Multiboson measurements in CMS

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on behalf of CMS collaboration

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Introduction

Multiboson = production of multiple $W$, $Z$ or $\gamma$

Diboson

Electroweak Diboson

triboson
Motivations

Why study multiboson production?

- test the structure of electroweak (EW) theory
  - Boson couplings affect cross-sections and polarization
  - anomalous (triple/quartic) gauge couplings
    - higher dimension EFT operators
- Probe EW symmetry breaking in Vector Boson Scattering (VBS)
  - unitarity preserved in VBS with Higgs
    - w/o: x-sec \( \sim E^2 \)
  - deviation would impact cross sections and aTGC/aQGC

![Graph showing EFT limits](twiki)
Recent CMS Results

Inclusive

- **VV** (V=W/Z)
  - **WW**: PhysRevD.102.092001
  - **ZZ**: EurPhysJC 81:200 (2021)
  - **VV@ 5.02 TeV**: PhysRevLett 127.191801

- **Wγ**
  - inclusive ; PhysRevLett. 126.252002
  - **differential**: arxiv 2111.13948

- **VVV**: PhysRevLett.125.151802
- **VVγ**: JHEP 2110.174
- **Vector Boson Fusion**:
  - **VV**: EurPhysJC 81:723 (2021)

VBS

- **Fully leptonic**
  - Polarized same-sign WW: PhysLetB.2020.136018
  - WZ & SS WW: PhysLetB.2020.135710
  - ZZ: PhysLetB.2020.135992
  - **OS WW**: SMP-21-001

- **Semi-leptonic**
  - **WV**: arxiv 2112.05259

- **VVγ**
  - **Zγ**: PhysRevD.104.072001
  - **Wγ**: PhysLetB.2020.135988

In **red**: results presented in this talk
Cross sections

CMS Preliminary

June 2021

Production Cross Section, $\sigma$ [pb]

- 7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)
- 13 TeV CMS measurement ($L \leq 137 \text{ fb}^{-1}$)
- Theory prediction
- CMS 95%CL limits at 7, 8 and 13 TeV

Diboson

Triboson

VBS

low cross section (XS) for VBS in particular!

All results at: http://cern.ch/go/pNj7
Low pile-up run: $\mu_{5\text{TeV}} = 2$ ($\mu_{13\text{TeV}} = 23,32$)

Categories:
- WW -> $\ell\ell$
- WZ -> (a) $3\ell$ (b) 2 same-sign muons
- ZZ (a) $4\ell$ (b) $2\ell + 2\nu$

**first measurement at 5.02 GeV**
Consistent with NNLO QCD + NLO EWK predictions

\[
\begin{align*}
\sigma_{WW} &= 37.0^{+5.5}_{-5.2} \text{(stat)}^{+2.7}_{-2.6} \text{(syst)} = 37.0^{+6.2}_{-5.8} \text{ pb}, \\
\sigma_{WZ} &= 6.4^{+2.5}_{-2.1} \text{(stat)}^{+0.5}_{-0.3} \text{(syst)} = 6.4^{+2.5}_{-2.1} \text{ pb}, \\
\sigma_{ZZ} &= 5.3^{+2.5}_{-2.1} \text{(stat)}^{+0.5}_{-0.4} \text{(syst)} = 5.3^{+2.6}_{-2.1} \text{ pb},
\end{align*}
\]
**Wγ : Differential Cross sections**

Differential cross section measurement to explore radiation amplitude zero effect RAZ interference in LO diagrams make xs vanish in certain phase space region, could be affected by BSM.

Good agreement with simulation, more signal in high Δη regions compared to predictions.

Tighter selections to observe RAZ

Bigger dip at Δη(ℓ, γ) = 0 than in NNLO predictions.

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arxiv 2111.13948
W_\gamma : aTGC constraints

Sensitive to dim-6 aTGC

New constraints on C_{3W}

\[ \sigma^{tot} = \sigma_{SM} + C_{3W} \sigma_{int} + C_{3W}^2 \sigma_{BSM} \]

- At \( E > m_W \), SM and BSM have different helicity configurations for \( W_VV \rightarrow angle\)-inclusive variables insensitive to \( \sigma_{int} \)
- Solution: search in 2D space of \( |\phi_f| \) and \( p_T^\gamma \)

10x improvement with \( \Phi \) binning

arxiv 2111.13948
VBS multiboson production

- Purely electroweak process with unique topology
  - two very forward jets, with large $\eta$ separation and invariant mass
- very rare process ($\sim fb^{-1}$) with high irreducible background (from QCD)
  - only accessible with LHC run II
  - sophisticated signal extraction and data driven bkg estimation
- longitudinal polarized part of V connected to Higgs mechanism
- SM extension with dim-8 operators standing for anomalous couplings
- different channels depending on both V decay mode
  - fully leptonic
  - semi leptonic (one V decay leptonically, the other hadronically)
  - full hadronic
Fully leptonic VBS $W^\pm W^\mp$

- select $e^+e^-$, $\mu^+\mu^-$, $e\mu$ final states, opposite charge
- $p_T^{\text{miss}} > 20$ GeV
- $m_{jj} > 300$ GeV, $\Delta\eta > 2.5$
- b-jet veto to suppress top bkg

Signal discrimination
- $e\mu$ category 1 variable depending on $m_{jj}/\Delta\eta$
  - $m_{jj}$ at high $m_{jj}/\Delta\eta$
  - number of events the rest of phase space
- $e\mu$: Deep Neural Network
  - Background data driven estimation
  - normalization in bins of $m_{jj}/\Delta\eta$

First observation
observed (expected) significance = 5.6 (5.2)$\sigma$
biggest nuisance: background data driven normalizations and QCD scale
VBS WV semi-leptonic

- larger XS than fully leptonic
- smaller bkg than fully hadronic
- two topologies: either two resolved jets or one boosted jet for the $V \rightarrow q\bar{q}$ candidate
- Data driven estimation in dedicated control regions for two main backgrounds: $W +$ jets and tops

arxiv 2112.05259
VBS WV semi-leptonic : results

Signal discrimination with DNNs

Simultaneous fit to QCD and EWK signal strengths

First evidence observed (expected) significance = 4.4(5.1)σ

$\mu_{EW} = \frac{\sigma^{\text{obs}}}{\sigma^{\text{SM}}} = 0.85 \pm 0.12 \, \text{(stat)}^{+0.19}_{-0.17} \, \text{(syst)} = 0.85^{+0.23}_{-0.21}$

$\mu_{EW+QCD} = 0.97 \pm 0.06 \, \text{(stat)}^{+0.19}_{-0.21} \, \text{(syst)} = 0.97^{+0.20}_{-0.22}$

12/15
VBS $Z\gamma$

- No photon coupling to Higgs
  - sensitivity to neutral (a)QGC and (a)TGC
- Main backgrounds:
  - QCD $Z\gamma$: estimated from MC, constrained in simultaneous fit
  - Non-prompt photon: data-driven estimate through photon shape fit
- Signal extracted with $m_{jj}$ and $\Delta\eta_{jj}$

Differential XS in $p_T$ of first lepton, first jet, photon & $m_{jj}$

Generally good agreement data/predictions
Invariant mass of Z and photon used for aQGC study.

- Most stringent limit to date on dim-8 operator $T_9$: $-0.91 < F_{T_9}/\Lambda^4 < 0.91$
- Competitive constraints on $M_0$ to $M_2$, $T_0$ to $T_2$ and $T_5$ to $T_9$

First observation at 9.4 (8.5) SD

$$\sigma_{EW}^{fid} = 5.21 \pm 0.52(stat) \pm 0.56(syst) \, fb = 5.21 \pm 0.76 \, fb$$

$$\sigma_{EW}^{theo} = 4.34 \pm 0.26(scale) \pm 0.06(PDF) \, fb$$

$$\sigma_{EW+QCD}^{fid} = 14.7 \pm 0.80(stat) \pm 1.26(syst) \, fb = 14.7 \pm 1.53 \, fb$$

$$\sigma_{EW+QCD}^{theo} = 13.3 \pm 1.72(scale) \pm 0.10(PDF) \, fb$$
Conclusion

- A lot of results in 2021 using run II data
  - measured XS generally agree well with predictions
  - limits on new physics with several EFT operators
- More results to come, several analysis are still underway
- Statistics is the limiting factor for most multiboson results
  - Run 3 is expected to improve them
  - large increase in HL-LHC