





EFT beyond Higgs: Measurements of diboson and multiboson production and associated EFT constraints, including global combination

Mia Liu On behalf of ATLAS and CMS

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## Diboson and Multibosons at the LHC



## Diboson and Multibosons at the LHC

Aug 2023		CN	IS Preliminary	
CMS measurements 5.02 vs. NNLO (NLO) theory		5.02, 7, 8, 13 TeV CMS measurements (stat,stat+sys)		
$\begin{array}{cccccccccccccccccccccccccccccccccccc$		$1.06 \pm 0.01 \pm 0.12$ $1.16 \pm 0.03 \pm 0.13$ $1.01 \pm 0.00 \pm 0.05$ $0.98 \pm 0.01 \pm 0.05$ $0.98 \pm 0.01 \pm 0.05$ $1.01 \pm 0.13 \pm 0.14$ $1.24 \pm 0.18 \pm 0.09$ $1.07 \pm 0.04 \pm 0.09$ $1.00 \pm 0.02 \pm 0.08$ $1.00 \pm 0.01 \pm 0.06$ $0.57 \pm 0.20 \pm 0.04$ $1.05 \pm 0.07 \pm 0.06$ $1.02 \pm 0.04 \pm 0.07$ $1.00 \pm 0.02 \pm 0.03$ $1.36 \pm 0.59 \pm 0.12$ $0.97 \pm 0.13 \pm 0.07$ $0.97 \pm 0.06 \pm 0.08$ $1.04 \pm 0.02 \pm 0.04$	$\begin{array}{c} 5.0 \ \text{fb}^{-1} \\ 5.0 \ \text{fb}^{-1} \\ 137 \ \text{fb}^{-1} \\ 5.0 \ \text{fb}^{-1} \\ 19.5 \ \text{fb}^{-1} \\ 4.9 \ \text{fb}^{-1} \\ 0.302 \ \text{fb}^{-1} \\ 19.4 \ \text{fb}^{-1} \\ 35.9 \ \text{fb}^{-1} \\ 0.302 \ \text{fb}^{-1} \\ 19.6 \ \text{fb}^{-1} \\ 137 \ \text{fb}^{-1} \\ 0.302 \ \text{fb}^{-1} \\ 137 \ \text{fb}^{-1} \\ 19.6 \ \text{fb}^{-1} \\ 137 \ \text{fb}^{-$	
0 1 All results at: http://cern.ch/go/pNj7	Prod	uction Cross Section Ratio	$\sigma_{exp}^4 / \sigma_{theo}^4$	

Aug 2023		CMS	3 Preliminary
CMS measurements vs.	7 TeV CMS measurement (stat,stat+sys)		H-0+1
	8 TeV CMS measurement (stat,stat+sys)		<b>⊢</b> +●+-1
	13 TeV CMS	measurement (stat,stat+sys)	⊢∔●∔⊣
VVV +++		$1.02 \pm 0.21 \pm 0.14$	137 fb <sup>-1</sup>
WWW ++ ++		$1.16 \pm 0.30 \pm 0.28$	137 fb <sup>-1</sup>
WWZ 🗝		0.85 ± 0.31 ± 0.13	137 fb <sup>-1</sup>
WZZ ++		2.18 ± 1.47 ± 0.49	137 fb <sup>-1</sup>
WWy 💾 🗕 🖂		$1.30 \pm 0.22 \pm 0.29$	138 fb <sup>-1</sup>
₩γγ ⊢ <del>· <mark>•</mark> · · ·</del>		$1.03 \pm 0.29 \pm 0.34$	19.4 fb <sup>-1</sup>
₩γγ ⊢+∙++	$\Lambda \Lambda \Lambda$	$0.73 \pm 0.10 \pm 0.22$	137 fb <sup>-1</sup>
Ζγγ μ <mark>ο μ</mark>	vvv	$0.98 \pm 0.11 \pm 0.14$	19.4 fb <sup>-1</sup>
Ζγγ ++ <mark>+</mark> +		$0.91 \pm 0.09 \pm 0.11$	137 fb <sup>-1</sup>
All results at: http://cern.ch/go/pNj7	Productio	n Cross Section Ratio:	$\sigma_{\rm exp}/\sigma_{\rm theo}^{8}$



- **Diboson**: access to triple gauge boson coupling (TGCs), entering precision era.
- Vector Boson Scattering (VBS) and triboson: Access to quartic gauge boson couplings (QGCs), first evidences and observations
- **BSM** effects parametrized by higher dimension operators in an effective field theory framework

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{c_{i}^{(5)}}{\Lambda} O_{i}^{(5)} + \sum_{i} \frac{c_{i}^{(6)}}{\Lambda^{2}} O_{i}^{(6)} + \dots$$

## Connection with the Higgs

Vector boson scattering



VVV: TGC mediated, Higgs mediated, QGC



## **SM processes with QGC**

process\QGC	wwww	WWZZ	WWZγ	WWγγ
WWjj	Х	x	X	X
WZjj		х	X	
ZZjj		x		
W/Zγjj			X	X
WW (via γγ)				X
WWW	Х			
WWZ		Х	Х	
WZZ		Х		
Wγγ				Х
WZγ			Х	
WWγ			Х	Х

- TGCs/diboson are relatively well-known
- More channels are sensitive to Dim (6) and Dim(8) operators. E.g. ZZZ

#### **Evidences/Discoveries of processes with QGC**

Process\QGC	LHC results
WWjj	Observation of EWK production, search with τ leptons, Evidence of VBS WV, Obs of EWK. Obs OS WW
WZjj	Evidence of VBS WV, Observation
ZZjj	Evidence, Observation
W/Zγjj	Observation, Evidence
WW (via γγ)	Search for exclusive production
www	Observation (VVV), Evidence, Observation
WWZ	Observation (VVV), Evidence
WZZ	Observation (VVV)
Wγγ	Observation, Evidence
WZγ	<b>Observation</b>
WWγ	Observation

An incomplete list, please see the latest results here: <u>ATLAS</u> and <u>CMS</u>

# Today's talk

- Highlight recent experiment results from ATLAS and CMS, focused on recent observations, new signatures, new (or resurrection) techniques
  - New results completing the 'observation chart'
    - Constraints on Higgs couplings from VVV
  - Include hadronic τ leptons
  - CP violating terms
  - Differential measurements
  - Interference as a probe for higher order operators
  - Run 3 result at 13.6 TeV



#### W and Z decay leptonically:

3 leptons (e/ $\mu$ ) plus additional photon, full Run-2 data. **6.3 (5)**  $\sigma$  observed(expected)

#### Observation of WWγ & constraints on Higgs coupling to light fermions

link

![](_page_8_Figure_1.jpeg)

![](_page_9_Figure_0.jpeg)

#### EWK W±W±jj constraints on Dim-8 operators

![](_page_10_Figure_1.jpeg)

link

![](_page_11_Figure_0.jpeg)

### Differential measurements of $ZZ \rightarrow 4I$

link

![](_page_12_Figure_1.jpeg)

- High m<sub>41:</sub> MC over predicts, needs EWK correction
- nNNLO+PS prediction describes the distribution of jet multiplicities better

![](_page_13_Figure_0.jpeg)

link

![](_page_13_Figure_2.jpeg)

Inferences between TGC and ISR modify angular distributions.

Constraints on C<sub>3w</sub>

**Differential distributions** 

#### **VBS Wy also measured** differentially: Link

![](_page_13_Figure_7.jpeg)

1500

![](_page_14_Figure_0.jpeg)

![](_page_14_Figure_1.jpeg)

25

LHC Data 2022 √s=13.6 TeV

● ATLAS ZZ→ IIII (m, 66-116 GeV) 29 fb

[qd

<u>link</u>

![](_page_15_Figure_0.jpeg)

# Final Remark

- LHC data provides opportunities in discovering and studying events with multiple bosons.
- More in the pipeline with full Run-2 data
  - e.g. VVV with boosted jets targeting EFT
- LHC Run 3 data collection on-going at 13.6 TeV
  - Measurements at different center of mass. More stats provides opportunities in differential measurements, more extensive studies on dim-6 and dim-8 operators, isolating longitudinally polarized components.
  - And other creative ways of analyzing our datasets.
- Stay tuned!

![](_page_17_Figure_0.jpeg)

W) with a

DNN as main discriminate for background suppression

- ratio of  $p_T$  of the leading track of the jet associated with  $\tau_h$  to the  $\tau_h p_T$ .
- Significance:
  - 2.7 standard deviations observed (1.9 expected) for electroweak same-sign WW scattering, QCD production fixed to SM.
  - Simultaneous fits: observed (expected) significance of 2.9 (2.0) standard deviation
- VBS EWK production has been confirmed in e/µ channels.e.g. Observation of VBS WW EWK

## Evidence of pair production of longitudinally polarized vector bosons and study of CP properties in $ZZ \rightarrow 4I$

![](_page_18_Figure_1.jpeg)