Search for heavy neutral resonances in vector boson fusion in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC

PhD thesis defense

Guangyi Zhang$^{1,2}$

Supervisor: Liang Han$^1$, Suen Hou$^2$

$^1$University of Science and Technology of China
$^2$Institute of Physics, Academia Sinica

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Outline

- **Introduction**
  - Standard model
  - Vector boson fusion
  - LHC and ATLAS detector

- **Physics analyses**
  - Search for new resonances (R) in $qq \rightarrow Rqq \rightarrow \ell^+\nu\ell^-\bar{\nu}qq$ ($\ell = e, \mu$) using 3.2 fb$^{-1}$ data collected in 2015
  - Search for new resonances (X) in $qq \rightarrow Xqq \rightarrow WWqq \rightarrow e\nu\mu\nu qq$ using 36.1 fb$^{-1}$ data collected in full 2015 and 2016

- **Summary**
Introduction
Standard Model

- Standard Model (SM)
  - Most successful and well-tested theory
    - describing the elementary particles and their interactions
  - Elementary particles:
    - leptons, quarks (spin-½ fermions) => constituents of matter
    - gauge bosons (W/Z, γ, g), spin-1 => force mediators
    - Higgs boson, spin-0 => origin of mass
  - Fundamental forces:
    - electromagnetic, weak, strong forces
    - gravitation not described in the SM
  - Origin of mass:
    - Higgs Mechanism, EWSB
    - particles acquire mass via interactions with Higgs field (υ ≠ 0)
Vector boson fusion

- In the SM, vector boson fusion (VBF) is an important class of processes
  - provide a unique means to directly examine the EWSB mechanism

\[ M_{gauge} = -\frac{g^2}{4m_W^2} u + \mathcal{O}\left(\frac{E}{m_W}\right)^0, \quad \text{unitarity violated} \]

W^+W^- scattering/fusion without a SM Higgs

\[ M_{Higgs} = -\frac{g^2}{4m_W^2} \left[ \left( s - m_W^2 \right)^2 + \left( t - m_W^2 \right)^2 \right] \approx \frac{g^2}{4m_W^2} u, \quad \text{unitarity restored} \]

W^+W^- scattering/fusion with a SM Higgs
Vector boson fusion

- VBF is very sensitive to phenomena beyond the SM
  - Unknown issues about Higgs boson discovered at the LHC:
    - fully or only partially unitarizes the VBF amplitude?
    - is the coupling $H\rightarrow VV$ exactly the one that SM predicted?
      (low measurement precision $\sim 20\%$)

- New resonance needed:
  - Higgs partially unitarizes the VBF amplitude $\Rightarrow$ new resonances
  - Any non-SM HVV coupling $\Rightarrow$ new physics
  - If new resonance has no/weak coupling to fermions
    $\Rightarrow$ VBF is a leading search channel
Vector boson fusion

- Characteristics of VBF

  - Relatively small production cross sections
    => Experimental studies of VBF are feasible only at the LHC so far
  - Fully-leptonic channels have lower SM background
    => Considered in the analyses
  - VBF event topology at the LHC

- VBF signal characteristics:
  - Large $m_{jj}$ (>500 GeV)
  - Large $\Delta\eta_{ij}$ (>2.4)

- Two charged leptons (ee, $\mu\mu$, $e\mu$), $E_T^{miss}$, two forward jets (tagging jets)
Large Hadron Collider (LHC)

- World’s largest and most powerful particle accelerator
- **Purpose:** Higgs boson, new physics (eg. dark matter), etc.
- **Two separate rings:** 26.7 km, 45-175m underground
- **Four major detectors:** ATLAS, CMS, ALICE and LHCb
- **pp collisions:** $2835 \times 2835$ bunches, bunch spacing 25 ns (7.5 m), $10^{11}$ protons/bunch
- **Designed luminosity and center-of-mass energy:**
  \[ \mathcal{L} = 10^{34} \text{cm}^{-2} \text{s}^{-1}, \sqrt{s} = 13 \text{ TeV (2015-2018)}, 14 \text{ TeV (2021-2037)} \]
ATLAS detector

- ATLAS detector: a general purpose detector at the LHC

**Muon spectrometer** $(|\eta|<2.7)$
- precise tracking and triggering on muons
- precision-tracking systems: MDT, CSC
- trigger systems: RPC, TGC

**HAD calorimeter** $(|\eta|<4.9)$:
- hadronic measurements
- scintillating tiles-steel (central), LAr-Cu/tungsten (forward)

**EM calorimeter** $(|\eta|<3.2)$:
- $e/\gamma$ measurement
- LAr-Pb accordion

**Magnet system**:
- solenoid magnet (barrel), 2 T
- toroid magnets, 0.5 T (barrel), 1 T (end-cap)

**Inner detector** $(|\eta|<2.5)$:
- precise measurement of tracking and vertices
- Pixel, SCT, TRT
Search for new resonances (R) in
qq → Rqq → ℓ⁺νℓ⁻̅νqq (ℓ = e, μ)
using 3.2 fb⁻¹ data collected in 2015

- ATLAS conference note:  [ATLAS-CONF-2016-053](#)
- Proceeding paper:  [EPJ Web of Conferences 137, 08016 (2017)](#)
- My contributions: All physics analysis work
Introduction

- **Analysis goal:**
  - Search for new resonances (R) in VBF $qq \rightarrow Rqq \rightarrow \ell^+\nu\ell^-\bar{\nu}qq$ ($\ell = e, \mu$)
  - three decay channels: $ee, \mu\mu, e\mu$

- **Signal model:**
  - **Benchmark model:** EW chiral Lagrangian (EWChL) with K-matrix unitarization
  - **New resonances:** only couples to vector boson, thus mainly produced via VBF
  - **Free parameters:** coupling RVV ($g=2.5$) & mass [200, 500] GeV

<table>
<thead>
<tr>
<th>Type</th>
<th>Spin $J$</th>
<th>Isospin $I$</th>
<th>Electric Charge</th>
<th>$\Gamma/\Gamma_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>scalar</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0</td>
<td>2</td>
<td>$--$, $-$, $0$, $+$, $++$</td>
<td>1</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1</td>
<td>1</td>
<td>$-$, $0$, $+$</td>
<td>$\frac{4}{3} \left( \frac{v^2}{m^2} \right)$</td>
</tr>
<tr>
<td>vector</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>$\frac{1}{5}$</td>
</tr>
<tr>
<td>tensor</td>
<td>2</td>
<td>2</td>
<td>$--$, $-$, $0$, $+$, $++$</td>
<td>$\frac{1}{30}$</td>
</tr>
</tbody>
</table>

$\Gamma_0 = g^2m^3/64\pi v^2$

$\sigma$: scalar isoscalar
$\phi$: scalar isotensor
$\rho$: vector isovector
$f$: tensor isoscalar
$t$: tensor isotensor
Signal

- Signal definition:

  Signal sample

  - New resonance
  - SM EW $qq \rightarrow \ell^+ \nu \ell^- \bar{\nu}qq$
  - Interference

  SM continuum sample

  - SM EW $qq \rightarrow \ell^+ \nu \ell^- \bar{\nu}qq$

  $= \text{Signal (New resonance + interference)}$

Using Whizard+Pythia8 to generate both samples

Signal Xsec vs. resonance mass
Data/MC samples

Data samples:
- 25 ns data in 2015, Luminosity = 3.2 fb$^{-1}$

MC samples:
- $t\bar{t}$: Powheg
- Wt: Powheg
- Z+jets: MadGraph (QCD) and Sherpa (EW)
- diboson: Sherpa (QCD) and Whizard (EW)
- Z$\gamma$: Sherpa
- ttV: MadGraph
- SM Higgs: Powheg (ggH and VBF)

MC corrections:
- Lepton energy/momentum scale/resolution
- Lepton Reco/ID/Iso/Trig effSF
- Jet energy scale/resolution, b–tag effSF
- Pile-up reweighting
## Event selection

- **Event selections for signal region (SR):**

<table>
<thead>
<tr>
<th>#</th>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>event preselection requirements, see text</td>
</tr>
<tr>
<td>2</td>
<td>exactly two leptons with $p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td>3</td>
<td>pass single lepton trigger and trigger matching</td>
</tr>
<tr>
<td>4</td>
<td>third lepton veto</td>
</tr>
<tr>
<td>5</td>
<td>dilepton mass $m_{\ell\ell} &gt; 40$ GeV</td>
</tr>
<tr>
<td>6</td>
<td>$q_{\ell_1} \times q_{\ell_2} &lt; 0$</td>
</tr>
<tr>
<td>7</td>
<td>$</td>
</tr>
<tr>
<td>8</td>
<td>at least two selected jets with $p_T &gt; 30$ (50) GeV and $</td>
</tr>
<tr>
<td>9</td>
<td>b-jet veto</td>
</tr>
<tr>
<td>10</td>
<td>$E_T^{\text{miss}} &gt; 35$ GeV</td>
</tr>
<tr>
<td>11</td>
<td>$m_{jj} &gt; 500$ GeV</td>
</tr>
<tr>
<td>12</td>
<td>$</td>
</tr>
<tr>
<td>13</td>
<td>$\eta_{j_1} \times \eta_{j_2} &lt; 0$</td>
</tr>
<tr>
<td>14</td>
<td>lepton centrality $\zeta &gt; -0.5$</td>
</tr>
<tr>
<td>15</td>
<td>$f_{\text{recoil}} &lt; 2.0$</td>
</tr>
</tbody>
</table>
Background estimation

- Strategy of background estimation:

  - SM processes that can produce events with two OS leptons
    - Z+jets
    - t\bar{t}
    - Wt
    - ttV
    - Z\gamma+jets
    - diboson (WW/WZ/ZZ)
    - SM Higgs (ggH, VBF)
  
  - SM processes that have one or two leptons from jets (faked)
    - W+jets
    - QCD

  - Backgrouds of ll'+E_T^{miss}+2jets

MC prediction

Data driven (Matrix method)
Background estimation

- Dominant background sources:
  - For ee/\mu\mu channel: \(Z+\text{jets} \& t\bar{t}\)
  - For e\mu channel: \(t\bar{t}\)

- Validation regions (VRs):
  - Selection criteria listed on slide 14 is assumed unless otherwise specified

<table>
<thead>
<tr>
<th>Region</th>
<th>Purpose</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z+\text{jets} \text{ VR})</td>
<td>Validate (Z+\text{jets}) background modelling</td>
<td>(</td>
</tr>
<tr>
<td>(t\bar{t} \text{ VR})</td>
<td>Validate (t\bar{t}) background modelling</td>
<td>at least one (b)-tagged jet, no (m_{jj}) cut</td>
</tr>
<tr>
<td>low-(m_{jj}) \text{ VR}</td>
<td>Validate low-mass background estimation</td>
<td>(m_{jj} &lt; 500\ \text{GeV})</td>
</tr>
</tbody>
</table>
Data vs. prediction in Z+jets VR

- Z pT reweighting for the Z+jets prediction:
  - Some discrepancy is found between data & MC for Z pT distribution
  - Reweighing function is derived by using a polynomial fit for the spectrum
    \((\text{Data-Non-Z+jets}) / \text{Z+jets})\)
  - Cut 1-9 in slide 14, \(|m_{\ell\ell} - m_Z| < 25 \text{ GeV}\)
  - This reweighting function used in both VRs and SR

Reweighting fit function

Before reweighting

After reweighting
Data vs. prediction in Z+jets VR

- Z+jets VR: $|m_{\ell\ell} - m_Z| < 25$ GeV, no $m_{jj}$ cut

Reasonable agreement of data and the SM prediction observed in Z+jets VR
Data vs. prediction in $t\bar{t}$ VR

- $t\bar{t}$ VR: $N_{b\text{-jets}} > 1$, no $m_{jj}$ cut

Good agreement of data and the SM prediction observed in $t\bar{t}$ VR
Fake background estimation (matrix method)

- Matrix Method: a data-driven method to estimate fraction of jets misidentified as leptons.
- This matrix method depends on two parameters:
  - Real rate: probability for a real lepton identified as a loose lepton to pass tight lepton selection;
  - Fake rate: probability for a real jet identified as a loose lepton to pass tight lepton selection.

- Relation for the event numbers in the different subsamples:

\[
\begin{pmatrix}
N_{TT} \\
N_{TL} \\
N_{LT} \\
N_{LL}
\end{pmatrix} =
\begin{pmatrix}
r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\
(1-r_1) r_2 & r_1 (1-f_2) & f_1 (1-r_2) & f_1 (1-f_2) \\
(1-r_1) r_2 & (1-r_1) f_2 & (1-f_1) r_2 & (1-f_1) f_2 \\
(1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2)
\end{pmatrix}
\begin{pmatrix}
N_{RR} \\
N_{RF} \\
N_{FR} \\
N_{FF}
\end{pmatrix}
\]

- \(r_1, r_2 (f_1, f_2)\): the real (fake) rates evaluated for leading(1) and sub-leading(2) leptons

- Fake contribution estimation:
  - Measure the real rate of electron: tag-probe method is used to extract it from di-el data sample
  - Measure the fake rate of electron: obtained from a fake enriched data sample, MC subtraction.
  - Measure \(N_{TL}, N_{LT}, N_{TT}, N_{LL}\), then invert the matrix to get the fake contribution--\(N_{RF}, N_{FR}, N_{FF}\)
  - The matrix method is applied event by event
Fake background estimation (matrix method)

- Real rate of electron vs. el_pt, el_\(\eta\):

![Real rate graph](image1)

- Fake rate of electron vs. el_pt, el_\(\eta\):

![Fake rate graph](image2)
Data vs. prediction in low-$m_{jj}$ VR

- low-$m_{jj}$ VR: $m_{jj} < 500$ GeV, validate the overall background estimation

Reasonable agreement of data and the SM prediction observed in low-$m_{jj}$ VR
Data vs. prediction in the signal region

- Signal region (SR):
  - Based on all selections on slide 14

<table>
<thead>
<tr>
<th></th>
<th>ee</th>
<th>μμ</th>
<th>eμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z+jets</td>
<td>17.6 ± 1.2 ± 11.6</td>
<td>36.6 ± 2.3 ± 19.0</td>
<td>6.7 ± 1.2 ± 1.7</td>
</tr>
<tr>
<td>t̅t̅</td>
<td>12.1 ± 0.6 ± 3.2</td>
<td>18.2 ± 0.7 ± 4.6</td>
<td>46.9 ± 1.2 ± 12.1</td>
</tr>
<tr>
<td>Wt</td>
<td>1.2 ± 0.2 ± 0.3</td>
<td>1.5 ± 0.2 ± 0.5</td>
<td>3.1 ± 0.3 ± 0.8</td>
</tr>
<tr>
<td>diboson_QCD</td>
<td>3.1 ± 0.3 ± 0.5</td>
<td>4.2 ± 0.3 ± 0.7</td>
<td>10.2 ± 0.3 ± 1.6</td>
</tr>
<tr>
<td>diboson_EW</td>
<td>1.2 ± 0.1 ± 0.1</td>
<td>1.7 ± 0.1 ± 0.2</td>
<td>3.6 ± 0.1 ± 0.4</td>
</tr>
<tr>
<td>Zγ</td>
<td>2.1 ± 0.3 ± 0.6</td>
<td>3.8 ± 0.3 ± 0.7</td>
<td>0.1 ± 0.0 ± 0.1</td>
</tr>
<tr>
<td>Higgs</td>
<td>0.3 ± 0.0 ± 0.1</td>
<td>0.4 ± 0.0 ± 0.1</td>
<td>0.8 ± 0.0 ± 0.1</td>
</tr>
<tr>
<td>ttV</td>
<td>0.0 ± 0.0 ± 0.0</td>
<td>0.0 ± 0.0 ± 0.0</td>
<td>0.1 ± 0.0 ± 0.0</td>
</tr>
<tr>
<td>fake-lepton</td>
<td>0.6 ± 0.6 ± 0.1</td>
<td>0.0 ± 0.0 ± 0.0</td>
<td>1.3 ± 0.7 ± 0.1</td>
</tr>
<tr>
<td>σ (m = 300 GeV)</td>
<td>5.1 ± 0.3 ± 0.6</td>
<td>7.5 ± 0.3 ± 0.9</td>
<td>14.4 ± 0.4 ± 1.9</td>
</tr>
<tr>
<td>φ (m = 300 GeV)</td>
<td>0.3 ± 0.1 ± 0.2</td>
<td>1.0 ± 0.1 ± 0.4</td>
<td>1.6 ± 0.2 ± 0.4</td>
</tr>
<tr>
<td>ρ (m = 300 GeV)</td>
<td>8.0 ± 0.4 ± 1.6</td>
<td>11.7 ± 0.4 ± 1.4</td>
<td>24.1 ± 0.6 ± 3.1</td>
</tr>
<tr>
<td>f (m = 300 GeV)</td>
<td>15.6 ± 0.6 ± 1.9</td>
<td>22.6 ± 0.8 ± 1.9</td>
<td>50.4 ± 1.2 ± 3.8</td>
</tr>
<tr>
<td>t (m = 300 GeV)</td>
<td>3.3 ± 0.2 ± 0.4</td>
<td>4.7 ± 0.2 ± 0.6</td>
<td>6.9 ± 0.3 ± 1.1</td>
</tr>
</tbody>
</table>

| Total background | 38.2 ± 1.6 ± 13.9 | 66.4 ± 2.5 ± 21.6 | 72.6 ± 1.9 ± 14.8 |
| Data            | 40                | 74                | 86                |

No significant data excess above the SM background prediction is observed in SR23/48.
Data vs. prediction in the signal region

-- Due to two neutrinos in the final state, $M_T^{WW}$ is a useful discriminating variable:

$$(M_T^{WW})^2 = (P_{\ell_1} + P_{\ell_2} + P_{\text{miss}})(P_{\ell_1} + P_{\ell_2} + P_{\text{miss}})$$

-- No significant excess beyond the SM background prediction is found
Systematic uncertainties

- Experimental uncertainties(%) on the backgrounds in the signal region:

<table>
<thead>
<tr>
<th>Source</th>
<th>ee</th>
<th>μμ</th>
<th>εμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES and JER</td>
<td>33%</td>
<td>29%</td>
<td>12%</td>
</tr>
<tr>
<td>b-tagging</td>
<td>8%</td>
<td>7%</td>
<td>16%</td>
</tr>
<tr>
<td>(E_T^{miss}) modelling</td>
<td>7%</td>
<td>6%</td>
<td>1%</td>
</tr>
<tr>
<td>Lepton</td>
<td>3.1%</td>
<td>2.2%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Matrix method</td>
<td>0.2%</td>
<td>0.0%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Z boson (p_T) reweighting</td>
<td>0.5%</td>
<td>0.4%</td>
<td>0.0%</td>
</tr>
<tr>
<td>MC statistics</td>
<td>4.1%</td>
<td>3.7%</td>
<td>2.6%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.1%</td>
<td>2.1%</td>
<td>2.1%</td>
</tr>
<tr>
<td>Total experimental uncertainty</td>
<td>35%</td>
<td>31%</td>
<td>20%</td>
</tr>
</tbody>
</table>

- Theoretical uncertainties on the production Xsec of the backgrounds

- Additional shape systematic uncertainties for two dominant backgrounds
  (Z+jets, \(t\bar{t}\)) are included.

- Experimental uncertainties on signal considered (JES/JER, b-tagging, \(E_T^{miss}\) etc.)
95% CL upper limits

- No significant excess above the SM background expectation is observed.
- 95% CL upper limits are derived on $\sigma \times \text{Br}$ for new resonances ($\sigma$, $\varphi$, $\rho$, $f$ and $t$).
- Number counting as inputs to set limit due to limited signal statistics.
- The frequentist method (CLs), is used to compute 95% CL upper limits.

$$L(\mu, \bar{\alpha}) = \prod_{i \in \{ee, \mu\mu, e\mu\}} \text{Pois} \left( N_i^{\text{obs}} | N_i^{\text{exp}}(\mu, \bar{\alpha}) \right) \prod_{j \in \text{syst}} g(\alpha'_j | \alpha_j), \quad q = -2 \ln \left( \frac{L(\mu, \bar{\alpha}(\mu))}{L(\hat{\mu}, \hat{\alpha})} \right),$$

![Graphs showing 95% CL limits for $\sigma$ and $\rho$](image)
95% CL upper limits

** φ**

ATLAS Preliminary

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ \int Ldt = 3.2 \text{ fb}^{-1} \]

95% CL Limit on \( \sigma(qq \rightarrow Rqq \rightarrow \Gamma'/\Gamma(qq)) \) [fb]

```
\begin{align*}
\text{m}_\phi & \geq 270 \text{ GeV} \\
\text{Observed Limit} & \geq 380 - 220 \text{ fb} \\
\text{Expected Limit} & \geq 460 - 240 \text{ fb} \\
\end{align*}
```

m_R < 230 (300) GeV for \( \phi \) (f) excluded

** f**

ATLAS Preliminary

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ \int Ldt = 3.2 \text{ fb}^{-1} \]

95% CL Limit on \( \sigma(qq \rightarrow Rqq \rightarrow \Gamma'/\Gamma(qq)) \) [fb]

```
\begin{align*}
\text{m}_f & \geq 340 \text{ GeV} \\
\text{Observed Limit} & \geq 310 - 260 \text{ fb} \\
\text{Expected Limit} & \geq 330 - 270 \text{ fb} \\
\end{align*}
```

** t**

ATLAS Preliminary

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ \int Ldt = 3.2 \text{ fb}^{-1} \]

95% CL Limit on \( \sigma(qq \rightarrow Rqq \rightarrow \Gamma'/\Gamma(qq)) \) [fb]

```
\begin{align*}
\text{m}_t & \geq 310 \text{ GeV} \\
\text{Observed Limit} & \geq 260 - 210 \text{ fb} \\
\text{Expected Limit} & \geq 270 - 230 \text{ fb} \\
\end{align*}
```

Observed 95% CL exclusion limits in 200-500 GeV mass region:

- 380 – 220 fb (σ particle)
- 460 – 240 fb (φ particle)
- 330 – 270 fb (ρ particle)
- 340 – 260 fb (f particle)
- 310 – 260 fb (t particle)

m_R < 230 (300) GeV for ρ (f) excluded
Summary for analysis 1

- Search for new resonances (R) in $qq \rightarrow Rqq \rightarrow \ell^+\ell^-(\bar{u}qq)$ ($\ell = e, \mu$) using 3.2 fb$^{-1}$ data
  - SM backgrounds are carefully studied using MC simulation and data-driven (matrix method) and validated in several VRs.
  - all the possible uncertainties are well evaluated
  - no significant data excess above the SM prediction is observed
  - First 95% CL upper limits derived, $m_R < 230$ (300) GeV for $\rho$ ($f$) resonance excluded
  - Published on:
    - EPJ Web of Conferences 137, 08016 (2017)
    - ATLAS-CONF-2016-053

- Need to update:
  - Small data set (3.2 fb$^{-1}$)
  - Signal samples – low statistics
  - Three decay channels ($ee, \mu\mu, e\mu$) studied, but the most sensitive one is $e\mu$
Search for new resonances (X) in
\( qq \rightarrow Xqq \rightarrow WWqq \rightarrow e\mu\nu\nuqq \)
using 36.1 fb\(^{-1}\) data (2015+2016)


- My contributions: signal Monte Carlo samples generation, signal
  acceptance and predictions, event selection optimization, systematic
  uncertainties, etc.
Introduction

➢ Analysis goal:

• Search for new resonances (X) in VBF $qq \rightarrow Xqq \rightarrow WWqq \rightarrow e\mu\nu\nu qq$

➢ Main differences with the previous analysis:

• Data: 3.2 fb$^{-1}$ in 2015 $\Rightarrow$ 36.1 fb$^{-1}$ in full 2015+2016

• Signal model: EWChL model $\Rightarrow$ several individual signal models covering scalar, vector and tensor resonances

• Signal mass range: extended from 500 GeV up to 3000 GeV

• Decay channel: $ee, \mu\mu, e\mu \Rightarrow e\mu$ (most sensitive one and easier to handle the SM bkg)

• Event categories: $\text{VBF } N_{\text{jet}} \geq 2$ $\Rightarrow$ $\text{VBF } N_{\text{jet}} \geq 2 + \text{VBF } N_{\text{jet}} = 1$ (gain more sensitivities)

• Event selection and background estimation: optimized and updated accordingly
Signal models

- **Signal models**: new **scalar, vector and tensor** resonances introduced

<table>
<thead>
<tr>
<th>Resonance Spin</th>
<th>Signal Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin-0</td>
<td>NWA, LWA, GM</td>
</tr>
<tr>
<td>Spin-1</td>
<td>HVT</td>
</tr>
<tr>
<td>Spin-2</td>
<td>ELM</td>
</tr>
</tbody>
</table>

- **Heavy Higgs with a Narrow Width Approximation (NWA, scalar)**
  - width = 4 MeV (same widths for different heavy Higgs masses)
  - mass = [200, 3000] GeV

- **Heavy Higgs with a Large Width Assumption (LWA, scalar)**
  - width = 5%, 10% and 15% of heavy Higgs mass
  - mass = [200, 3000] GeV

- **Georgi-Machacek (GM, scalar) model**
  - new scalar resonance: $H_5^0$ (does not couple to fermions)
  - parameters:
    - $H_5^0VV$ coupling, proportional to $\sin \theta_H$ (= 0.4)
    - mass = [200, 1000] GeV
Signal models

• Heavy Vector Triplet (HVT, vector) model
  - new vector resonance: $Z'$
  - parameters:
    - $Z'VV$ coupling $g_V (=1)$
    - mass = [300, 1000] GeV
    - to suppress the non-VBF contributions, assume that $Z'$ bosons
does not couple to fermions

• Effective Lagrangian Model (ELM, tensor)
  - new tensor resonance (spin-2): $T$
  - parameters:
    - $TVV$ coupling $f_i (=1)$
    - mass = [200, 1000] GeV
    - $T$ resonance doesn’t couple to fermions
Event selection

- Event selections for signal regions (VBF $N_{\text{jet}} = 1$ SR, VBF $N_{\text{jet}} \geq 2$ SR)

**VBF $N_{\text{jet}} = 1$ SR**

- Preselection cuts
  - pass single-lepton triggers
    - $N_{\ell} = 2$ ($\ell = e, \mu$)
    - $p_T^{\ell} > 25$ GeV
    - veto if $p_T^{\ell,\text{other}} > 15$ GeV
    - $m_{\ell\ell} > 10$ GeV

**VBF $N_{\text{jet}} \geq 2$ SR**

- Common selections
  - $N_{b,\text{jet}} = 0$
  - $|\Delta \eta_{\ell\ell}| < 1.8$
  - $m_{\ell\ell} > 55$ GeV
  - $p_T^{\ell,\text{lead}} > 45$ GeV
  - $p_T^{\ell,\text{sublead}} > 30$ GeV
  - $\max(m_T^W) > 50$ GeV

**VBF1J phase space**

- $N_{\text{jet}} = 1$
- $|\eta_j| > 2.4$
- $\min(|\Delta \eta_{j\ell}|) > 1.75$

**VBF2J phase space**

- $N_{\text{jet}} \geq 2$
- $m_{jj} > 500$ GeV
- $|\Delta y_{jj}| > 4$

$$m_T^W = \sqrt{2p_T^{\ell}E_T^{\text{miss}} \left(1 - \cos(\phi^{\ell} - \phi^{E_T^{\text{miss}}})\right)}$$
**Background estimation**

- **Backgrounds:**
  - Top, WW, non-WW diboson, Z+jets, W+jets, Higgs production

- **Background estimation**
  - Top and WW (dominant backgrounds):
    - Normalization factors obtained from simultaneously fitting top and WW contributions to data in control and signal regions
    - WW in VBF 2J category which was from MC prediction (small contribution, difficult to isolate a kinematic region with high purity of WW)
  - W+jets: data driven method - “fake-factor” method
  - Z+jets, non-WW diboson, Higgs production: small contribution, MC simulation
Control regions

- Definition of Top and WW control regions (CRs)

  - some cuts inverted, removed or loosened to gain more data statistics and higher purity

<table>
<thead>
<tr>
<th>WW CR\textsubscript{VBF1J}</th>
<th>Top CR\textsubscript{VBF}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection cuts</td>
<td>Preselection cuts</td>
</tr>
<tr>
<td>$N_{b\text{-jet}} = 0$</td>
<td>$N_{b\text{-jet}} \geq 1$</td>
</tr>
<tr>
<td>($</td>
<td>\Delta \eta_{\ell\ell}</td>
</tr>
<tr>
<td>$10 \text{ GeV} &lt; m_{\ell\ell} &lt; 55 \text{ GeV}$</td>
<td>$m_{\ell\ell} &gt; 10 \text{ GeV}$</td>
</tr>
<tr>
<td>$p_{T}^{\ell,\text{lead}} &gt; 25 \text{ GeV}$</td>
<td>$p_{T}^{\ell,\text{lead}} &gt; 25 \text{ GeV}$</td>
</tr>
<tr>
<td>$p_{T}^{\ell,\text{sublead}} &gt; 25 \text{ GeV}$</td>
<td>$p_{T}^{\ell,\text{sublead}} &gt; 25 \text{ GeV}$</td>
</tr>
<tr>
<td>VBF1J</td>
<td>VBF1J and VBF2J</td>
</tr>
<tr>
<td>phase space</td>
<td>phase space</td>
</tr>
</tbody>
</table>

**WW background:**
- VBF $N_{\text{jet}} = 1$: WW CR
- VBF $N_{\text{jet}} \geq 2$: WW MC simulation

**Top background:**
- Top CR: combined VBF $N_{\text{jet}} = 1$ and VBF $N_{\text{jet}} \geq 2$ to gain more statistics
Data vs. prediction in the control regions

- Top control region:
  \[ \text{NF}_{\text{Top\_VBF}} = 1.12^{+0.13}_{-0.12} \]

- WW control region:
  \[ \text{NF}_{\text{WW\_VBF1J}} = 1.0 \pm 0.2 \]
W+jets estimation

- Use a data-driven method - "fake factor method" to estimate its contribution.

\[ N_{id+id}^{W+jets} = N_{id+anti-id}^{W+jets} \times \text{fake factor} \]

\[ = \left( N_{id+anti-id} - N_{EW}^{id+anti-id} \right) \times \frac{N_{id}}{N_{anti-id}} \]

- Two basic components: W+jets control sample and the fake factor.

W+jets control sample (\(N_{id+anti-id}\)):
  - Selected from the data using the same event selections as SR but requiring one pair of id+anti-id leptons.
  - Non-W+jets contributions (e.g., Top and WW) \(N_{id+anti-id}^{EW}\) subtracted using MC.
W+jets estimation

- fake factor \( \left( \frac{N_{id}}{N_{anti-id}} \right) \):
  - measured using a fake-enriched dijet data sample, with EW (W/Z+jets) subtraction
  - small trigger bias also considered (more in backup)
Data vs. prediction in the signal region

- **Signal region:**

<table>
<thead>
<tr>
<th></th>
<th>VBF $N_{jet} = 1$ SR</th>
<th>VBF $N_{jet} \geq 2$ SR</th>
<th>Top CR$_{VBF}$</th>
<th>WW CR$_{VBF1J}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>390 ± 50</td>
<td>120 ± 26</td>
<td>61 ± 11</td>
<td>265 ± 32</td>
</tr>
<tr>
<td>Top quark</td>
<td>450 ± 50</td>
<td>391 ± 24</td>
<td>5650 ± 90</td>
<td>167 ± 18</td>
</tr>
<tr>
<td>$Z/\gamma^*$</td>
<td>45 ± 11</td>
<td>24 ± 6</td>
<td>68 ± 19</td>
<td>74 ± 12</td>
</tr>
<tr>
<td>$W+jets$</td>
<td>52 ± 13</td>
<td>8.9 ± 2.5</td>
<td>91 ± 24</td>
<td>43 ± 11</td>
</tr>
<tr>
<td>$VV$</td>
<td>32 ± 7</td>
<td>16.6 ± 1.9</td>
<td>20 ± 9</td>
<td>38 ± 4</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>972 ± 29</td>
<td>563 ± 22</td>
<td>5890 ± 80</td>
<td>596 ± 22</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>978</td>
<td>560</td>
<td>5889</td>
<td>594</td>
</tr>
</tbody>
</table>

No significant data excess above the SM background prediction observed.
Systematic uncertainties

- Uncertainties of Top background (%):
  - Only dominant uncer. shown, others included in “Total”
  - Single top: theoretical uncer. on single-top-quark production

<table>
<thead>
<tr>
<th>Source</th>
<th>Jet</th>
<th>b-tag</th>
<th>ME+PS</th>
<th>Scale</th>
<th>Single top</th>
<th>PDF</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF $N_{jet} = 1$ SR</td>
<td>9.6</td>
<td>7.8</td>
<td>1.0</td>
<td>1.6</td>
<td>5.9</td>
<td>3.5</td>
<td>15</td>
</tr>
<tr>
<td>VBF $N_{jet} \geq 2$ SR</td>
<td>9.7</td>
<td>14</td>
<td>9.5</td>
<td>5.0</td>
<td>2.1</td>
<td>3.6</td>
<td>21</td>
</tr>
<tr>
<td>Top CR$_{VBF}$</td>
<td>8.2</td>
<td>3.5</td>
<td>10</td>
<td>1.5</td>
<td>1.3</td>
<td>3.6</td>
<td>14</td>
</tr>
<tr>
<td>WW CR$_{VBF1J}$</td>
<td>9.9</td>
<td>8.3</td>
<td>9.4</td>
<td>3.9</td>
<td>5.3</td>
<td>3.4</td>
<td>18</td>
</tr>
</tbody>
</table>

- Uncertainties of WW background (%):
  - Only dominant uncer. shown, others included in “Total”

<table>
<thead>
<tr>
<th>Source</th>
<th>Jet</th>
<th>Pile-up</th>
<th>ME+PS</th>
<th>$\mu_R$</th>
<th>Resummation</th>
<th>PDF</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF $N_{jet} = 1$ SR</td>
<td>17</td>
<td>2.8</td>
<td>11</td>
<td>7.3</td>
<td>5.0</td>
<td>1.0</td>
<td>23</td>
</tr>
<tr>
<td>VBF $N_{jet} \geq 2$ SR</td>
<td>18</td>
<td>3.1</td>
<td>38</td>
<td>18</td>
<td>1.4</td>
<td>1.3</td>
<td>47</td>
</tr>
<tr>
<td>WW CR$_{VBF1J}$</td>
<td>16</td>
<td>4.5</td>
<td>12</td>
<td>11</td>
<td>2.3</td>
<td>1.6</td>
<td>23</td>
</tr>
</tbody>
</table>

- Shape uncertainties of Top and WW:
  - $m_T$ shape dependence for the PDF uncertainty in the SRs considered
Systematic uncertainties

- Uncertainties of $W+\text{jets}$ background:
  - mainly arise from jet flavor composition, EW subtraction, stat. uncertainty, etc.
  - VBF 1J SR: 32%, VBF 2J SR: 35%

- Uncertainties of other background:
  - smaller contributions on the uncertainties
  - experimental uncertainties, normalized to high-order Xsec. prediction

- Uncertainties of signal (NWA):
  - mainly arise from parton shower, PDF, QCD scales, etc.
  - VBF 1J SR: 5.1% - 9.0%, VBF 2J SR: 3.3% - 8%
95% CL upper limits

- No data excess above the SM prediction is observed.
- 95% CL upper limits are derived on $\sigma_X \times \text{Br}(X \rightarrow WW)$
- The frequentist method (CLs), is used to compute 95% CL upper limits

$$\mathcal{L}(\mu, \theta) = \left\{ \prod_{k=e,\mu} \prod_{j=0} N_{\text{category}} \prod_{i=1} N_{\text{bias}} \text{Pois}(N_{ijk} | \mu^s_{ijk} + \sum_m b_{ijkm}) \right\} \times \prod_{i=1} N(\theta | \theta), \quad q_\mu = -2 \ln \left( \frac{\mathcal{L}(\mu; \hat{\theta}_\mu)}{\mathcal{L}(\mu; \hat{\theta})} \right),$$

**ATLAS**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- $H \rightarrow WW \rightarrow ev\bar{\nu}$ (VBF, NWA)

**NWA**

- Values above 1.3 pb at 200 GeV and above 0.006 pb at 3 TeV for NWA and 15% LWA are excluded

**LWA**

**GM**

Scalar resonances
95% CL upper limits

Current sensitivity not sufficient to exclude the VBF signals from GM, HVT and ELM models
Summary for analysis 2

- Search for new resonances (X) in $qq \rightarrow Xqq \rightarrow WWqq \rightarrow e\nu\mu\nu qq$ using 36.1 fb⁻¹ data
  - SM backgrounds are carefully studied using simultaneous fit, fake factor method and MC simulation, and validated in specific CRs.
  - all the possible uncertainties are properly evaluated
  - no evidence of such heavy neutral resonances is found
  - 95% CL upper limits set on $\sigma_X \times Br(X \rightarrow WW)$ of new scalar, vector and tensor resonances predicted by several individual signal models

- Published on:
ATLAS MDT gas work (install, repair and maintain)

- MDT (Monitored Drift Tubes) gas system repairs and maintenance:
  - Installation of MDT gas system for BME chambers:

Obtained the ATLAS authorship and took a lot of shift work assigned to USTC
Publications

- “Search for heavy resonances decaying into WW in the $e\nu\mu\nu$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”

- “Search for heavy resonances in vector boson fusion”
  EPJ Web of Conferences 137, 08016 (2017)

- “Search for heavy neutral resonances in vector boson fusion in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector at the Large Hadron Collider”
  ATLAS-CONF-2016-053

- “Multi-Boson Simulation for 13 TeV ATLAS Analyses”
  ATL-PHYS-PUB-2017-005

Paper in ATLAS EB review

- “Measurement of $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ production in proton-proton collisions at $\sqrt{s} = 13$ TeV with ATLAS detector”
Conference talks and posters

➢ Conference talks

• “Search for heavy resonances in vector boson scattering”, XII Quark Confinement and the Hadron Spectrum, Thessaloniki, Greece, Aug. 29 - Sep. 03, 2016. https://indico.cern.ch/event/353906/contributions/2257680/


• “Search for heavy neutral resonances in vector boson fusion $qq \rightarrow \ell\nu\ell\nu qq$ with the ATLAS detector”, Second China LHC Physics Workshop, Peking University, Beijing, China, 16-19 December, 2016 http://indico.ihep.ac.cn/event/6062/contribution/66

➢ Conference posters

• “Search for heavy resonances in vector boson fusion at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC”, The 9th Joint Meeting of Chinese Physicists Worldwide, Tsinghua University, Beijing, China, 17-20 July, 2017 http://meetings.csp.escience.cn/dct/page/1 (2017 APS-OCPA Outstanding Conference Poster Award)
Summary

- Two physics analyses performed using $pp$ collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC
  - Search for new resonances (R) in $qq \rightarrow R qq \rightarrow \ell^+\ell^-\bar{\nu}\nu qq$ ($\ell = e, \mu$) using 3.2 fb$^{-1}$ data collected in 2015
  - Search for new resonances (X) in $qq \rightarrow X qq \rightarrow WW qq \rightarrow e\nu\mu\nu qq$ using 36.1 fb$^{-1}$ data collected in full 2015 and 2016
- ATLAS MDT gas system installation, repair and maintenance
- 4 publications, 1 paper under ATLAS review, 3 conference talks, 1 conference poster (outstanding award) and many important ATLAS group talks (eg. unblinding & approval talks)
Backup
Mandelstam variables (analysis 1)

- Definitions of Mandelstam variables (s, t, u)
  - \( s = (p_1 + p_2)^2 = (p_3 + p_4)^2 \)
  - \( t = (p_1 - p_3)^2 = (p_4 - p_2)^2 \)
  - \( u = (p_1 - p_4)^2 = (p_3 - p_2)^2 \)

- Relativistic limit (large \( p \))
  - \( E^2 = p \cdot p + m_0^2 \Rightarrow E^2 \approx p \cdot p \)
  - \( s = (p_1 + p_2)^2 = p_1^2 + p_2^2 + 2p_1 \cdot p_2 \)
    \( \approx 2p_1 \cdot p_2 \)
    where \( p_1^2 = m_1^2, p_2^2 = m_2^2 \)
  - \( s \approx 2p_1 \cdot p_2 \approx 2p_3 \cdot p_4 \)
  - \( t \approx -2p_1 \cdot p_3 \approx -2p_2 \cdot p_4 \)
  - \( u \approx -2p_1 \cdot p_4 \approx -2p_3 \cdot p_2 \)
Feynman diagrams of VBF (analysis 1)

- NonVBF-EW process

- VBF-QCD process
Effective theories and Unitarity (analysis 1)

* non-linear representation
  - Unitary matrix contains 3 Goldstone bosons and is non-linear
    \[ U = \exp\left(-\frac{i}{\nu}(\omega^+\tau^+ + \omega^3\tau^3 + \omega^-\tau^-)\right) = 1 - \frac{i}{\nu}(\omega^+\tau^+ + \omega^3\tau^3 + \omega^-\tau^-) + \ldots \]
  - Higgs added as a singlet \( U \rightarrow (1 + f(\frac{\Lambda}{\nu}))U \)
  - independent couplings to longitudinal GB’s need to be fine-tuned to avoid unitarity violation of VB scattering amplitude → strongly interacting
  - need a cut-off scale \( \Lambda \sim 4\pi\nu \)

* linear representation
  - field has a linear dependence on GB and Higgs is embedded in the same matrix as GB’s
    \[ U = -i\frac{\omega}{v}\tau^i + \frac{h}{v}1 \]
  - automatic cancellation of longitudinal VB scattering amplitudes, leaving only transverse contributions → weak coupling

* Effective field theories
  - assume new physics at high scale and parameterize in Taylor expansion
    - non-linear representation: Higgs couplings are independent and additional parameters are present at leading order in EFT, \( \Lambda \sim 4\pi\nu \).
    - linear representation: Higgs couplings fixed at leading order; anomalous couplings at higher order
      - 1 dimension-6 operator and 2 dimension-8 operators important for VBS with parameters \( F_{\text{HD}} \) and \( F_{S,0} \) and \( F_{S,1} \) respectively
Adding a resonance (analysis 1)

- If the mass is very high, \((M^2 \gg s)\)
  - EFT approach valid

- If the mass is lower than experimental reach, \((M^2 \ll s)\)
  - embed the state in an extended EFT
  - coupling of particle to VB yields an anomalous quartic coupling which can be matched to a low energy EFT operator where the resonance is integrated out.
  - EFT alone will not describe the resonance, but will only produce a rise in amplitude
  - unitarity broken → need unitarization procedure: K-matrix

Kilian et al., 1511.00022

Now, must add to ChL, interactions with the Higgs:

\[
\frac{v^2}{4} \left( 1 + 2a \left( \frac{h}{v} \right) + b \left( \frac{h}{v} \right)^2 + \ldots \right) \text{Tr} D_\mu U^\dagger D^\mu U
\]

\[
U = \exp \left( i \frac{\vec{\alpha} \cdot \vec{\tau}}{v} \right)
\]

\(a = 1, \quad b = 1 \quad \Rightarrow \text{SM couplings to Higgs}\)

Solid line: unitarized results, dashed lines: naive result, black dashed line: limit of saturation of \(A_{20} (W^+W^+) / A_{00} (ZZ)\).

Cuts: \(M_{JJ} > 500 \text{ GeV}; \Delta \eta_{JJ} > 2.4; p_T^J > 20 \text{ GeV}; |\eta| > 4.5.\)

(c) \(pp \rightarrow ZZjj\), low lying isoscalar-scalar with \(m_\sigma = 650 \text{ GeV}\) and \(\Gamma_\sigma = 240 \text{ GeV}\).
K-matrix unitarization (analysis 1)

Scattering matrix (S-matrix) \( S_{ij} = \langle j | S | i \rangle \) is a matrix of amplitudes relating initial state \( i \) at \( t = -\infty \) to state \( j \) at \( t = +\infty \).

- It is complex but unitary (conservation of probability) and symmetric (time-reversal).
- Related to transition matrix \( S = 1 + iT \) (normalized such as anything different from 1 is inelastic). \( T_{ij} \) is proportional to the matrix element between \( i \) and \( j \).
- Unitarity implies optical theorem: relation between \( \text{Im}(\text{forward scattering amplitudes}) \) and total cross section. \( S\bar{S} = 1 \Rightarrow T\bar{T} = -i(T - T^\dagger) \).
  - After partial wave decomposition, each partial wave must satisfy \( |a_\ell - i/2| < 1/2 \).
  - In complex plane, this is the Argand circle.

\[ |a_\ell - i/2| = 1/2 \]

\[ \text{Im}(a_\ell) \]

\[ \text{Re}(a_\ell) \]
K-matrix unitarization (analysis 1)

- many unitarization procedures in the market which saturate the amplitude (see discussion at https://indico.cern.ch/event/570648/).
  - K-matrix: 2-step process:
    - estimate real value of Hermitian K operator, then extrapolate to Argand circle

Define a Hermitian operator K (related to interaction Hamiltonian)

\[
S = \frac{1 + iK/2}{1 - iK/2} \quad S = 1 + iT
\]

It can be shown that if the eigenvalue of \( T/2 \) is \( a \) (on the Argand circle), then the eigenvalue of K is:

\[
a_K = \frac{a}{1 + ia} \quad \text{or} \quad a = \frac{a_K}{1 - ia_K}
\]

Geometrically

(a) K-matrix projection: (Perturbative) construction of a real \( a_K \) in the first step.
# Object definition (analysis 1)

<table>
<thead>
<tr>
<th>Selection</th>
<th>Electron</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ (GeV)</td>
<td>$&gt;25$</td>
<td>$&gt;25$</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>,$</td>
</tr>
<tr>
<td>$</td>
<td>d_0/\sigma(d_0)</td>
<td>,$</td>
</tr>
<tr>
<td>$</td>
<td>z_0\sin\theta</td>
<td>,$ (mm)</td>
</tr>
<tr>
<td>ID</td>
<td>TightLH (if $E_{t_{el}}&lt;300$ GeV)</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>MediumLH (if $E_{t_{el}}&gt;300$ GeV)</td>
<td></td>
</tr>
<tr>
<td>Isolation</td>
<td>passTightIso</td>
<td>passTightIso</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Selection</th>
<th>Jet</th>
<th>Selection</th>
<th>MET</th>
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</thead>
<tbody>
<tr>
<td>Jet type</td>
<td>AntiKt4EMTopoJets</td>
<td>METContainer</td>
<td>MET_Reference_AntiKt4EMTopo</td>
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<tr>
<td>$p_T$ (GeV)</td>
<td>$&gt;30$ ($&gt;50$ if $2.5&lt;</td>
<td>\eta</td>
<td>&lt;4.5$)</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>,$</td>
<td>$&lt;4.5$</td>
</tr>
<tr>
<td>JVT</td>
<td>$JVT &gt; 0.64$ if $</td>
<td>\eta</td>
<td>&lt; 2.4$ and $p_T &lt; 50$ GeV</td>
</tr>
<tr>
<td>Jet quality</td>
<td>Not badjet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet flavor tagger</td>
<td>MV2c20 (85% efficiency)</td>
<td></td>
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</tr>
</tbody>
</table>
Triggers and signal acceptance (analysis 1)

- Single-lepton triggers:

<table>
<thead>
<tr>
<th>Single-lepton triggers</th>
<th>Trigger name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-electron triggers</td>
<td>HLT_e24_lhmedium_L1EM20VH</td>
</tr>
<tr>
<td></td>
<td>HLT_e24_lhmedium_L1EM18VH</td>
</tr>
<tr>
<td></td>
<td>HLT_e60_lhmedium</td>
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<tr>
<td></td>
<td>HLT_e120_lhloose</td>
</tr>
<tr>
<td>Single-muon triggers</td>
<td>HLT_mu20_iroose</td>
</tr>
<tr>
<td></td>
<td>HLT_mu50</td>
</tr>
</tbody>
</table>

- Signal acceptance times efficiency:

![Graph showing Acceptance x Efficiency vs Resonance mass](image)
Lepton centrality and $f_{\text{recoil}}$ (analysis 1)

- **Lepton centrality $\zeta$**:
  \[
  \zeta = \min\{\eta_{1}^{\text{jet}} - \eta_{1}^{\ell}, \eta_{2}^{\ell} - \eta_{2}^{\text{jet}}\} \text{ where } \eta_{1}^{\ell} \geq \eta_{2}^{\ell} \text{ and } \eta_{1}^{\text{jet}} \geq \eta_{2}^{\text{jet}}
  \]
  - $\zeta$ in VBF topology tends to be positive
  - To reduce the background from strong production of double vector boson processes ($\zeta > -0.5$)

- **$f_{\text{recoil}}$**:
  \[
  f_{\text{recoil}} = \frac{\sum_{\text{soft jets}} \mathbf{JVT}_j \cdot \mathbf{p}_T^j}{\mathbf{p}_T^{\ell\ell}}
  \]
  - Measures the strength of the recoil system relative to the dilepton system
  - Useful to reject the $Z/\gamma^* \rightarrow \ell\ell$ background
  - $f_{\text{recoil}} < 2$
Real rate of electron (analysis 1)

- Tight/Loose electron definitions:

<table>
<thead>
<tr>
<th>Selection</th>
<th>Tight Electron</th>
<th>Loose Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ (GeV)</td>
<td>&gt;25</td>
<td>&gt;25</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>d_0/\sigma(d_0)</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>z_0 \sin \theta</td>
<td>$ (mm)</td>
</tr>
<tr>
<td>ID</td>
<td>TightLH</td>
<td>LooseLH</td>
</tr>
<tr>
<td></td>
<td>(MediumLH, if $Et_{el}&gt;300$GeV)</td>
<td></td>
</tr>
<tr>
<td>Isolation</td>
<td>passTightIso</td>
<td>No isolation requirement</td>
</tr>
</tbody>
</table>

- Cut flow:
  - Basic event pre-selection, event cleaning/GRL cut/PV cut.
  - Single-electron trigger chain (e24_lhmedium_L1EM20VH || e60_lhmedium || e120_lhloose)
  - Exactly two LOOSE electrons with opposite sign
  - $m_Z -10$GeV < $m_{ee}$ < $m_Z +10$GeV
  - At least one Tight lepton as Tag
  - For the probe lepton, real rate = $N_{\text{Tight}}/N_{\text{Loose}}$
Fake rate of electron (analysis 1)

- **Tight/Loose electron definitions:**

<table>
<thead>
<tr>
<th>Selection</th>
<th>Tight Electron</th>
<th>Loose Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ (GeV)</td>
<td>&gt;25</td>
<td>&gt;25</td>
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<tr>
<td>$</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>d_0/\sigma(d_0)</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>z_0 \sin \theta</td>
<td>$ (mm)</td>
</tr>
<tr>
<td>ID</td>
<td>TightLH (MediumLH, if Et_el&gt;300GeV)</td>
<td>LooseLH</td>
</tr>
<tr>
<td>Isolation</td>
<td>passTightIso</td>
<td>No isolation requirement</td>
</tr>
</tbody>
</table>

- **Cut flow:**
  - Basic event pre-selection, event cleaning/GRL cut/PV cut.
  - use single-electron trigger chain $(e24_lhloose_L1EM20VH || e60_lhloose || e120_lhloose)$
  - At least one LOOSE electrons
  - reject events with two loose electrons in Z mass window($|M_{ee}-M_Z|<20\text{GeV}$)
  - reject events with two or more tight electrons
  - MET<25GeV
  - Fill histograms, fake rate $= N_{\text{Tight}}/N_{\text{Loose}}$
Signal models (analysis 2)

- Signal models: new scalar, vector and tensor resonances introduced

<table>
<thead>
<tr>
<th>Resonance Spin</th>
<th>Signal Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin-0</td>
<td>NWA, LWA, GM</td>
</tr>
<tr>
<td>Spin-1</td>
<td>HVT</td>
</tr>
<tr>
<td>Spin-2</td>
<td>ELM</td>
</tr>
</tbody>
</table>

- Heavy Higgs with a Narrow Width Approximation (NWA)
  - width = 4 MeV (same widths for different heavy Higgs masses)
  - mass = [200, 3000] GeV

- Heavy Higgs with a Large Width Assumption (LWA)
  - width = 5%, 10% and 15% of heavy Higgs mass
  - Mass = [200, 3000] GeV

- Georgi-Machacek (GM) model
  - extend Higgs sector with additional one real and one complex triplets
  - scalar potential determined to keep the ratio of charged to neutral currents as in SM (ρ parameter = 1)
Signal models (analysis 2)

- **Georgi-Machacek (GM) model**
  - reorganize the physical states to have
    - 2 singlet neutrals \((h, H)\)
    - triplet \((H_3^+, H_3^0, H_3^-)\)
    - fiveplet \((H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})\)
  - parameters
    - All the H\(_{5VV}\) couplings are proportional to \(\sin \theta_H\) (fraction of the gauge boson masses \(m_W\) and \(m_Z\) generated by the vev of the triplets)
    - resonance mass: [200, 1000] GeV
    - H\(_5\) scalars does not couple to fermions

- **Heavy Vector Triplet (HVT) model**
  - parameterizes the couplings of the HVT bosons to the SM gauge bosons and Higgs with \(c_h g_V\), to the fermions with \(g^2 c_F / g_V\)
  - new resonances \((Z', W')\)
  - parameters
    - XVV coupling \(g_V\) (=1), resonance mass [300, 1000] GeV
    - to suppress the non-VBF contributions, assume that HVT bosons does not couple to fermions \((c_F=0)\)
Signal models (analysis 2)

- An an effective Lagrangian model (ELM)
  - introduce general spin-2 fields $T_{\mu
u}$ (singlet) and $T_{j}^{\mu
u}$ (triplet)
  - spin-2 singlet case considered, its effective Lagrangian

$$\mathcal{L} = \frac{1}{\Lambda} T_{\mu\nu} \left( f_1 B^{\alpha\nu} B_{\alpha}^{\mu} + f_2 W^{\alpha\nu}_{i} W_{\alpha}^{i,\mu} + 2 f_5 (D^\mu \Phi)^\dagger (D^\nu \Phi) \right),$$

- a form factor introduced to multiply with the amplitudes to preserve unitarization

$$f(p_1^2, p_2^2, k_{sp2}^2) = \left( \frac{\Lambda_{ff}^2}{|p_1^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_2^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|k_{sp2}^2| + \Lambda_{ff}^2} \right)^{n_{ff}}$$

- parameters
  - characteristic energy scale: $\Lambda = 1.5$ TeV
  - cut-off energy scale and suppression power: $\Lambda_{ff} = 3$ TeV, $n_{ff} = 4$
  - variable coupling parameters: $f_1 = f_2 = f_5 = 1$
  - resonance mass: $[200, 1000]$ GeV
  - Spin-2 resonances doesn’t couple to fermions
GM model (analysis 2)


The scalar sector of the GM model [1, 2] consists of the usual complex isospin doublet \((\phi^+, \phi^0)\) with hypercharge\(^1\) \(Y = 1\), a real triplet \((\xi^+, \xi^0, \xi^-)\) with \(Y = 0\), and a complex triplet \((\chi^{++}, \chi^+, \chi^0)\) with \(Y = 2\). The doublet is responsible for the fermion masses as in the SM.

The scalar potential is chosen by hand to preserve a global SU(2)\(_L\)×SU(2)\(_R\) symmetry. This ensures \(\rho = 1\) at tree level. In order to make the global SU(2)\(_L\)×SU(2)\(_R\) symmetry explicit, we write the doublet in the form of a bidoublet \(\Phi\) and combine the triplets to form a bitriplet \(X\):

\[
\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^{++*} & \phi^0 \end{pmatrix}, \quad X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{++*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^* & \chi^0 \end{pmatrix}.
\]

The vevs are defined by \(\langle \Phi \rangle = \frac{v_\phi}{\sqrt{2}} 1_{2\times2}\) and \(\langle X \rangle = v_\chi 1_{3\times3}\), where the Fermi constant \(G_F\) fixes the combination of vevs,

\[
v^2 = v_\phi^2 + 8v_\chi^2 \equiv v^2 = \frac{1}{\sqrt{2}G_F} \approx (246\text{ GeV})^2.
\]

\(^1\) We normalize the hypercharge operator such that \(Q = T^3 + Y/2\).

These vevs are parameterized in terms of a mixing angle \(\theta_H\) according to

\[
c_H \equiv \cos \theta_H = \frac{v_\phi}{v}, \quad s_H \equiv \sin \theta_H = \frac{2\sqrt{2}v_\chi}{v}.
\]

The quantity \(s_H^2\) represents the fraction of the gauge boson masses-squared \(M_W^2\) and \(M_Z^2\) that is generated by the vev of the triplets, while \(c_H^2\) represents the fraction generated by the usual Higgs doublet.

A detailed discussion of the most general gauge-invariant scalar potential involving these fields that conserves custodial SU(2) can be found, e.g., in Ref. [7]. Here we briefly summarize the field content, masses, and relevant Feynman rules.
GM model (analysis 2)


The physical fields can be organized by their transformation properties under the custodial SU(2) symmetry into a fiveplet, a triplet, and two singlets. The fiveplet and triplet states are given by

\[
\begin{align*}
H_5^{++} &= \chi^{++}, \\
H_5^+ &= \frac{\chi^+ - \xi^+}{\sqrt{2}}, \\
H_5^0 &= \sqrt{\frac{2}{3}} \xi^0 - \sqrt{\frac{1}{3}} \chi^{0,r}, \\
H_3^+ &= -s_H \phi^+ + c_H \frac{\chi^+ + \xi^+}{\sqrt{2}}, \\
H_3^0 &= -s_H \phi^{0,i} + c_H \chi^{0,i},
\end{align*}
\]

where we have decomposed the neutral fields into real and imaginary parts according to

\[
\begin{align*}
\phi^0 &\rightarrow \frac{v \phi}{\sqrt{2}} + \frac{\phi^{0,r} + i \phi^{0,i}}{\sqrt{2}}, \\
\chi^0 &\rightarrow v_\chi + \frac{\chi^{0,r} + i \chi^{0,i}}{\sqrt{2}}, \\
\xi^0 &\rightarrow v_\chi + \xi^0.
\end{align*}
\]

The states of the custodial fiveplet \((H_5^{\pm\pm}, H_5^+, H_5^0)\) have a common mass \(m_5\) and the states of the custodial triplet \((H_3^+, H_3^0)\) have a common mass \(m_3\). Because the states in the custodial fiveplet contain no doublet field content, they do not couple to fermions.

The two custodial singlets mix by an angle \(\alpha\), and the resulting mass eigenstates are given by

\[
\begin{align*}
h &= \cos \alpha \phi^{0,r} - \sin \alpha H_1^{0r}, \\
H &= \sin \alpha \phi^{0,r} + \cos \alpha H_1^{0r},
\end{align*}
\]

where

\[
H_1^{0r} = \sqrt{\frac{1}{3}} \xi^0 + \sqrt{\frac{2}{3}} \chi^{0,r}.
\]

We denote their masses by \(m_h\) and \(m_H\). \(h\) is normally identified as the 125 GeV SM-like Higgs boson discovered at the LHC [8].

The fiveplet states couple to vector bosons according to the following Feynman rules [3, 7, 9]:

\[
H_5^0 W_\mu^+ W_\nu^- : \sqrt{\frac{2}{3}} g^2 v_\chi g_{\mu\nu} = 2i \frac{M_W^2}{v} \left( \frac{1}{\sqrt{3}} s_H \right) g_{\mu\nu} = 2(\sqrt{2} G_F)^{1/2} M_W^2 \left( -\frac{1}{\sqrt{3}} s_H \right) (-i g_{\mu\nu}),
\]

where we write the coupling in multiple forms to make contact with the notation of Refs. [3, 5]. The triplet vev \(v_\chi\) is called \(v'\) in Ref. [3], and the factors \(F_{VV}\) in Eq. (5.2) of Ref. [5] correspond in this model to

\[
F_{W^+ W^-} = -\frac{1}{\sqrt{3}} s_H \quad (H_5^0 \text{ production}),
\]
In addition to the SM fields and interactions we consider a real vector \( V^a_\mu \), \( a = 1, 2, 3 \), in the adjoint representation of \( SU(2)_L \) and with vanishing hypercharge. It describes one charged and one neutral heavy spin-one particle with the charge eigenstate fields defined by the familiar relations

\[
V^\pm_\mu = \frac{V^1_\mu \mp iV^2_\mu}{\sqrt{2}} , \quad V^0_\mu = V^3_\mu .
\]  
(2.1)

Similarly to Ref. [12], we describe the dynamics of the new vector by a simple phenomenological Lagrangian

\[
\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_\nu] D^{\mu \nu} V^a - \frac{m^2_2}{2} V^a_\mu V^a_\mu + i g_V c_H V^a_\mu H^\dagger \tau^a D^\mu H + \frac{g^2}{g_V} c_F V^a_\mu J^a_F
\]
\[
+ \frac{g_V}{2} c_{VVV} \epsilon_{abc} V^a_\mu V^b_\nu D^{\mu \nu} V^c + g^2 c_{VVHH} V^a_\mu V^a_\mu H^\dagger H - \frac{g^2}{2} c_{VVW} \epsilon_{abc} W^{\mu \nu} V^a_\mu V^b_\nu V^c.
\]  
(2.2)

The first line of the above equation contains the \( V \) kinetic and mass term, plus trilinear and quadrilinear interactions with the vector bosons from the covariant derivatives

\[
D_{[\mu} V^a_\nu] = D_\mu V^a_\nu - D_\nu V^a_\mu , \quad D_\mu V^a_\nu = \partial_\mu V^a_\nu + g \epsilon^{abc} W^b_\mu V^c ,
\]  
(2.3)

where \( g \) denotes the \( SU(2)_L \) gauge coupling. Notice that the \( V^a_\mu \) fields are not mass eigenstates as they mix with the \( W^a_\mu \) after EWSB and the mass parameter \( m_V \) does not coincide with the physical mass of the resonances.

The second line contains direct interactions of \( V \) with the Higgs current

\[
i H^\dagger \tau^a \tilde{D}_\mu H = i H^\dagger \tau^a D^\mu H - i D^\mu H^\dagger \tau^a H ,
\]  
(2.4)

and with the SM left-handed fermionic currents

\[
J^\mu_F = \sum_f \bar{\psi}_L \gamma^\mu \tau^a f_L ,
\]  
(2.5)
For the present analysis of spin-2 resonances in vector-boson-fusion processes, we have constructed an effective model describing the interaction of spin-2 particles with electroweak bosons. Two cases are considered: A spin-2 state which behaves as a singlet under SU(2) transformations and a spin-2 state which is a weak isospin triplet.

These states are described by the general spin-2 fields $T^\mu_\nu$ (singlet) and $T^\mu_\nu$ (triplet),

$$T^\mu_\nu(x) = \int \frac{d^3k}{(2\pi)^3 2k_0} \sum_{\lambda=-2}^{2} \left( \varepsilon^\mu_\nu(k, \lambda) a_{\lambda(J)}(k)e^{-i kx} + \varepsilon^{*\mu_\nu}(k, \lambda) a^\dagger_{\lambda(J)}(k)e^{i kx} \right).$$  \hspace{1cm} (2.1)

The free Lagrangian for a general spin-2 field with mass $m$ is given by [13]

$$\mathcal{L}_{\text{free}} = - (\partial_\mu T^\mu_\nu)^\dagger (\partial_\nu T^\rho_\sigma) + \frac{1}{2} (\partial_\mu T^\mu_\nu)^\dagger (\partial_\nu T^\sigma_\lambda) + \frac{m^2}{2} T^\mu_\nu T^\mu_\nu.$$ \hspace{1cm} (2.2)

For the triplet field, the partial derivatives are to be replaced by covariant ones in order to account for its gauge couplings to electroweak bosons. Note, however, that these couplings induce $TTV$ or $TTVV$ vertices, which do not appear in the processes studied in this paper. The fields are symmetric in $\mu, \nu$, transverse and $T^\mu_\nu = T^{\mu\nu} = 0$. $\varepsilon^{\mu_\nu}$ is a symmetric polarization tensor built from the usual spin-1 polarization vectors [14]:

$$\varepsilon^{\mu_\nu}(p, \pm 2) = \varepsilon^\mu(p, \pm)\varepsilon^\nu(p, \pm)$$

$$\varepsilon^{\mu_\nu}(p, \pm 1) = \frac{1}{\sqrt{2}} \left( \varepsilon^\mu(p, \pm)\varepsilon^\nu(p, 0) + \varepsilon^\mu(p, 0)\varepsilon^\nu(p, \pm) \right)$$

$$\varepsilon^{\mu_\nu}(p, 0) = \frac{1}{\sqrt{6}} \left( \varepsilon^\mu(p, +)\varepsilon^\nu(p, -) + \varepsilon^\mu(p, -)\varepsilon^\nu(p, +) + 2\varepsilon^\mu(p, 0)\varepsilon^\nu(p, 0) \right).$$ \hspace{1cm} (2.3)

While the spin-2 singlet involves only one uncharged particle, called $T$, the triplet consists of three spin-2 particles, $T^1$, $T^2$ and $T^3$, or, equivalently, a charged pair and a neutral particle:

$$T^\pm = \frac{1}{\sqrt{2}}(T^1 \mp iT^2),$$

$$T^0 = T^3.$$ \hspace{1cm} (2.4)
Spin-2 Model (analysis 2)


Since in the present analysis we only study spin-2 resonances which are produced in electroweak-boson fusion, we restrict ourselves to a model of the interaction of a single spin-2 particle with electroweak bosons. The building blocks of the corresponding singlet and triplet Lagrangian were chosen to be the spin-2 field(s), the vector fields of the electroweak gauge bosons and the scalar Higgs field $\Phi$. Respecting gauge and Lorentz invariance and neglecting higher dimensional operators, we end up with the following effective Lagrangian for the singlet case:

$$\mathcal{L}_{\text{singlet}} = \frac{1}{\Lambda} T_{\mu\nu} \left( f_1 B^{\alpha\nu} B^\alpha_\mu + f_2 W^{\alpha\nu}_i W^{i,\mu}_\alpha + 2 f_5 (D^\mu \Phi) (D^\nu \Phi) \right), \quad (2.5)$$

while the Lagrangian corresponding to the triplet case reads

$$\mathcal{L}_{\text{triplet}} = \frac{1}{\Lambda} T_{\mu\nu\lambda} \left( f_6 (D^\mu \Phi)^\dagger \sigma^\lambda (D^\nu \Phi) + f_7 W^{\mu\lambda}_j B^{\alpha\nu} \right). \quad (2.6)$$

$\Lambda$ is the characteristic energy scale of the underlying new physics, $f_i$ are variable coupling parameters, $B^{\alpha\nu}$ and $W^{\alpha\nu}_i$ are the usual electroweak field strength tensors and $D^\mu$ is the covariant derivative

$$D^\mu = \partial^\mu - igW^\mu_i \frac{\sigma^i}{2} - ig'YB^\mu. \quad (2.7)$$

Since the present spin-2 model is based on an effective Lagrangian approach, it violates unitarity above a certain energy scale. In order to parametrize high-energy contributions beyond this effective model, we introduce the following formfactor, which can be multiplied with the amplitudes:

$$f(p_1^2, p_2^2, k_{sp2}^2) = \left( \frac{\Lambda_{ff}^2}{|p_1^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_2^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|k_{sp2}^2| + \Lambda_{ff}^2} \right)^{n_{ff}}, \quad (2.13)$$

where $p_1^2$ and $p_2^2$ are the invariant masses of the initial electroweak bosons and $k_{sp2}^2$ is the squared invariant mass of the sum of the initial boson momenta, equivalent to that of an $s$-channel spin-2 particle. The energy scale $\Lambda_{ff}$ and the exponent $n_{ff}$ are free parameters, describing the scale of the cutoff and the suppression power, respectively.
Triggers and $m_T$ definition (analysis 2)

- Nominal triggers

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Period</th>
<th>High-level trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>2015</td>
<td>24m</td>
</tr>
<tr>
<td></td>
<td>2016 up to $0.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>24m_i</td>
</tr>
<tr>
<td></td>
<td>2016 up to $1.0 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>24t_i</td>
</tr>
<tr>
<td></td>
<td>2016 up to $1.2 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>26t_i</td>
</tr>
</tbody>
</table>

- $m_T$ definition

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|p_T^{\ell\ell} + E_T^{\text{miss}}\right|^2}, \quad E_T^{\ell\ell} = \sqrt{|p_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$$
Data/MC sample for analysis 2

- **Data samples:**
  - Full data in 2015+2016, Luminosity = 36.5 fb$^{-1}$

- **MC samples:**
  - Signal samples
    - NWA: Powheg + Pythia8
    - LWA: MG5_aMC@Nlo + Pythia8
    - GM/HVT: MG5_aMC@Nlo + Pythia8
    - ELM: VBFNLO + Pythia8
  - Background samples
    - Top: Powheg + Pythia8
    - WW: Sherpa 2.2.1
    - Non-WW diboson: Sherpa 2.2.1
    - Z+jets: Sherpa 2.1.1
    - Higgs: Powheg + Pythia8
Signal acceptance times efficiency (analysis 2)
W+jets estimation (analysis 2)

- Dijet sample for fake factor measurement:
  - selected using the single-lepton prescaled triggers with the low-p_T thresholds of 12 (14) GeV for electrons (muons)
  - Exactly one fake candidate object
  - Number of jets > 0
  - $p_{T}^{\text{jet}} > 22$ GeV
  - $p_{T}^{\text{fake}} > 15$ GeV
  - $\Delta\phi_{\text{fake,jet}} > 2.5$
  - $E_{T}^{\text{miss}} < 30$ GeV
  - $m_{T} < 60$ GeV
W+jets estimation - trigger bias (analysis 2)

- A small trigger bias:
  - Introduced when the anti-lepton fires the triggers while the id lepton does not fire the triggers.
  - Triggered fake factor: using the nominal unprescaled single-lepton triggers to select dijet sample

Nominal fake factor: applied to the most of events (92%) in the W+jets control sample
Triggered fake factor: only applied to the events (8%) where the anti-lepton fires the triggers and the id lepton does not fire the triggers.
W+jets estimation - CR (analysis 2)

- VBF 1J category

- VBF 2J category
Figure 58: Distributions of $m_{\ell\ell}$ (left) and $m_T$ (right) for the estimation obtained with the fake-factor method (data points) and the corresponding MC prediction (histogram) at the preselection level. The error bands in the lower plots correspond to the statistical uncertainty of the $W$+jets MC sample.
W+jets estimation (analysis 2)

Uncertainty associated with the jet flavour composition is estimated by summing in quadrature the two kinds of differences: the differences between the fake factors measured in the dijet data sample and those measured in the \(Z/\gamma^*\) + jets data sample, and the differences between the fake factors measured in the \(W\) + jets MC simulated event sample and those measured in the \(Z/\gamma^*\) + jets MC simulated event sample.

| Kinematic region (\(|\eta|\) and \(p_T\) range) | Flavour composition | EW subtraction | \(p_T\) dependence | Statistics | Total |
|-----------------------------------------------|---------------------|----------------|---------------------|------------|-------|
| Electron:                                     |                     |                |                     |            |       |
| \(0 < |\eta| < 1.5\)                           |                     |                |                     |            |       |
| \(15 - 20 \text{ GeV}\)                      | 36                  | 1              | \(-\)               | 2          | 36    |
| \(20 - 25 \text{ GeV}\)                      | 36                  | 2              | \(-\)               | 4          | 37    |
| \(25 - 35 \text{ GeV}\)                      | 36                  | 4              | \(< \) 1            | 4          | 37    |
| \(35 - 1000 \text{ GeV}\)                    | 36                  | 14             | 13                  | 8          | 42    |
| \(1.5 < |\eta| < 2.5\)                          |                     |                |                     |            |       |
| \(15 - 20 \text{ GeV}\)                      | 36                  | 1              | \(-\)               | 3          | 36    |
| \(20 - 25 \text{ GeV}\)                      | 36                  | 1              | \(-\)               | 4          | 37    |
| \(25 - 35 \text{ GeV}\)                      | 36                  | 3              | 1                   | 4          | 37    |
| \(35 - 1000 \text{ GeV}\)                    | 36                  | 7              | 10                  | 7          | 39    |
| Muon:                                         |                     |                |                     |            |       |
| \(0 < |\eta| < 1.1\)                           |                     |                |                     |            |       |
| \(15 - 20 \text{ GeV}\)                      | 39                  | 1              | \(-\)               | 1          | 39    |
| \(20 - 25 \text{ GeV}\)                      | 39                  | 2              | \(-\)               | 3          | 39    |
| \(1.1 < |\eta| < 2.5\)                         |                     |                |                     |            |       |
| \(15 - 20 \text{ GeV}\)                      | 39                  | 1              | \(-\)               | 1          | 39    |
| \(20 - 25 \text{ GeV}\)                      | 39                  | 3              | \(-\)               | 2          | 39    |
| \(0 < |\eta| < 2.5\)                          |                     |                |                     |            |       |
| \(25 - 1000 \text{ GeV}\)                    | 39                  | 21             | 11                  | 3          | 46    |

Table 6.5 Relative systematic uncertainties (in %) associated with the fake factor measurements at the preselection level. The column labeled "Total" is the sum in quadrature of all systematic sources.
$m_T$ shape uncertainties of Top and WW (analysis 2)
m_T shape uncertainties of NWA signal (analysis 2)
Correlations among nuisance parameters (analysis 2)

- NWA $m = 800$ GeV:

```
Correlation coefficients > 0.4 are shown
```
ATLAS MDT gas system work

Off-detector MDT gas system

- Supplies a steady gas flow
- Baseline of MDT gas mixture: Ar ~93%, CO₂ ~ 7%, H₂O~0.075%
- Chamber volume: ~725000 nl
- Operating pressure: 3 bar
- Running in a loop, driven by a pump
- Fresh gas input is 10% per day, 10% of gas is flushed per day.
- 15 distribution racks, each one contains 16 ~ 24 gas channels
- Controlled by GCS.

https://atlasop.cern.ch/twiki/bin/view/Main/MDTGasSystemOverview
ATLAS MDT gas system work

- On-detector MDT gas system

https://atlasop.cern.ch/twiki/bin/view/Main/MDTGasSystemOverview

On-detector MDT gas system
ATLAS MDT gas system work

- MDT leak measurement

Leak rate = 104 mbar/d

Procedure:

- Rack channel closed
- Measuring temperature and pressure
- Calculating temperature corrected pressure (normalized to $T_n=20^\circ C$)

Calculating gas loss using

\[ p_1 V_0 / T_1 = p_n V_n / T_n \]

- \( p_1 \): measured (uncorr.) pressure
- \( V_0 \): channel gas volume
- \( T_1 \): measured temperature
- \( V_n \): norm volume (3*\( V_0 \))
- \( T_n \): norm temperature (293K)
- \( P_n \): derived normalized pressure
## ATLAS MDT gas system work

- **MDT EO gas leak repairs (2014-2015)**

### 2014

<table>
<thead>
<tr>
<th></th>
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</table>

**EO A side:** Philipp Fleischmann, Guangyi Zhang

**EO C side:** Anatoli Kozhin, Vladimir Gushchin

### 2015

In the most case, gas leaks of EO are caused by cracks of gas jumpers made of NORYL.

1: gas-jumpers made of NORYL (old), 2: gas-jumper made of POCAN (new)
ATLAS MDT gas system work

  - BIS6C14_ML1
  - BOL2A03_ML1
  - BOL5A01_ML2

  - BME4A13_ML1
  - BMF2A14_ML1
  - EIL2A11_ML2
  - BIL4A01_ML1
ATLAS MDT gas system work

- MDT EO gas leak measurement and repairs (2016-2017)

Before repairs (2016)

After repairs (2017)

- Gas connections and leak measurement for all new MDT BMG chambers (2017):
Data taking
LHC / HL-LHC Plan

- **LS1**
  - 2011-2012: splice consolidation, button collimators, R2E project
  - 2013-2014: experiment beam pipes
  - 2015-2016: 7 TeV
  - 2017: 8 TeV

- **LS2**
  - 2018-2019: injector upgrade, cryo Point 4, Civil Eng. P1-P5
  - 2020: experiment upgrade phase 1

- **LS3**
  - 2021-2023: HL-LHC installation
  - 2024-2026: experiment upgrade phase 2
  - 2027: 300 fb⁻¹

- **EYETS**
  - 2017: experiment upgrade phase 1

- **Run 1**
  - 2011: 30 fb⁻¹

- **Run 2**
  - 2013-2016: 13-14 TeV
  - 2017-2018: 14 TeV

- **Run 3**
  - 2019-2020: 14 TeV

- **Run 4 - 5...**
  - 2021-2027: 2 x nominal luminosity

- **Energy**
  - 7 TeV
  - 8 TeV

- **Nominal Luminosity**
  - 75% nominal luminosity
  - 2 x nominal luminosity

- **Integrated Luminosity**
  - 3000 fb⁻¹