Recent results on VBF and VBS measurements

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On behalf of the ATLAS and CMS Collaborations
Motivation for VBF/VBS Measurements

Since LHC is a QCD machine, electroweak (EWK) production cross-sections are the smallest measured processes
Since LHC is a QCD machine, electroweak (EWK) production cross-sections are the smallest measured processes.
Experimental uncertainties are much larger than theoretical.
EW sector can serve as a portal to discoveries in the near future.
Standard Model processes - constrains on particle properties and gauge couplings

- HVV coupling with VBF (2208.02338)
- EWK Zγ+jj (2208.12741)
- EWK Wγ+jj (SMP-21-011)
- Exclusive WW/ZZ (2211.16320)
- Exclusive γγ (CMS-PAS-EXO-21-007)
• Probe of the CP structure of HVV interactions
• SM Lagrangian augmented with CP-odd dim-6 operators involving Higgs and EW gauge fields in EFT formalism

\[ |\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2 \cdot c_i \cdot \text{Re}(\mathcal{M}^*_\text{SM} \cdot \mathcal{M}_{CP-odd}) + c_i^2 \cdot |\mathcal{M}_{CP-odd}|^2.\]

• H→γγ channel was studied, and the results were combined with 36 fb\(^{-1}\) H→ττ (PLB 805 2020 135426)
• Analysis used BDT-based event categorization
Optimal Observable method used to probe the CP structure of interactions:

\[ OO = 2 \cdot \text{Re}(\mathcal{M}^*_\text{SM} \cdot \mathcal{M}_{\text{cp-odd}})/|\mathcal{M}_{\text{SM}}|^2 \]

The most stringent constraints on CP-properties of HVV coupling to date.
• Electro-Weak production of $Z\gamma$, in $Z \rightarrow \nu\nu$ decay mode
• Produced via WW scattering and characterized by two forward jets
• High $p_T^\gamma$ region serves as an important probe of the QGC
• First Observation of EWK $Z(\nu\nu)\gamma+2j$ at $5.2\sigma$ was reported by ATLAS collaboration ([EPJC 82 (2022) 105](https://link.springer.com/article/10.1140/epjc/s10052-022-10230-6)) with $p_T^\gamma \in [60,115]$ more details later
• Early measurements of EWK $Z(\ell\ell)\gamma+2$ reported last year by ATLAS ([ATLAS-CONF-2021-038](https://atlas.cern.ch/)) and CMS ([PRD 104 (2021) 072001](https://link.aps.org/doi/10.1103/PhysRevD.104.072001)) collaborations, with measured $\sigma_{fid}$ of $4.49 \pm 0.58$ fb and $5.21 \pm 0.76$ fb respectively

**Signature:** highly energetic photon, high MET and two jets
Backgrounds:

- Main backgrounds: QCD $Z(\nu\nu)\gamma+2j$ (36%) and QCD $W(\ell\nu)\gamma+2j$ (25%)
Validation:

- Fitted distributions in the Wγ CR, Wγ CR and the SR
Results:

- Observed (expected) significance: 3.2 σ (3.7σ)
- Fiducial cross-section: $0.77^{+0.34}_{-0.30}$ fb
- Dim-8 aQGC limits are based on MET distribution, results with and w/o cut-off scale were extracted

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>$E_c$ [TeV]</th>
<th>Observed limit [TeV$^{-4}$]</th>
<th>Expected limit [TeV$^{-4}$]</th>
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<tbody>
<tr>
<td>$f_{T0}/\Lambda^4$</td>
<td>1.7</td>
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<tr>
<td>$f_{M2}/\Lambda^4$</td>
<td>$[-1.9, 1.9]$</td>
<td>$[-2.6, 2.6]$</td>
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</tbody>
</table>
• Electro-Weak production of \( W \gamma \), in \( W \rightarrow \ell \nu \) decay mode
• Produced via \( W \gamma \) scattering and characterized by two forward jets
• Extend the first observation paper, PLB 811 (2020) 135988, to full Run 2 dataset
• The first Observation of EWK \( W \gamma +2j \) at 5.3\( \sigma \) obs. RunI+20106EWK production is sensitive to TGC and QGC couplings
• Fiducial and differential cross-section measurement

Signature: Isolated lepton, high \( M_{W\gamma} \) and two jets

https://cms.cern/news/lhc-w-photon-collider
Signal and Background:

- Main background $\text{QCD } W(\ell\nu)\gamma$
- Fit performed in 2D distribution of $m_{jj}$ and $m_{\ell\nu}$

QCD $W\gamma$ CR:

$200 < m_{jj} < 400$
Results:

- Observed (expected) significance: $6.03 \sigma$ ($6.79 \sigma$)
- Fiducial cross-section: $90.2^{+10.7}_{-10.3}$ fb, differential: see backup
- Dim-8 aQGC limits are based on $M_{WY}$ distribution, tightening selection cuts: $m_{jj} > 800$ (SR=500), photon $p_T > 100$ GeV (SR=25)
• Electro-Weak production of WW/ZZ pairs, in fully hadronic decay mode

• Produced via γγ scattering and characterized by two forward protons using forward proton spectrometers (sensitive to proton momentum loss of 4%-20%)

• Sensitive to TGC and QGC, QGC enhance high mass spectra
• Electro-Weak production of WW/ZZ pairs, in fully hadronic decay mode
• Produced via $\gamma\gamma$ scattering and characterized by two forward protons using forward proton spectrometers (sensitive to proton momentum loss of 4%-20%)
• Sensitive to TGC and QGC, QGC enhance high mass spectra
• In Central exclusive production:

  **Central system kinematics**

  \[ \text{Central system kinematics} = \text{Proton kinematics} \]

  **Signature: Two V-tagged jets, two tagged forward protons**
Results:

• At high mass, SM cross-sections are very small
• The obtained limit on SM fiducial cross-section:
  \[ \sigma_{WW} < 67 \text{fb} \text{ and } \sigma_{ZZ} < 43 \text{fb} \] for \( 0.04 < \xi < 0.2 \) and \( m_{VV} > 1 \text{TeV} \)
• Limits on EFT operators (clipping at 1.4 TeV)

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Observed (expected) 95% CL upper limit</th>
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<tr>
<td>(</td>
<td>f_{M,0}/\Lambda^4</td>
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\( a_0^W/\Lambda^2 \text{ and } a_0^Z/\Lambda^2 \text{ and } a_C^W/\Lambda^2 \text{ and } a_C^Z/\Lambda^2 \text{ limits:} \)

\[ |a_0^W/\Lambda^2| < 4.3 \times 10^{-6} \text{ GeV}^{-2} \]
\[ |a_0^Z/\Lambda^2| < 1.6 \times 10^{-5} \text{ GeV}^{-2} \]
\[ |a_C^W/\Lambda^2| < 0.9 \times 10^{-5} \text{ GeV}^{-2} \]
\[ |a_C^Z/\Lambda^2| < 4.0 \times 10^{-5} \text{ GeV}^{-2} \]
Motivated by sensitivity to BSM:


Almost background free after requiring matching between proton and photon kinematics.

First measurement with 2016 (~10fb$^{-1}$) publish the first limit on 4-photon coupling, *PRL 129 (2022) 1, 011801*

\[
|\zeta_1| < 2.9 \times 10^{-13} \text{ GeV}^{-4} (\zeta_2 = 0) \\
|\zeta_2| < 6.0 \times 10^{-13} \text{ GeV}^{-4} (\zeta_1 = 0)
\]
**Results:**

- The full Run 2 data – low background
- Limit on 4-photon coupling improved by x4(!)

\[ |\zeta_1| < 7.3 \times 10^{-14} \text{ GeV}^{-4} \ (\zeta_2 = 0) \]

\[ |\zeta_2| < 1.5 \times 10^{-13} \text{ GeV}^{-4} \ (\zeta_1 = 0) \]

First search for ALPs in mass range between 500 GeV to 2000 GeV
Searches Beyond the Standard Model using VBS / VBF production processes

- VBF Majorana neutrinos (2206.08956)
- VBF $H\rightarrow\text{Inv.}$ (PRD 105 2022 092007, JHEP 08 2022 104)
- EW MET+$\gamma$+jj (EPJC 82 2022 105)
- Exclusive missing mass (CMS-PAS-EXO-21-007)
Many ways to explain $m_\nu \neq 0$: the neutrinos may be either Dirac or Majorana fermions (Majorana → Lepton Number Violation)

- Neutrinoless $\beta \beta$-like process at colliders: VBF process $pp \rightarrow \ell \ell jj$
- Motivated by PRD.103.055005 (heavy neutrino) or PRD.103.115014
- Produced via WW scattering and characterized by two forward jets

**Signature:** Two same-sign leptons, two VBF jets
Heavy Majorana neutrino and Weinberg operator analyses are defined in bins of $\Delta \phi_{ll}$ and MET, respectively, apply VBF selection

Discriminating variable: HT/leading lep pT

The most stringent constraints at the LHC to date for $m > 650$ GeV!!!
- Exploit VBF topology – events with a pair of jets with large angular separation on the $\eta$ plane and large invariant mass
- Produced via WW scattering and characterized by two forward jets
- Backgrounds: $Z \rightarrow \nu\nu$ (QCD and EWK), $W \rightarrow \ell\nu$ with lost lepton

Systematic strongly reduced exploiting $2\ell$ and $1\ell$ CRs
• Categorize event selection to 16 bins of MET, $m_{jj}$, $\Delta \phi_{jj}$

• Results (observed):

  Upper limit of BR(H125→inv) = 0.145

• Categorize event selection to 2 regions:
  MET Triggered, VBF jet triggered

• Results (observed):

  Upper limit of BR(H125→inv) = 0.18
• Categorize event selection to 16 bins of MET, $m_{jj}$, $\Delta\phi_{jj}$

• Results (observed):
  \[
  \text{Upper limit of BR}(H_{125} \rightarrow \text{inv}) = 0.145
  \]

• Categorize event selection to 2 regions: MET Triggered, VBF jet triggered

• Results (observed):
  \[
  \text{Upper limit of BR}(H_{125} \rightarrow \text{inv}) = 0.18
  \]
• Similar VBF-like selection + one extra photon
• Usually radiated from the scattering W within the large rapidity gap between two VBF jets
• Final state dominated by $\text{EWK } Z(\nu\nu)\gamma+2j$

Paper reports first observation of this process at the LHC!!!
DNN-based classification used as a discriminating variable

Most important inputs:

- Leading jet kinematics and angular separation
- Invariant mass of two VBF jets
- Missing energy
- Photon pseudorapidity

Assuming SM cross-section, Upper limit of BR(H125→inv) = 0.37

Results are limited by statistics
• Dark photon interpretation of semi-invisible Higgs decays
  Upper limit of: $\text{BR}(H125\rightarrow\gamma\gamma_D) = 0.018$

• ATLAS Combination among all Higgs production modes: $\text{BR}(H125\rightarrow\text{inv}) = 0.107$
Searching for unknown particles using the "missing mass"

- Implemented for the first time in hadron collider, based on $4\pi$ event reconstruction
Searching for unknown particles using the “missing mass”

- Implemented for the first time in hadron collider, based on $4\pi$ event reconstruction
- The 4-vector of unknown state $\chi$ is determined from protons and measured boson

\[ m_{\text{miss}}^2 = \left[ \left( P_{p_1}^{\text{in}} + P_{p_2}^{\text{in}} \right) - \left( P_V + P_{p_1}^{\text{out}} + P_{p_2}^{\text{out}} \right) \right]^2 \]

- Bump hunt of mass of $\chi$ state is performed in $Z+\chi$ and $\gamma+\chi$ channels
Exclusive missing mass

- Searching for unknown particles using the “missing mass”
  - Benefit from supreme mass resolution
Searching for unknown particles using the "missing mass"

- Benefit from supreme mass resolution
- Data agree with the background-only model, a limit on the production cross-section of $Z/\gamma+\chi$ was derived
• Recent measurements of VBF and VBS topologies were presented, with no discrepancies with Standard Model predictions.

• The newly presented probes in the EW sector are limited by statistical uncertainties – to be pursued with Run 3 and beyond.

• VBF / VBS topologies can serve as a tool to look at new physics, in particular, to search for invisible decay modes (H->invisible, missing mass, etc).
Backup
References to public plots

Standard model (constraints on $a_{QGC}$)

- EW $Z\gamma jj$ ([STDM-2018-59](#)), via $Z(\nu\nu)$ decay
- EW $W\gamma jj$ ([CMS-PAS-SMP-21-011](#))
- Exclusive $WW/ZZ$ ([CMS-PAS-SMP-21-014](#))
- Exclusive $\gamma\gamma$ ([CMS-PAS-EXO-21-007](#))

Beyond the Standard model

- VBF Majorana neutrinos ([EXO-21-003](#))
- VBF $H\rightarrow Inv.$ ([HIG-20-003, EXOT-2020-11](#))
- EW MET+$\gamma$+$jj$ ([EXOT-2021-17](#))
- Exclusive missing mass ([CMS-PAS-EXO-19-009](#))
**Dim-8 Operators**

- Eboli and Gonzalez-Garcia parametrization ([1310.6708](#))

**M operators**

\[
O_{M,0} = \text{Tr}\left[\bar{W}_{\mu\nu}W^{\mu\nu}\right] \times \left( (D_\beta \Phi)^\dagger (D^\beta \Phi) \right)
\]

\[
O_{M,1} = \text{Tr}\left[\bar{W}_{\mu\nu}W^{\nu}\right] \times \left( (D_\beta \Phi)^\dagger (D^\mu \Phi) \right)
\]

\[
O_{M,2} = B_{\mu\nu}B^{\mu\nu} \times \left[ (D_\beta \Phi)^\dagger (D^\beta \Phi) \right]
\]

\[
O_{M,3} = B_{\mu\nu}B^{\nu} \times \left[ (D_\beta \Phi)^\dagger (D^\mu \Phi) \right]
\]

\[
O_{M,4} = \left( (D_\mu \Phi)^\dagger \bar{W}_{\beta\nu}(D^\mu \Phi) \right) \times B^{\beta\nu}
\]

\[
O_{M,5} = \left( (D_\mu \Phi)^\dagger \bar{W}_{\beta\nu}(D^\nu \Phi) \right) \times B^{\beta\mu}
\]

\[
O_{M,6} = \left( (D_\mu \Phi)^\dagger \bar{W}_{\beta\nu}\bar{W}^{\beta\nu}(D^\mu \Phi) \right)
\]

\[
O_{M,7} = \left( (D_\mu \Phi)^\dagger \bar{W}_{\beta\nu}\bar{W}^{\beta\mu}(D^\nu \Phi) \right)
\]

**T operators**

\[
O_{T,0} = \text{Tr}\left[\bar{W}_{\mu\nu}W^{\mu\nu}\right] \times \text{Tr}\left[\bar{W}_{\alpha\beta}W^{\alpha\beta}\right]
\]

\[
O_{T,1} = \text{Tr}\left[\bar{W}_{\alpha\nu}W^{\nu}\right] \times \text{Tr}\left[\bar{W}_{\mu\beta}W^{\alpha\nu}\right]
\]

\[
O_{T,2} = \text{Tr}\left[\bar{W}_{\alpha\mu}W^{\mu\beta}\right] \times \text{Tr}\left[\bar{W}_{\beta\nu}W^{\nu}\right]
\]

\[
O_{T,3} = \text{Tr}\left[\bar{W}_{\alpha\mu}W^{\mu\beta}\bar{W}^{\nu}\right] \times B^{\beta\nu}
\]

\[
O_{T,4} = \text{Tr}\left[\bar{W}_{\alpha\mu}W^{\alpha\mu}\right] \times B^{\beta\nu}
\]

\[
O_{T,5} = \text{Tr}\left[\bar{W}_{\mu\nu}W^{\alpha\beta}\right] \times B^{\alpha\beta}
\]

\[
O_{T,6} = \text{Tr}\left[\bar{W}_{\alpha\nu}W^{\mu}\right] \times B^{\beta\nu}
\]

\[
O_{T,7} = \text{Tr}\left[\bar{W}_{\alpha\mu}W^{\mu\beta}\right] \times B^{\beta\nu}
\]

\[
O_{T,8} = B_{\mu\nu}B^{\mu\nu}B^{\alpha\beta}
\]

\[
O_{T,9} = B^{\beta\nu}B^{\nu\alpha}
\]
Event selection: highly energetic photon, high MET and two jets

- Trigger: Single photon trigger, with $p_T > 140\text{ GeV}$ with loose ID
- Exactly one photon, lepton veto, missing energy above 120 GeV, at least two jets ($j_1, j_2$)
- Angular separation $\Delta \phi (j_{1,2}, E_T^{miss}) > 0.3$ and $\Delta \phi (\gamma, E_T^{miss}) > 0.4$
- VBS selection: $m_{jj} > 300\text{ GeV}$, $\gamma$-centrality $\zeta = \frac{y(\gamma)-0.5(y(j_1)+y(j_2))}{y(j_1)+y(j_2)} < 0.6$

Object selection:

- Photons with $p_T > 150\text{ GeV}$ and $|\eta|<2.37$, Electrons with $p_T > 7\text{ GeV}$ and $|\eta|<2.47$, both outside calorimeter transition region ($1.37<|\eta|<1.52$)
- Muons with $p_T > 7\text{ GeV}$ and $|\eta|<2.47$
- Jets with $p_T > 50\text{ GeV}$ and $|\eta|<4.5$, Radius parameter $R = 0.4$
Discriminating variable:

- BDT used as final discriminator, where the BDT was trained against Zγ inclusive region
- The following input variables are used in the training
  - $m_{jj}$
  - $\Delta y_{jj}$, $\sin(\Delta \phi_{jj}/2)$, $\Delta y_{\gamma j_1}$
  - $E_T^{\text{miss}}$
  - pT-balance (+reduced) $\Sigma \vec{p}_T / \Sigma E_T$
  - $\eta(j_2), \eta(\gamma)$
  - $p_T(j_1)$
  - $N_{\text{jets}}$
Systematics:

- Fitted distributions in the $W\gamma$ CR, $W\gamma$ CR and the SR

<table>
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<tr>
<th>Source of uncertainty</th>
<th>$\Delta \sigma / \sigma$ [%]</th>
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<tbody>
<tr>
<td>Jets</td>
<td>$-3.2$ / $+3.4$</td>
</tr>
<tr>
<td>Electrons and photons</td>
<td>$-0.3$ / $+1.7$</td>
</tr>
<tr>
<td>Muons</td>
<td>$-0.4$ / $+0.5$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>$-1.8$ / $+2.2$</td>
</tr>
<tr>
<td>Pile-up modelling</td>
<td>$-1.7$ / $+3.2$</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>$-0.9$ / $+2.1$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$-1.2$ / $+2.6$</td>
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</table>

### Experiment

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta \sigma / \sigma$ [%]</th>
</tr>
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<tbody>
<tr>
<td>$Z(\nu\bar{\nu})\gamma j j$ EWK/QCD interference</td>
<td>$-0.6$ / $+2.6$</td>
</tr>
<tr>
<td>$Z(\nu\bar{\nu})\gamma j j$ EWK process</td>
<td>$-6$ / $+12$</td>
</tr>
<tr>
<td>$Z(\nu\bar{\nu})\gamma j j$ QCD process</td>
<td>$-15$ / $+16$</td>
</tr>
<tr>
<td>Other processes</td>
<td>$-5.3$ / $+7.7$</td>
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### Theory

<table>
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<th>Source of uncertainty</th>
<th>$\Delta \sigma / \sigma$ [%]</th>
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<tbody>
<tr>
<td>Data-driven backgrounds</td>
<td>$-0.9$ / $+1.2$</td>
</tr>
<tr>
<td>Pile-up background</td>
<td>$-1.2$ / $+2.6$</td>
</tr>
<tr>
<td>$Z(\nu\bar{\nu})\gamma j j$ QCD $m_{jj}$ modelling</td>
<td>$-4.4$ / $+4.4$</td>
</tr>
</tbody>
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![Graph of fitted distributions in the $W\gamma$ CR, $W\gamma$ CR and the SR](chart.png)
Event selection: Isolated lepton, high $M_{W\gamma}$ and two jets

- Trigger: Single lepton trigger
- Exactly one $\ell + \gamma$, transverse mass of $W > 100$ GeV, in electron channel $|m_{\ell\gamma} - m_Z| > 10$ GeV
- Missing energy above 30 GeV, at least two jets ($j_1$, $j_2$), veto additional leptons with $p_T > 10$ GeV
- Angular separation $\Delta R > 0.5$, $|m_{jj}| > 500$ GeV and $|\eta_{jj}| > 2.5$, $y(W\gamma) - 0.5(y(j_1) + y(j_2)) > 1.2$ and $\Delta \phi(W\gamma) > 2$

Object selection:

- Photons/Electrons with $p_T > 25/35$ GeV, $|\eta| < 2.5$, both outside transition region (1.444 < $|\eta|$ < 1.566)
- Muons with $p_T > 35$ GeV and $|\eta| < 2.4$
- Jets with $p_T > 50$ GeV and $|\eta| < 4.5$, Radius parameter $R = 0.4$
Results:

- Differential cross-section obtained for EWK only
Results:

- Differential cross-section obtained for EWK only
Results:

- Differential cross-section obtained for EWK+QCD
Results:

- Differential cross-section obtained for EWK+QCD
Event selection: Two V-tagged jets, two tagged forward protons

- Trigger: jet triggers ($p_T$ or HT) depends on year
- At least two V-tagged jets
- Jet1 $p_T / $ Jet2 $p_T < 1.3, |\Delta n_{jj}|<1.3$ 1126 < $m_{jj}$/GeV < 2500,
- Elastic selection: $|1 – \phi_{jj}/\pi|<0.01$, two forward protons matched kinematically to VV

Object selection:

- Jets with $p_T > 200$ GeV and $|\eta|<2.5$, Radius parameter $R = 0.8$
Backgrounds:

- Dominated by inclusive QCD dijet production
- Estimated using the ABCD method – $N_A = N_B \cdot N_C / N_D$