237</td>
</tr>
</tbody>
</table>
Signal extraction

Three regions are included in the fit:

- **Signal region:**
  - 7 $m_{jj}$ bins: range from 50 to 120 GeV in steps of 10 GeV
  - 3 channels: $e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm$

- **Side Band validation region:**
  - 23 $m_{jj}$ bin: range from 0 to 50 GeV and 120 to 300 GeV in steps of 10 GeV
  - 3 channels: $e^\pm e^\pm, e^\pm \mu^\pm, \mu^\pm \mu^\pm$

- **WZ control region:**
  - 5 $m_{lll}$ bin: range from 110 to 610 GeV in steps of 100 GeV,
  - 4 channel: $eee, ee\mu, e\mu\mu, \mu\mu\mu$

Observed significance of $WWW$ production is $4.3\sigma$ (expected $1.7\sigma$) in $W^\pm W^\pm W^{\mp} \rightarrow l^\pm v l^\pm v jj$ channel

After combining with $W^\pm W^\pm W^{\mp} \rightarrow l^\pm v l^\pm v l^{\mp} v$, the observed significance is $3.3\sigma$ ($2.4\sigma$)
The electroweak physics is a sector of great interest in the SM. Two electroweak physics processes with the same final state $l^\pm v l^\pm v jj$ are studied:

- $W^\pm W^\pm jj \rightarrow l^\pm v l^\pm v jj$
- $W^\pm W^\pm W^\mp \rightarrow l^\pm v l^\pm v jj$

First observation of $W^\pm W^\pm jj$ electroweak production at the ATLAS experiment with a significance of 6.9 standard deviations:

- My main contribution: non-prompt background estimation

First evidence of $W^\pm W^\pm W^\mp$ production with a significance of 3.3 standard deviations:

- My main contribution: non-prompt background estimation and theoretical uncertainty calculation

Two analyses are statistically limited. With more collision data recorded from the LHC, these two rare electroweak processes can be studied more accurately.
Publications and Conferences

- **Publications:**
  -Observation of electroweak production of a same-sign WW boson pair in association with two jets in pp collisions at 13 TeV with the ATLAS detector. ATLAS-CONF-2018-030 (paper is in ATLAS review and will be submitted to PRL soon)
  -Evidence for the production of three massive vector bosons with the ATLAS detector. arXiv:1903.10415 (submitted to PLB)

- **Conferences:**
  -LP2017, The 28th International Symposium on Lepton Photon Interactions at High Energies
    -Poster, *Muon identification and performance in the ATLAS experiment*
  -HEPMAD18, 10th High-Energy Physics International Conference
    -Plenary talk, *Studying the Electroweak Sector with the ATLAS Detector*
  -CLHCP2018, The 4th China LHC Physics Workshop
    -Parallel talk, *Observation of electroweak production of a same-sign W boson pair*
Thanks to my supervisors!

Thanks to the committee members!
Backup
Same sign WW VBS
Without the SM Higgs, $\sigma_{\gamma\gamma \rightarrow \gamma\gamma}$ increases as center-of mass energy and violates unitarity at high energy.

- Can be solved by adding the Standard Model Higgs.

- VBS diagrams are not gauge invariant. To ensure gauge invariance, non-VBS processes with the same final state must be included in the analysis.

- Diagrams with the same final state categorized into two main groups:
  - **$VVjj$-EW**: only EWK vertices, $O(\alpha_{EW}^6)$
    
    ![Diagram](image)
  
  - **$VVjj$-QCD**: both Strong and EWK vertices, $O(\alpha_{EW}^4 \alpha_S^2)$
    
    ![Diagram](image)
Charge flip (1)

- Z → ee control region
  
  \[ p_T^{ele} > 20 \text{ GeV} \]
  \[ |\eta| < 1.37 \text{ and } 1.52 \leq |\eta| \leq 2.5 \]

  \[ \text{Author} = 1 \]
  \[ |d_0/\sigma_{d_0}| < 3 \]
  \[ |z_0 \times \sin \theta| < 0.5 \text{ mm} \]
  \[ N_{ele} = 2 \]
  \[ 75 < m_{ee} < 105 \text{ GeV} \]

- No-Z background is subtracted using sideband method (60 < M_{ll} < 75 GeV and 105 < M_{ll} < 120 GeV)

- Taking into account that either electron in the pair could be the mis-identified one

- A likelihood fit is used to measure the charge flip rate
  
  - Given the charge flip rate \( \epsilon_i \) and \( \epsilon_j \) for two electrons, the probability of observing same-signed \( ee \) event is a Poisson distribution

  \[
P(N_{SS}^{obs} | N_{SS}^{exp}) = \frac{e^{-N_{SS}^{exp}} \cdot (N_{SS}^{exp})^{N_{SS}^{obs}}}{N_{SS}^{obs}!}
\]

  \[
  N_{SS}^{exp} = N_{SS}^{obs} \{ (1 - \epsilon_i) \epsilon_j + (1 - \epsilon_j) \epsilon_i \}
\]

- The likelihood function is defined

  \[
  \mathcal{L} (\vec{\epsilon}) = \prod_i \prod_j P(N_{SS,ij}^{obs} | \epsilon_i, \epsilon_j, N_{SS+OS,ij}^{obs})
\]

- Minimize the negative log likelihood to extract the charge flip rate
The detector material that lead to charge mis-ID are usually not well modelled in MC
MC needs to be corrected with scale factors so that the charge mis-ID probability in MC is the same as the one measured in data.

\[ SF = \frac{\varepsilon_{\text{data}}}{\varepsilon_{\text{MC}}} \]

Energy correction
- Electrons with a wrongly reconstructed charge are on average reconstructed with a lower energy than 788 electrons reconstructed with the correct charge
- The $Z \rightarrow ee$ simulation sample is used to study the average loss of energy

\[ p_{T}^{\text{corrected}} = \frac{p_{T}^{\text{original}}}{1 + \alpha} + dE \]

\[ 1 + \alpha = \frac{\langle p_{T}^{\text{reco}}/p_{T}^{\text{truth}} \rangle_{\text{correct}}}{\langle p_{T}^{\text{reco}}/p_{T}^{\text{truth}} \rangle_{\text{wrong}}} \]

\[ c = \langle p_{T}^{\text{reco}}/p_{T}^{\text{truth}} \rangle_{\text{wrong}} - \langle p_{T}^{\text{reco}}/p_{T}^{\text{truth}} \rangle_{\text{correct}} \]
Charge flip (3)

- Systematic uncertainties:
  - Variation of Z mass window selection
  - Switching on and off the background subtraction
  - Closure test in MC
  - Bias from requiring one/two electron to fire the trigger
  - Switching on and off the energy loss correction

<table>
<thead>
<tr>
<th>Signal region</th>
<th>$e^+e^+$</th>
<th>$e^-e^-$</th>
<th>$e^+\mu^+$</th>
<th>$e^-\mu^-$</th>
<th>$\mu^+e^+$</th>
<th>$\mu^-e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge mis-ID bkg. (+ stat.)</td>
<td>1.33 ± 0.08</td>
<td>1.17 ± 0.08</td>
<td>2.36 ± 0.28</td>
<td>1.85 ± 0.21</td>
<td>1.11 ± 0.14</td>
<td>1.10 ± 0.15</td>
</tr>
<tr>
<td>SF up-variation</td>
<td>+0.13</td>
<td>+0.10</td>
<td>+0.08</td>
<td>+0.06</td>
<td>+0.03</td>
<td>+0.03</td>
</tr>
<tr>
<td>SF down-variation</td>
<td>−0.10</td>
<td>−0.10</td>
<td>+0.03</td>
<td>−0.04</td>
<td>−0.02</td>
<td>−0.02</td>
</tr>
<tr>
<td>Energy correction</td>
<td>±0.05</td>
<td>±0.03</td>
<td>±0.20</td>
<td>±0.18</td>
<td>±0.01</td>
<td>±0.01</td>
</tr>
</tbody>
</table>

Systematic variations of charge flip background
Non-prompt (1)

- Dijet event selections and Loose lepton definition

<table>
<thead>
<tr>
<th>Di-jet event selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{lepton} = 1$ and $p_T^{lepton} &gt; 15$ GeV</td>
</tr>
<tr>
<td>$N_{jet} &gt; 0$</td>
</tr>
<tr>
<td>Tagging jet is $b$-jet</td>
</tr>
<tr>
<td>$p_T^{tagging~jet} &gt; 25(30)$ GeV</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$m_T + E_{T,track}^{miss} &lt; 50$ GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loose muon</th>
<th>Loose electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>d_0/\sigma_{d_0}</td>
</tr>
<tr>
<td>$</td>
<td>z_0 \times \sin \theta</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>fail nominal muon</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>d_0/\sigma_{d_0}</td>
</tr>
<tr>
<td>$</td>
<td>z_0 \times \sin \theta</td>
</tr>
<tr>
<td>MediumLH and Author = 1</td>
<td></td>
</tr>
<tr>
<td>fail nominal electron</td>
<td></td>
</tr>
</tbody>
</table>

- Contamination of prompt leptons from $W+jets$, $Z+jets$, $t\bar{t}$ and single top processes are estimated using MC simulation and subtracted from dijet data sample
Non-prompt (2)

- $p_T$ for nominal lepton and $p_T + p_T^{\text{varcone30}}$ for loose lepton

- The black marker points represent observed data.
- The solid stack histograms are prompt MC backgrounds.
- The blue marker points represent observed data with prompt MC backgrounds subtracted.
Non-prompt (3)

- Systematic uncertainties:
  - Variation of di-jet event selections:
    - Tagging jet $p_T + 5$ GeV
    - $m_T + E_{T,\text{mis}}$ $\pm 5$ GeV
    - $\Delta \Phi(j, l)$ $\pm 0.1$
  - Prompt lepton subtraction: vary normalization correction by $\sim 10\%$
  - Jet flavor composition: without requiring the tagging jet to be a $b$-jet
  - Residual dependence on the jet $p_T$ spectrum: test with tag-jet $p_T$ reweighting
Non-prompt (4)

- Component of nominal+loose events:
  - The observed data is compared to background predictions obtained with MC simulation.
  - The dominant background process is the $t\bar{t}$, followed by $W+jets$ and $Z+jets$ processes.

⇒ the $m_{jj}$ distribution in this nominal+loose region after the $b$-jet veto cut

⇒ the $\Delta Y_{jj}$ distribution in this nominal+loose region after the $m_{jj} > 500$ GeV cut
The charge flip background in nominal+loose region is estimated with Data, it's then subtracted. The charge mis-identification rate for loose electron is calculated in $Z \rightarrow e^+e^-$ events using “tag&probe” method:

- Tag electron is nominal
- Charge mis-identification rate is calculated for probe, assuming it underwent the charge mis-identification

\[ \varepsilon = \frac{N_{\text{wrong charge loose electrons}}}{N_{\text{all loose electrons}}} \]

- Validated modeling in SS nominal+loose validation region
- Assigned systematic uncertainty of 10%

<table>
<thead>
<tr>
<th>charge flip</th>
<th>MC processes</th>
<th>data</th>
<th>data/predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>820.58</td>
<td>5.28</td>
<td>740.00</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Non-prompt (6)

- Studies with $p_T + p_{T^{\text{Varcone30}}}$ denominator in dijet MC and $t\bar{t}$ MC

- Estimate the remaining dependence on the underlying jet $p_T$ spectrum by reweighting the tag jet $p_T$ spectrum.

- The underlying jet $p_T$ spectrum in nominal+loose region was obtained from truth using MC simulation ($t\bar{t}, W + jets$)
  - Jet $p_T$ spectrum for b-jets which could fake leptons
  - The ratio of data to the combined MC results shown below is the weight applied to the tag jet distribution

- The tagging jet $p_T$ spectrum from the dijet data sample and the $t\bar{t}, W + jets$ $p_T$ distributions for b-jets which could fake leptons
Non-prompt (7)

- **Trigger correction:**
  - The fake factor method requires the ID lepton to trigger.
  - To account for the effect of the trigger, the estimated fake background is corrected for inefficiencies.
  - Event weight calculated as:
    \[
    w = \frac{1 - (1 - \epsilon_{\text{nominal}})(1 - \epsilon_{\text{loose}})}{\epsilon_{\text{nominal}}}
    \]
    
    - \(\epsilon_{\text{nominal}}\): trigger efficiency of the nominal lepton.
    - \(\epsilon_{\text{loose}}\): trigger efficiency of the loose lepton.
    
  - This increases the estimated fake yield by 20%.
  - Predicted yields in signal region:

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>(e\mu + \mu e)</th>
<th>(\mu\mu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/o trigger corr.</td>
<td>6.33 ± 2.30</td>
<td>15.69 ± 3.54</td>
<td>1.22 ± 0.22</td>
</tr>
<tr>
<td>w/ trigger corr.</td>
<td>6.55 ± 2.35</td>
<td>19.78 ± 4.67</td>
<td>1.54 ± 0.29</td>
</tr>
</tbody>
</table>
Full next-to-leading order corrections of the order $O(\alpha_{EW}^7)$ to the $W^\pm W^\pm jj$ EW are calculated in at parton level

- The LO and NLO $m_{jj}$ distributions at parton level are provided
- The ratio shows the NLO EW corrections
- It’s applied as a systematic uncertainty to the $W^\pm W^\pm jj$ EW signal sample in the fit

Comparison NLO and LO differential cross sections
Interference between $W^\pm W^\pm jj$ EW and QCD

- The distribution of invariant mass of two jets in signal region is compared
  - only the interference between EW and QCD using MadGraph
  - Combined $W^\pm W^\pm jj$ sample with EW productions, QCD productions and their interference effects
  - separated samples of QCD
  - separated samples of electroweak

- The bottom panel represents the ratio of interference to EW only (red), and interference to QCD only (blue)

- The interference effect in signal region is found to be $\approx 6\%$, it’s treated as an additional systematic uncertainty
Cross section extraction

- The likelihood method:
  - Simultaneously fit with more than one unknown parameters:
    - parameter of interest ($\mu$)
    - nuisance parameter ($\theta$)
  - Split into signal region (SR), control region (CR) and/or validation region (VR)
  - Each region has multiple bins of observables
- Build a global likelihood function for all the bins, including all the parameters

$$L(\mu, \theta) = Pois_{SR} \times Pois_{CR/VR} \times Gaus(\theta)$$

- Test statistic is defined as the profile likelihood ratio:

$$q_\mu = -2ln\lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}$$

- The compatibility of the observed data with the background-only hypothesis ($\mu = 0$) is calculated

$$p_0 = \int_{q_{0,obs}}^{\infty} f(q_0 | 0) d q_0$$

- From $p$-value get equivalent significance:

$$Z = \Phi^{-1}(1 - p_0)$$
Fiducial signal region

- Two prompt leptons ($e$ or $\mu$) with $p_T > 27$ GeV and $|\eta| < 2.5$;
- The two leptons must have same sign electric charge and have the invariant mass $m_{ll} \geq 20$ GeV;
- The two leptons must satisfy $\Delta R(ll) > 0.3$;
- The transverse momentum of the neutrino system must satisfy $p_T^{\nu} > 30$ GeV;
- At least two jets with $p_T > 65$ GeV for the leading, $p_T > 35$ for any sub-leading jet and $|\eta| < 4.5$, reconstructed with the anti-$kt$ algorithm with radius parameter $R = 0.4$;
- Minimum $\Delta R$ between selected leptons and jets must be $\min(\Delta R(l, j)) > 0.3$;
- The invariant mass of the two highest $p_T$ jets must be $m_{jj} > 500$ GeV;
- The separation in rapidity between the two highest $p_T$ jets has to be $\Delta Y(j, j) > 2.0$. Jets are obtained clustering all particles but neutrinos, prompt leptons, and prompt photons. Events where any of the selected leptons originate from a $\tau$ decay are not included in the acceptance calculation.
Signal extraction (1)
Signal extraction (2)
## Signal extraction (3)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Nuisance parameter</th>
<th>$\theta$</th>
<th>$\Delta \theta$</th>
<th>$\mu_{PF}^\text{up} - \bar{\mu}$</th>
<th>$\mu_{FF}^\text{down} - \bar{\mu}$</th>
<th>$\mu_{PF}^\text{up} - \bar{\mu}$</th>
<th>$\mu_{FF}^\text{down} - \bar{\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>signal_EW6_TheoShower</td>
<td>-0.0092</td>
<td>-1.4460</td>
<td>+1.0102</td>
<td>0.0007</td>
<td>-0.0802</td>
<td>0.0007</td>
</tr>
<tr>
<td>2</td>
<td>FakeElSys</td>
<td>-0.7632</td>
<td>-1.4482</td>
<td>+0.5850</td>
<td>-0.0501</td>
<td>0.0465</td>
<td>-0.0685</td>
</tr>
<tr>
<td>3</td>
<td>FakeMuSys</td>
<td>-0.1373</td>
<td>-1.4437</td>
<td>+0.6767</td>
<td>-0.0472</td>
<td>0.0064</td>
<td>-0.0733</td>
</tr>
<tr>
<td>4</td>
<td>signal_EW4_TheoScale</td>
<td>-0.0459</td>
<td>-1.4454</td>
<td>+0.9672</td>
<td>-0.0463</td>
<td>0.0306</td>
<td>-0.0478</td>
</tr>
<tr>
<td>5</td>
<td>JET_Flav_Composition</td>
<td>0.5148</td>
<td>-1.4462</td>
<td>+0.9089</td>
<td>-0.0291</td>
<td>0.0281</td>
<td>-0.0317</td>
</tr>
<tr>
<td>6</td>
<td>FT_EFF_Eigen_Light_0</td>
<td>-0.0571</td>
<td>-1.4465</td>
<td>+0.9923</td>
<td>-0.0275</td>
<td>0.0277</td>
<td>-0.0277</td>
</tr>
<tr>
<td>7</td>
<td>signal_EW6_TheoScale</td>
<td>0.1832</td>
<td>-1.4462</td>
<td>+1.0051</td>
<td>-0.0248</td>
<td>0.0218</td>
<td>-0.0247</td>
</tr>
<tr>
<td>8</td>
<td>PRW_DATASF</td>
<td>-0.0977</td>
<td>-1.4469</td>
<td>+0.9900</td>
<td>0.0211</td>
<td>-0.0215</td>
<td>0.0213</td>
</tr>
<tr>
<td>9</td>
<td>Conv_Model_Vgamma</td>
<td>0.1514</td>
<td>-1.4462</td>
<td>+0.9605</td>
<td>-0.0190</td>
<td>0.0212</td>
<td>-0.0200</td>
</tr>
<tr>
<td>10</td>
<td>signal_EW6_TheoEWCorr</td>
<td>-0.3561</td>
<td>-1.4459</td>
<td>+0.9675</td>
<td>0.0177</td>
<td>-0.0197</td>
<td>0.0183</td>
</tr>
<tr>
<td>11</td>
<td>JET_EtaIntercalibration_Modelling</td>
<td>0.0719</td>
<td>-1.4465</td>
<td>+1.0020</td>
<td>-0.0181</td>
<td>0.0181</td>
<td>-0.0181</td>
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<tr>
<td>12</td>
<td>WZ_TheoShower</td>
<td>-0.0339</td>
<td>-1.4440</td>
<td>+0.9520</td>
<td>0.0122</td>
<td>-0.0180</td>
<td>0.0130</td>
</tr>
<tr>
<td>13</td>
<td>MUON_EFF_SYS</td>
<td>0.0368</td>
<td>-1.4463</td>
<td>+0.9921</td>
<td>-0.0160</td>
<td>0.0166</td>
<td>-0.0162</td>
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<tr>
<td>14</td>
<td>TheoInterference</td>
<td>-0.1806</td>
<td>-1.4463</td>
<td>+0.9990</td>
<td>0.0130</td>
<td>-0.0165</td>
<td>0.0130</td>
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<tr>
<td>15</td>
<td>signal_EW4_TheoShower</td>
<td>-0.0190</td>
<td>-1.4467</td>
<td>+0.9246</td>
<td>-0.0122</td>
<td>0.0144</td>
<td>-0.0132</td>
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<tr>
<td>16</td>
<td>JET_Pileup_PtTerm</td>
<td>0.0860</td>
<td>-1.4465</td>
<td>+1.0086</td>
<td>-0.0096</td>
<td>0.0141</td>
<td>-0.0095</td>
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<tr>
<td>17</td>
<td>FakeMuSta</td>
<td>-0.0033</td>
<td>-1.4473</td>
<td>+0.9855</td>
<td>-0.0130</td>
<td>0.0085</td>
<td>-0.0131</td>
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<tr>
<td>18</td>
<td>WZ_TheoScale</td>
<td>-0.0589</td>
<td>-1.4443</td>
<td>+0.9998</td>
<td>0.0120</td>
<td>-0.0120</td>
<td>0.0120</td>
</tr>
<tr>
<td>19</td>
<td>Wgamma_XS</td>
<td>0.0572</td>
<td>-1.4466</td>
<td>+0.9863</td>
<td>-0.0107</td>
<td>0.0111</td>
<td>-0.0109</td>
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<tr>
<td>20</td>
<td>JET_JER_SINGLE_NP</td>
<td>-0.7122</td>
<td>-1.4474</td>
<td>+0.8170</td>
<td>0.0075</td>
<td>-0.0109</td>
<td>0.0076</td>
</tr>
</tbody>
</table>
Signal extraction (3)

<table>
<thead>
<tr>
<th>Nuisance Parameter</th>
<th>Figure</th>
<th>Direction of Pull</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF_NoCorr</td>
<td>83</td>
<td>Down</td>
<td>Increase background yield in high $m_{jj}$ bins</td>
</tr>
<tr>
<td>CF_SFunc</td>
<td>84</td>
<td>Down</td>
<td>Decrease background yield in low $m_{jj}$ bins, counteract increase in event yields due to CF_NoCorr in low $m_{jj}$ bins</td>
</tr>
<tr>
<td>Conv_Model_Vgamma</td>
<td>85</td>
<td>Up</td>
<td>Increase background yield in 1st and 3rd $m_{jj}$ bin. For reasons of lacking MC statistics, the $Z\gamma$ has a dip in the 2nd bin, which coincides with the underfluctuation in data</td>
</tr>
<tr>
<td>FakeElSys</td>
<td>86</td>
<td>Down</td>
<td>Decrease non-prompt yield in low $m_{jj}$ bins in channels containing electrons</td>
</tr>
<tr>
<td>FakeMuSys</td>
<td>87</td>
<td>Down</td>
<td>Decrease non-prompt yield in low $m_{jj}$ bins in channels containing muons</td>
</tr>
<tr>
<td>JET_EffectiveNP_2</td>
<td>88</td>
<td>Up</td>
<td>Very slightly increase total event yield in highest $m_{jj}$ bin</td>
</tr>
<tr>
<td>JET_Flavor_Composition</td>
<td>89</td>
<td>Up</td>
<td>Increase background yield in high $m_{jj}$ bins</td>
</tr>
<tr>
<td>JET_JER_SINGLE_NP</td>
<td>90</td>
<td>Down</td>
<td>Decrease event yield in 2nd $m_{jj}$ bin in signal region</td>
</tr>
<tr>
<td>TheoInterference</td>
<td>92</td>
<td>Down</td>
<td>Decrease (increase) signal yield in low (high) $m_{jj}$ bins</td>
</tr>
<tr>
<td>signal_EW6_TheoEWCorr</td>
<td>91</td>
<td>Down</td>
<td>Increase signal yield in high $m_{jj}$ bins</td>
</tr>
<tr>
<td>signal_EW6_TheoScale</td>
<td>93</td>
<td>Up</td>
<td>Increase signal yield in high $m_{jj}$ bins</td>
</tr>
</tbody>
</table>
WWW production
Full $M_{jj}$ region - $M_{ll}$
Non-prompt (1)

- $t\bar{t}$-enriched region selections and Loose lepton definition

<table>
<thead>
<tr>
<th>$t\bar{t}$-enriched region selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exactly two same-sign leptons</td>
</tr>
<tr>
<td>At least two jets with $p_T &gt; (20)$ 30 GeV and $</td>
</tr>
<tr>
<td>Exactly one $b$-tagged jet in the event</td>
</tr>
<tr>
<td>$40$ GeV $&lt; m_{\ell\ell} &lt; 400$ GeV</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$m_{jj} &lt; 300$ GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 55$ GeV in $ee$ channel</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loose Muon</th>
<th>Loose Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Medium}$</td>
<td>$\text{MediumLH}$ and Author = 1</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$</td>
<td>z_0 \times \sin\theta</td>
</tr>
<tr>
<td>$\frac{d_0}{\sigma_{d_0}} &lt; 10$</td>
<td>$\frac{d_0}{\sigma_{d_0}} &lt; 5$</td>
</tr>
<tr>
<td>fail nominal muon</td>
<td>fail nominal electron</td>
</tr>
</tbody>
</table>

- Contamination of $ttV$, $WZ$, and $ZZ$ processes are estimated using MC simulation and subtracted from data $t\bar{t}$-enriched sample
Non-prompt (2)

- As it is ambiguous in which lepton is the non-prompt lepton and which lepton is the real prompt leptons, a likelihood fit procedure is performed.

- The probability of observing a $l^\pm l^\pm$ event where one of the lepton is a non-prompt is given by the Poisson distribution:

$$P(N_{\text{nom}+\text{nom}}^{\text{exp}}, N_{\text{nom}+\text{nom}}^{\text{obs}} | f, N_{\text{nom}+\text{nom}}^{\text{exp}}) = \frac{e^{-N_{\text{nom}+\text{nom}}^{\text{exp}}} \cdot (N_{\text{nom}+\text{nom}}^{\text{exp}})^{N_{\text{nom}+\text{nom}}^{\text{obs}}}}{N_{\text{nom}+\text{nom}}^{\text{obs}}!}$$

$$N_{i_{\text{nom}+\text{nom}}}^{\text{exp}} = N_{i_{\text{nom}+\text{nom}}}^{\text{obs}} \cdot f_j + N_{i_{\text{loose}+\text{nom}}}^{\text{obs}} \cdot f_i$$

- determine the electron fake factor by minimizing the likelihood function:

$$L(f_i, f_j) = \prod_i \prod_j P(N_{i_{\text{nom}+\text{nom}}}^{\text{obs}} | f_i, f_j, N_{i_{\text{nom}+\text{nom}}}^{\text{obs}}, N_{i_{\text{loose}+\text{nom}}}^{\text{obs}})$$
Non-prompt (3)

- Distributions of leading lepton $p_T$ in the $ee$ (top left), $e\mu$ (top right), $\mu e$ (bottom left) and $\mu\mu$ (bottom right) channels in the $t\bar{t}$-enriched region.

- the event level shapes are well-predicted.
- important test of the assumption that using events with loose leptons to predict events with nominal leptons is reasonable
Non-prompt (4)

- Component of nominal+loose events:
  - The observed data is compared to background predictions obtained with MC simulation.
  - The dominant background process is the $t\bar{t}$, followed by $W+jets$ and $Z+jets$ processes.
  - dominated by $t\bar{t}$ and $W+$ b/c jet events
  - non-prompt lepton mainly due to heavy flavor decay
Non-prompt (5)

- $t\bar{t}$ MC Validation:
  - Fake factor is the same whether zero or one b-tags are reconstructed
  - $t\bar{t}$ kinematics have the same shapes whether one lepton is ID or anti-ID.

Fake factors derived from $t\bar{t}$ MC for muons (left) and electrons (right) in the b-tagged CR and in the signal region (0b). No statistically significant difference is observed for muons. One bin of the electron non-prompt factors is discrepant at 2–3σ, but since the factors are consistent in the bins to the left and right of this particular bin, we are led to believe this discrepancy is a fluctuation.

$t\bar{t}$ ID/ID/anti-ID events are scaled with the MC non-prompt factor and compared with ID+ID+ID. No statistically significant differences are observed.
Photon mis-reconstructed as an electron rate is measured using a 3 lepton $Z\gamma$ control region
- One pair of same-flavor, opposite-sign signal muons
- A third electron can either be a signal electron or a "photon-like" electron
- $80 < M_{\ell\ell\ell} < 100$ GeV

- the extrapolation of measuring a photon mis-identification rate in $Z\gamma$ events, and applying this in a region enriched in $W\gamma$
  - measure a photon mis-identification rate in $W\gamma$ MC and comparing it to the rate in $Z\gamma$ MC

Distribution of $m_{\ell\ell\ell}$ for ID+ID+ID (left) and ID+ID+NoBL (right) in $Z\gamma$ control region. Background predictions are obtained with MC simulation
WZ control region - $M_{\ell\ell}$
Side Band validation region

Distribution of $m_{jj}$

Distribution of MET
Signal extraction (1)
Signal extraction (2)

Fig. 6.13  Likelihood scan of the expected $\mu$ value.
Signal extraction (3)