Searches for Di-Boson and Di-Lepton Resonances at the LHC

(w/new results for La Thuile 2018!)

John Alison
University of Chicago

on behalf of the ATLAS and CMS Collaborations
Introduction

Searches for new resonances are a critical part of the LHC physic program

Generic signatures that arise in many models of new physics

**Di-Boson Resonances:**
- Discovered a new particle with di-boson resonances: $Z\gamma / \gamma\gamma / WW$
- Recent development improve acceptance/sensitivities at high $P_T$
- With Higgs, more di-boson final states to search

**Di-Lepton Resonances:**
- $Z' \rightarrow ll / W' \rightarrow lv$ flagship searches
- Lepton resonances also have a rich history of discoveries in the field:
  - charm / bottom / $W / Z / ...$
## Di-Boson Search Program

<table>
<thead>
<tr>
<th></th>
<th>g</th>
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<th>W</th>
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The background is estimated directly from data, assuming that the association with partons, and SM diboson processes.

Pending on the category, the remaining fraction is composed of vector boson production in 95% of the total background. The top quark pair contribution is approximately 3–4%. Considering events with a discriminator larger than 0.9,

**Figure 1:** Distribution of the soft-drop PUPPI mass after the kinematic selections on the two jets, for data, simulated background, and signal. The signal events with low mass correspond to boson decays where one of the two quarks is emitted outside the jet cone or the two quarks are overlapping. The distributions are normalized to the number of events observed in data.

The dashed vertical lines represent the boundaries between the jet mass categories.

Event numbers / 5.0 GeV

- g
- γ
- W
- Z
- W/Z (hadronic)
- H

Soft-drop PUPPI jet mass (GeV)
# Di-Boson Search Program

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*ATLAS CMS*

*Covered in this Talk*
$X \rightarrow VV \quad (V = W \text{ or } Z)$

Ws and Zs, in turn, decay into...

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- Backgrounds fall steeply
- Hadronic decays become increasingly more sensitive

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At high-masses,
- Backgrounds fall steeply
- Hadronic decays become increasingly more sensitive

Decay products become collimated at high W/Z boosts.
- Dedicated reconstruction techniques targeting boosted topology
- Widely used in searches / Whole industry devoted to this subject
Clean final state / Background dominated by ZZ production

 gluon fusion production
 inclusive events selection

Vector Boson Fusion
 $M_{jj} \geq 400$ GeV

![Graphs showing distributions and comparisons between data and predictions](Image)

$X \rightarrow ZZ \rightarrow 4l$
X → WW → eνμν

- eμ requirement kills dominant Drell-Yan background
- Left with WW and ttbar production (constrained w/data using control regions)

Gluon fusion production
jet-veto

Vector Boson Fusion
\[ M_{jj} \geq 500 \text{ GeV} / \text{b-jet veto} \]
The momenta of the reconstructed jets are varied 1.5–3%, depending on the lepton flavor. The uncertainties in the lepton momentum and energy isolation are extracted from dedicated studies of events with leptonic Z decays, and amount to the recent CMS measurement of top quark pair production in dilepton events [37].

$\text{Z} \rightarrow \text{ll (e/\mu)}$ provides triggers / kills non-EW/top background.

**Low Mass Channel**
- jets ($r = 0.4$)

**High-Mass Channel**
- jets ($r = 0.8$) / mass $m_V$

$X \rightarrow \text{ZV} \rightarrow \text{llqq}$

The graviton signal prediction is represented by the black dashed histogram. The gray band indicates the statistical and post-fit systematic uncertainties in the normalization and shape of the $ZV$ background. The bottom panels show the pull distribution between data and post-fit SM prediction, where a 4% uncertainty is estimated, by comparing the background fit, where

In the background, the top quark production distributions for the low-mass search, in the the merged $VZ$ category and sideband regions. Electron and muon events are shown combined. A 600 GeV bulk $X$ background normalization, a 4% uncertainty is estimated, by comparing the

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In the background, the top quark production distributions for the low-mass search, in the the merged $VZ$ category and sideb
X → ZV → llqq

Z→ll (e/μ) provides triggers / kills non-EW/top background

Low Mass Channel
jets (r = 0.4) / b-tag channel

High-Mass Channel
jets (r = 0.8) / mass mv
$X \rightarrow WV \rightarrow lvqq$

$W \rightarrow lv$ / trigger (fit for $P_z(v)$ using $m_W$ constraint)
Larger jet mass window ($30 < m_\jet < 310$ GeV)

**Background estimation:** 2D likelihood fit to $(m_\jet, m_X)$
The lower panels show the significance of the observed event yield relative to the background fits taking their
the shaded bands represent the uncertainty in the background expectation. The lower panels show the significance
combined (d)

Figure 4

\[ V = \text{Significance} \]

Hadronic trigger + 2 large-R jets w/mass \( \sim m_V \)
Dominated by QCD multi-jet background.
Background shape from \( M_{VV} \) fit to data (using empirical parametric function)
Sensitive to signals with localized excess

\[ \chi^2/\text{DOF} = 8.1/9 \]

Study bkg shape in \( m_J \) sidebands
Relative VV Sensitivities

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

$\sigma (pp \rightarrow HVT W' W') [pb]$ v "Observed"

95% C.L. exclusion limits

- HVT model B $g'_v = 3$
- Observed
- Expected
- $qqqq$
- $lvqq$
- $llqq$
- $vqqq$

$\sigma (pp \rightarrow HVT W' W') [pb]$ vs $m_{W'} [TeV]$
$X \rightarrow HH$

- Signature predicted in several models
  \textit{Extra-dimensions / 2HDM / ...}

- Didn’t know how to look for it at previous colliders
  \textit{Interesting at relatively low-masses/large couplings}

- Potential large non-resonant enhancements in HH final state

- Long-term program to measure Higgs self-coupling
HH Final States

HH is an entire program in itself…
HH is an entire program in itself...

Analyses performed in ATLAS

Larger $\text{Br}-h$ decay

Rarer $\text{Br}-h$ decay
HH Final States

HH is an entire program in itself…

Analyses performed in ATLAS
Analyses performed in CMS

Larger Br-h decay
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Larger Br-$h$ decay

Rarer Br-$h$ decay

Analyses performed in ATLAS

HH Final States

Analyses performed in CMS

Summary of resonant searches D.
Majumder / SUSY 2017

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)

$\sigma(pp \to X \to HH)$ [fb]

95% CL limit on $\sigma(pp \to X \to HH)$ [fb]

bbVV arXiv:1708.04188
bb$\tau\tau$ arXiv:1707.02909
bb$\tau\tau$ PAS-B2G-17-006
bbbb PAS-HIG-17-009
bbbb arXiv:1710.04960
bb$\gamma\gamma$ PAS-HIG-17-008

- Expected
- Observed

Spin-2

Spin-0

bbWW

bb$\gamma\gamma$

4b

bb$\tau\tau$
HH Final States

HH is entire program in itself…

Larger Br-ħ decay

Focus on 4b in following

CMS Preliminary 35.9 fb⁻¹ (13 TeV)

95% CL limit on σ(pp→X→HH) [fb]

bbVV arXiv:1708.04188
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bbbb arXiv:1710.04960
bbγγ PAS-HIG-17-008

Expected
Observed
Spin-2

Rarer Br-ħ decay

Spin-0

bbWW

bbγγ

4b

bbττ

CMS

300 400 500 1000 2000 3000 4000

m_X [GeV]
X → HH → 4b

Select events with 4-b-tagged jets:
- Low-mass search: jets (r = 0.4) / b-jet trigger
- High-mass search: jets (r = 1.0) / b-tagging on sub-jet (track-jet)

Backgrounds: 
- ~90% Multi-jet
- ~10% ttbar

2b+2j to model 4 b-jet background

Control regions using $m_H$ sidebands
Select events with 4-b-tagged jets:

Low-mass search: jets (r = 0.4) / b-jet trigger

High-mass search: jets (r = 1.0) / b-tagging on sub-jet (track-jet)

Control regions using m_H sidebands
Select events with 4-b-tagged jets:

- **Low-mass search:** jets (r = 0.4) / b-jet trigger
- **High-mass search:** jets (r = 1.0) / b-tagging on sub-jet (track jet)

**non-resonant hh:**

- $\mu_{hh} < 13.0$ (20.7 expected) Strongest constraint on SM hh
Two large-R jets: $m_V$ one side / $m_H$ with btags other

Background dominated by multi-jets:
CMS: parametric fit (a la $X \rightarrow VV$)
ATLAS: extrapolate from 0-tags (a la $X \rightarrow HH$)

**Figure 4:** Dijet invariant distribution

<table>
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<tr>
<td>10^0</td>
</tr>
<tr>
<td>10^1</td>
</tr>
<tr>
<td>10^2</td>
</tr>
<tr>
<td>10^3</td>
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- **Data:** 468 events
- **Bkg. fit (2 par.):** $m_V = 2000$ GeV
- **Bkg. fit (3 par.):** $m_V = 2000$ GeV
- **HVT model B ($g_\gamma=3$):**

**ATLAS**

- **$\sqrt{s} = 13$ TeV**
- **36.1 fb$^{-1}$**

**2-tag WH**

- **Data:**
- **HVT Model B W' (2 TeV) x 50**
- **Multijet**
- **Other Backgrounds**
- **Pre-fit**
- **Uncertainty**

**CMS**

- **Z mass, high purity, tight b tag**

**HVT model B ($g_\gamma=3$)**
Model background expectations and only small discrepancies are observed, with local (global) significance.

A search for evidence of an excess in the large radius parameter. Jet substructure and

Figure 7:

Two large-R jets: (N_\text{bkg})/(N_\text{data}), expressed in terms of multiples of 2

100 200 300 400 500 600 700 800 900 1000

Y

\text{Events} / (100 \text{ GeV})

\text{Events} / (100 \text{ GeV})

X \rightarrow VH \rightarrow qqbb

\text{Harbinger of things to come: } Y \rightarrow XH \rightarrow qqbb

10^{-1}

10^{-2}

10^{-3}

\text{ATLAS}

\sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1}

\text{Observed CLs}

\sigma(p p \rightarrow \text{ZH}) \rightarrow \bar{q} \bar{q} \bar{b} \bar{b}) [\text{pb}]

1

\text{Events} / (100 \text{ GeV})

\text{Events} / (100 \text{ GeV})

m(X) [\text{GeV}]

m(Y) [\text{TeV}]

m_\text{VH} [\text{GeV}]

\text{arXiv:1709.06783}
## Di-Lepton Search Program

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**ATLAS**

**CMS**

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     | PAS-EXO-16-031 | arXiv:1607.08079  
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     | PAS-EXO-16-031 | arXiv:1706.04786  
     | PAS-EXO-16-031 | arXiv:1612.09274  
| µ   | arXiv:1707.02424  
     | PAS-EXO-16-031 | arXiv:1607.08079  
     | PAS-EXO-16-031 | arXiv:1607.08079  
     | PAS-EXO-16-031 | arXiv:1706.04786  
     | PAS-EXO-16-031 | arXiv:1612.09274  
| τ   | ATLAS         | CMS          | arXiv:1709.07242  
     | PAS-HIG-17-020 | arXiv:1801.06992  
     | PAS-EXO-16-006 | arXiv:1711.03301  
     |              | arXiv:1712.02345 |

Covered in this Talk
To reconstruct an electron candidate, energy depositions in the ECAL are first combined into a single event. Electrons and muons are reconstructed and identified using standard CMS algorithms, deeming them as candidates for the signal.

The CMS detector [18] with respective transverse momentum (p_{T}) thresholds of 50 and 175 GeV for muons and photons is used. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke. Electromagnetic calorimeters extend the pseudorapidity (|η|), providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two end sections, reside within the solenoid volume. Forward calorimeters extend the pseudorapidity (|η|) beyond the chosen |η| bounds. Lower: The cumulative (integral) distribution in events integrated over l_{1311} masses up to 1.28 TeV for l_{1311}. The present search significantly extends these limits.

The search is designed to be inclusive and model independent, requiring at least one prompt, isolated electron and at least one prompt, isolated muon in the event. This minimal selection, prior to the fit. Some events in the invariant mass distribution can have a negative event weight beyond the chosen |η| bounds. Also shown are the expectations for two possible signals. The two lower panels show the ratio of data to background predictions of data to background expectations before and after the fit. The total systematic uncertainties are given by the gray bands. Lower: The cumulative (integral) distribution in events integrated over l_{1311} masses up to 1.28 TeV for l_{1311}. The present search significantly extends these limits.

Inclusive Selection: e/µ: P_{T} > 53 GeV

Sensitive to variety of models

X → eµ

Targets models with lepton flavor violation

Different flavor requirement suppress large Drell-Yan production

Inclusive Selection:
e/µ: P_{T} > 53 GeV

Sensitivity to variety of models

Jet → e misidentification
QBH, n = 1, m_{q} = 1500 GeV
Single t
RPV, m_{l} = 1 TeV, λ = λ' = 0.01
Systematic uncertainty
Data
Critical channel search heavy Higgs 2HDM (MSSM)
ATLAS 36.1 fb\(^{-1}\) (CMS 35.9 fb\(^{-1}\))

Separate event selection targeting different:
Production modes: gluon-fusion / associated b-jet production
\(\tau\)-decay modes: \(\tau_{\text{lep}}\tau_{\text{had}} / \tau_{\text{had}}\tau_{\text{had}}\) (had-had stronger sensitivity)
(Pt: 30+25 165+45 GeV)

Most important background from multijets w/fake \(\tau\)s
- Data-driven modeling using fake-factors
- Systematic uncertainty varies between 10\% — 50 \%

Total transverse mass used for final discriminant:

\[
m_{T}^{\text{tot}} = \sqrt{(p_{T}^{\tau_{1}} + p_{T}^{\tau_{2}} + E_{T}^{\text{miss}})^2 - (p_{T}^{\tau_{1}} + p_{T}^{\tau_{2}} + E_{T}^{\text{miss}})^2}
\]
X → ττ

ATLAS √s = 13 TeV, 36.1 fb⁻¹

τ_hadτ_had b-veto

Events / GeV

ATLAS √s = 13 TeV, 36.1 fb⁻¹

τ_hadτ_had b-tag

Events / GeV

m_T^\text{tot} [GeV]

m_T^\text{tot} [GeV]

Significance

Significance

\frac{1}{2} \left( \frac{1}{p_T^2} + p_T^2 + E_{miss}^\text{miss} \right)^2 - 1
This paper presents the results of a search for neutral MSSM Higgs bosons as well as a resonance $X \rightarrow \tau\tau$. The data-driven technique used to estimate the dominant multijet background in the absence of jets tagged as originating from $\tau$-leptons from the lepton flavor violation processes are weighted by fake-rates measured in $\tau$-$\gamma$ decays. The search is performed in the 2015-2016 period. The lineshape of a resonance is considered "narrow" if the lineshape has no impact on experimental observables. The significance is calculated with conclusions in section 7.
**X \rightarrow \tau_{\text{had}} \nu**

Mono-$\tau_{\text{had}}$ signature / Interpreted in $W'$ scenario
Particularly important in models with enhanced 3rd generation couplings

**Event Selection:**
- MeT Trigger
- MeT > 150 GeV
- $P_T$ tau > 50 GeV
- $\tau$-ID: $\varepsilon \sim 60\%$ @ 100GeV (~30% @ 2 TeV)

**Counting experiment in m$_T$ in tail**

**Bkg Uncertainties:** 10 – 30%

**Figure 1:**
Transverse mass distribution after the event selection. The total impact of the statistical and systematic uncertainties on the SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is shown in the lower panel. The prediction for $W_0^{\text{SSM}}$ and $W_0^{\text{NU}}$ ($\cot \nu = 5.5$) bosons with masses of 3 TeV are superimposed.

To reduce the impact of statistical fluctuations in the jet background estimate, a function $f(m_T) = m_a + b \log m_T$, where $a$ and $b$ are free parameters, is fitted to the estimate in the range $400 < m_T < 800$ GeV and is used to evaluate the jet background in the range $m_T > 500$ GeV. The impact of altering the fit range leads to an uncertainty that increases with $m_T$, reaching 50% at $m_T = 2$ TeV. The statistical uncertainty from the control regions is propagated using pseudo-experiments and also reaches 50% at $m_T = 2$ TeV.

**Figure 2** shows the observed $m_T$ distribution of the data after event selection, including the estimated SM background contributions and predictions for $W_0^{\text{SSM}}$ and $W_0^{\text{NU}}$ ($\cot \nu = 5.5$) bosons with masses of 3 TeV. The number of observed events is consistent with the expected SM background. Therefore, upper limits are set on the production of a high-mass resonance decaying to $\tau \nu$. The statistical analysis uses a likelihood function constructed as the Poisson probability describing the total number of observed events given the signal-plus-background expectation. Systematic uncertainties in the expected number of events are incorporated into the likelihood via nuisance parameters constrained by Gaussian prior probability density distributions. Correlations between signal and background are taken into account. A signal-strength parameter, with a uniform prior probability density distribution, multiplies the expected signal. The dominant relative uncertainties in the expected signal and background contributions are shown in Figure 2 as a function of the $m_T$ threshold.

Limits are set at the 95% credibility level (CL) using the Bayesian Analysis Toolkit [60]. Figure 3 shows the model-independent upper limits on the visible $\tau \nu$ production cross section, $(pp \rightarrow \tau \nu + X) \cdot A \cdot $, as a function of the $m_T$ threshold, where $A$ is the fiducial acceptance (including the $m_T$ threshold) and $\epsilon$ is the reconstruction efficiency. Model-specific limits can be derived by evaluating $\epsilon$, $A$, and $\sigma$ for the model in question and checking if the corresponding visible cross section is excluded at any $m_T$ threshold. This allows the results to be reinterpreted for a broad range of models, regardless of their $m_T$ distribution. Good agreement between the generated and reconstructed $m_T$ distributions is found, indicating that a reliable calculation of the $m_T$ threshold acceptance can be made at generator level. The reconstruction efficiency
Conclusions

Rich program of resonance searches at LHC. *Lot I could not cover!*

Broad coverage targeting ~all relevant final states:
- Trend of targeting different production modes will continue
- Look for more relaxing of mass cuts: *1D searches → 2D scans*

*Expect updates with full run-2 data (~150/fb) set next spring/summer.*
Backup
Clean final state / Background dominated by ZZ production

Fig. 4: Distribution of the four-lepton invariant mass

No excess seen in CMS CMS-PAS-HIG-17-012
\(X \rightarrow ZZ \rightarrow 4l\)
The results of the present analysis were obtained using a model with a pair of quarks. Two analysis strategies, dedicated to the low- and high-mass regimes, have been employed, with the resonance mass. The dashed vertical line represents the separation between the low- and high-mass regions. Figure 7 shows the observed local p-values for W → ZV → llqq.

Figure 6 displays the observed and expected 95% CL upper limits on σ(13 TeV) X → ZZ → llqq with 35.9 fb⁻¹ of data. The CMS Preliminary data is shown, along with the 95% CL upper limits on the cross-section as a function of the resonance mass, including all statistical and systematic uncertainties.

The momenta of the reconstructed jets are varied, and the uncertainties in the lepton momentum and energy scales are taken into account, and propagated to the signal shapes and normalization, with uncertainties of 1.5–3%, depending on the lepton flavor. The uncertainties in the lepton isolation, identification, and efficiency for electron and muon reconstruction, identification, and measurement of tW WW, tW WW, and ZV, with a typical impact on the normalization of about 0.5–2% depending on the lepton flavor. Systematic uncertainties in the ZV and WW processes are fitted to data, excluding 1.5σ events with ee, mu pairs.

Electron and muon events are shown combined. A 600 GeV bulk graviton signal is compared to the signal shape of the background and signal samples. The signal region is defined according to the event topology. The data are well described by the background expectation, with a significance of 0.5σ.

CMS Preliminary data/fit = 0.5σ is consistent with SM predictions. The significance of the signal is consistent with the observed significance in data, and the expected significance in the SM. The observed and expected limits on the cross-section are compared for the total mass range.

The CMS Preliminary data/fit = 0.5σ in the signal region is consistent with SM predictions. The significance of the signal is consistent with the observed significance in data. The observed and expected limits on the cross-section are compared for the total mass range.
X → HH → 4b

\( \sqrt{s} = 13 \text{ TeV}, 27.5-36.1 \text{ fb}^{-1} \)

**ATLAS Preliminary**

- Observed 95% CL limit
- Expected 95% CL limit

<table>
<thead>
<tr>
<th>± 1σ</th>
<th>± 2σ</th>
</tr>
</thead>
</table>

Scalar → HH → b\(\bar{b}\)b\(\bar{b}\)

\( m_{\text{Scalar}} \) [TeV] vs. \( m_{4j} \) [GeV]

Expected 95% CL limit

Observed 95% CL limit

<table>
<thead>
<tr>
<th>Events / 12 GeV</th>
<th>Data / Bkgd</th>
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Select

Low

High

Resolved h Candidate Mass Plane

\( m_{4j} \) [GeV] vs. \( m_{4j} \) [GeV]

Resolved Control Region

(a)

(b)
Mono-$\tau_{\text{had}}$ Signals

Particularly important in models with enhanced 3rd generation couplings

Event Selection
- MeT Trigger
- MeT $> 1200$ GeV
- PT tau $> 50$ GeV
- $\tau$-ID: $\varepsilon \sim 60\%$ at 100 GeV ($\sim 30\%$ at 2 TeV)

Counting experiment in $m_T$ in tail

Limit on Production Cross Section

The 95% CL upper limit on the production cross section as a function of the $m_{W'}$

The $W'$ signal and background contributions are shown

Upper limits are set on the production of a high-mass resonance decaying to $\tau\nu$

The dominant relative uncertainties in the expected signal and background contributions are shown

Model-specific limits can be derived by evaluating

The reconstruction efficiency. Model-specific limits can be derived by evaluating

The impact of statistical fluctuations in the jet background estimate, a function

The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is depicted by the hatched area.
Di-Photons

**Experimental Signature**
- Two high pT (>75 GeV), isolated photons
- At-least one photon in barrel

**Background**
- Dominated by irreducible SM \(\gamma\gamma\) production: ~90%
- Parametric fit to data with empirical function

**Possible Interpretations**
- Spin 0: e.g. heavy scalar in non minimal Higgs sector
- Spin 2: e.g. graviton, as predicted in several extra-dimensions model (RS model)

**Figure 1:**
- ATLAS: Data vs. Background-only fit
  - Spin-2 Selection
  - \(\sqrt{s} = 13\) TeV, 36.7 fb\(^{-1}\)
- CMS: Data vs. Fit model
  - 12.9 fb\(^{-1}\) (13 TeV)
  - ± 1 s.d.
  - ± 2 s.d.
$\nu\tau \rightarrow pp$ ($\sigma_{ATLAS}^{-1} = 13$ TeV, 36.1 fb$^{-1}$)

Model independent 95% CL limits

$\nu\tau \rightarrow W'$

$\sigma_{SSM}$

Observed

Expected

$\sigma_{SSM}$

$\pm 1\sigma$

$\pm 2\sigma$

SSM

$W'_{SSM}$

$\pm 1\sigma$

ATLAS

$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

$W'_{SSM} \rightarrow \tau\nu$ 95% CL limits

Figure 4:

(a) The 95% CL upper limit on the cross section times $\tau\nu$ branching fraction for $W'_{SSM}$. The $W'_{SSM}$ cross section is overlaid where the additional lines represent the total theoretical uncertainty. (b) Excluded region for $W'_{SSM}$. The 95% CL limits from the ATLAS $ee$, $\mu\mu$ [62] and $\tau\tau$ [58] searches and indirect limits at 95% CL from fits to electroweak precision measurements (EWPT) [63], lepton flavor violation (LFV) [64], CKM unitarity [65] and the original $Z$-pole data [2] are overlaid.

Figure 3:
The 95% CL upper limit on the visible $\tau\nu$ production cross section as a function of the $m_{W'}$ threshold.
$\sigma(pp \rightarrow X \rightarrow ZZ)$ [pb]

$\Gamma = 0$ GeV

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

- Expected ± 1\(\sigma\)
- Expected ± 2\(\sigma\)
- Observed
- Expected 4l
- Expected 2l2q
- Expected 2l2\(\nu\)
Figure 8: Comparisons of the observed data and expected background distributions of the final discriminants of the ggF category for the $H \rightarrow ZZ \rightarrow \ell\ell qq$ search: $m_{\ell\ell}$ of (a) high-purity and (b) low-purity signal regions; $m_{jj}$ of (c) $b$-tagged and (d) untagged signal regions. For illustration, expected distributions from the ggF production of a 1 TeV Higgs boson with $\tilde{p} B(H \rightarrow ZZ)$ = 20 fb are also shown. The middle panes show the ratios of the observed data to the background predictions. The uncertainty in the total background prediction, shown as bands, combines statistical and systematic contributions. The blue triangles in the middle panes indicate bins where the ratio is nonzero and outside the vertical range of the plot. The bottom panes show the ratios of the post-fit and pre-fit background predictions.
The measurement, background modelling and luminosity. For signals with higher mass, the data statistical uncertainty becomes dominant. The expected limits.

For bulk RS model with on the mass in this model is 1.3 (1.6) TeV for the observed (expected) limit. Similar results are obtained from 3.3 pb at 300 GeV to 0.74 fb at 5 TeV for the bulk RS model with between 300 GeV and 5 TeV, as shown in Figure 13.

The theoretical predictions of the HVT model. The observed limit ranges from 5.7 pb at 300 GeV to 1.3 fb at 5 TeV for DY production and from 0.98 pb at 300 GeV to 2.8 fb at 4 TeV for VBF production. The theoretical predictions of the HVT model space can be excluded for the VBF process with the current sensitivity of the analysis.

The effects of systematic uncertainties are studied for hypothesised signals using the signal-strength parameter. The relative uncertainties in the best-fit value from the leading sources of systematic uncertainties are shown in Table 13.
Figure 3. Schematic of the fake-factor background estimation in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel. The fake-factors, $f_X$ ($X = \text{MJ, W, L}$), are defined as the ratio of events in data that pass/fail the specified selection requirements, measured in the fakes-regions: MJ-FR, W-FR and L-FR, respectively. The multijet contribution is estimated by weighting events in CR-2 by the product of $f_L$ and $f_{\text{MJ}}$. The contribution from $W$+jets and $t\bar{t}$ events where the $\tau_{\text{had-vis}}$ candidate originates from a jet is estimated by subtracting the multijet contribution from CR-1 and then weighting by $f_W$. There is a small overlap of events between L-FR and the CR-1 and CR-2 regions. The contribution where both the selected $\tau_{\text{had-vis}}$ and lepton originate from leptons is estimated using simulation (not shown here).