

QCD@LHC 2026

University of Oxford • Department of Physics • St. Anne's College

Vector Boson Scattering Measurements at CMS

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on behalf of the CMS Collaboration



Motivation: Why measure VBS?

❖ Tests EWSB directly

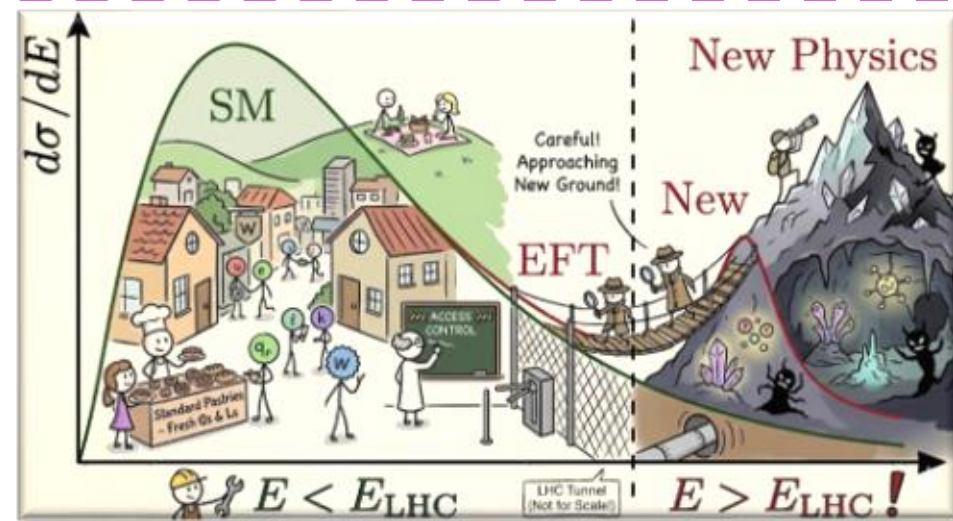
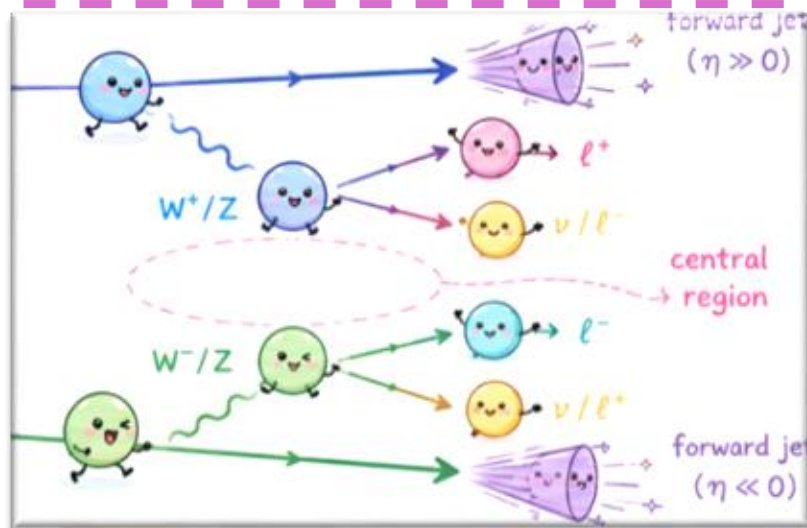
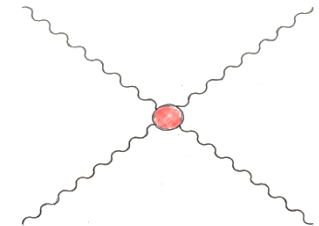
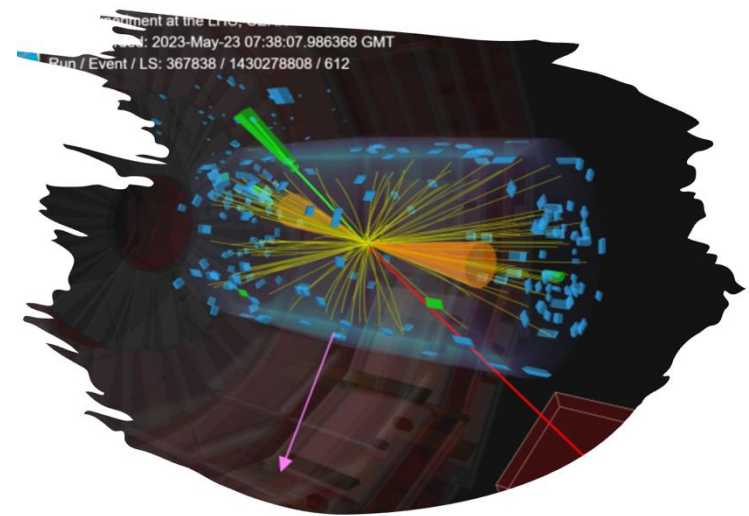
- $W_L W_L \rightarrow W_L W_L$ requires the Higgs to cancel the growth with energy
- Longitudinal scattering = Goldstone bosons of EWSB

❖ Probes the gauge structure of the SM

- Tree-level access to triple and quartic gauge couplings
- Rate relies on cancellations between diagrams $\rightarrow$ sharp test of gauge invariance

❖ Window on new physics

- Probes the high-energy electroweak/Higgs sector
- Heavy new states show up in the high-mass tails, parametrised via SMEFT



Why VBS: EWSB is the LHC's central question



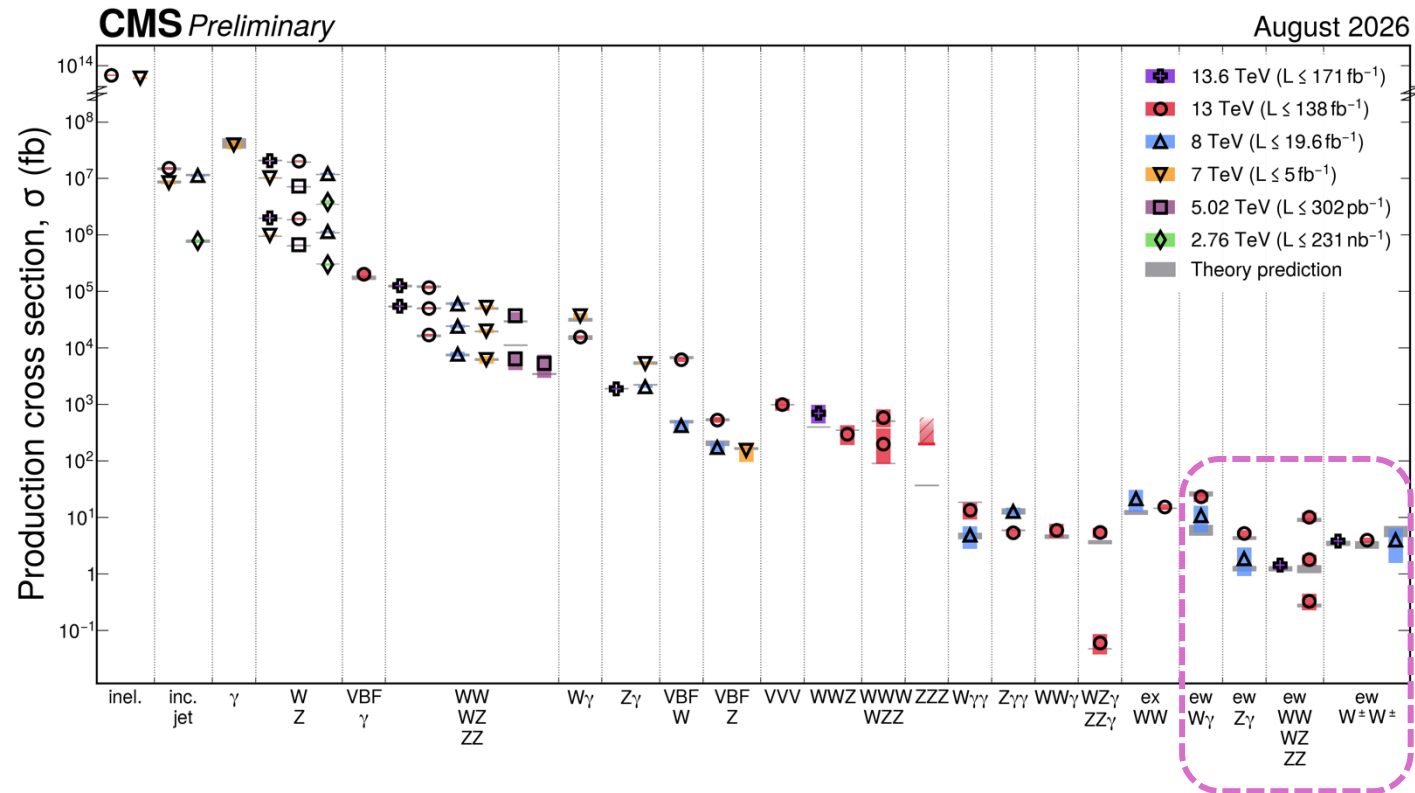
Introduction

[CMS TDR](#)

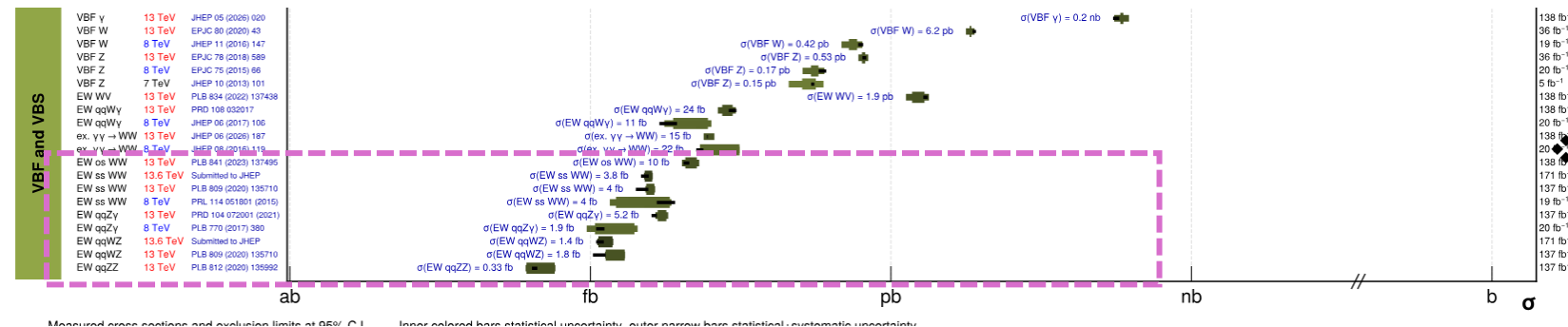
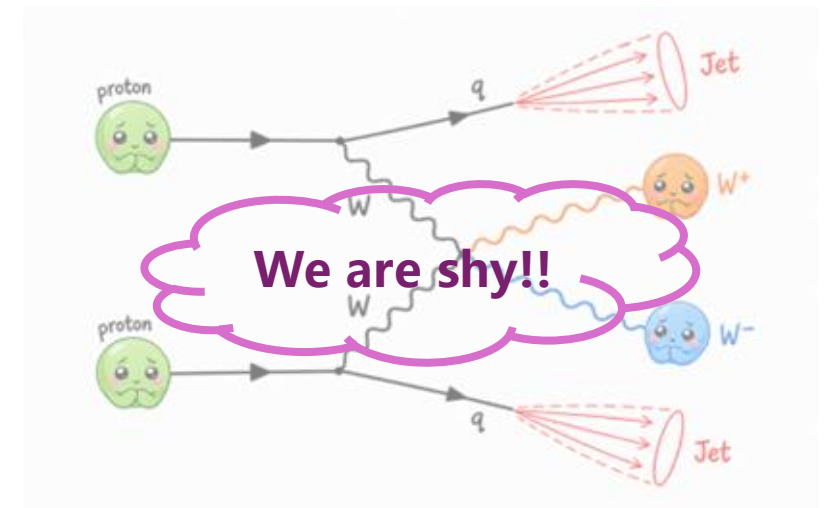
Although the Standard Model (SM) of particle physics has so far been tested to exquisite precision, it is considered to be an effective theory up to some scale $\Lambda \approx \text{TeV}$. The prime motivation of the Large Hadron Collider (LHC) is to elucidate the nature of electroweak symmetry breaking for which the Higgs mechanism is presumed to be responsible. The experimental study of the Higgs mechanism also can shed light on the mathematical consistency of the SM at energy scales above about 1 TeV. However, there are alternatives that invoke more symmetry such as supersymmetry or invoke new forces or constituents such as strongly-broken electroweak symmetry, technicolour, etc. An as yet unknown mechanism is also possible.

Why VBS: rare, but now accessible

[CMSPublic_PhysicsResultsCombined](#)



- ❖ VBS processes have among the **smallest cross sections** in the Standard Model.
- ❖ The pure electroweak VBS signal appears at $\mathcal{O}(\alpha_{EW}^4)$.
- ❖ EW signal $\mathcal{O}(\alpha^4)$ under a large QCD background Oparen. $\rightarrow$ precision needs good QCD modelling
- ❖ With the rapidly increasing LHC dataset, these rare processes are now experimentally accessible.



VBS Production

❖ VBS topology:

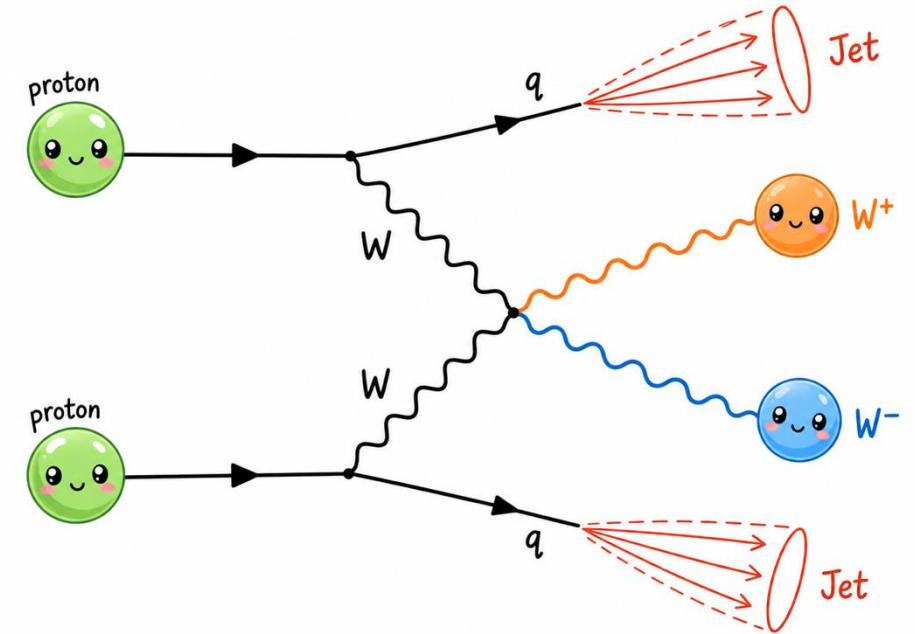
- Producing massive vector bosons requires energetic incoming quarks that radiate vector bosons, which then scatter.

❖ Initial states:

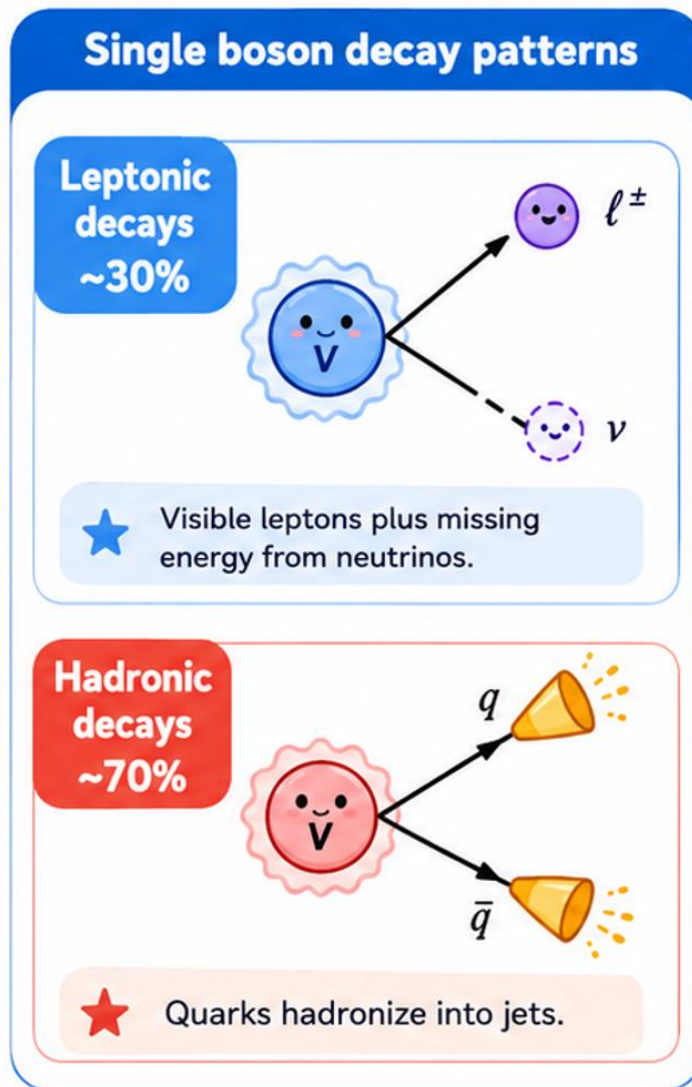
- Quarks from the incoming protons, selected according to the proton PDFs, radiate W/Z bosons
- W^+ production is generally favored by the proton's quark content.

❖ Final states:

- The quarks continue into the forward region as the characteristic **tagging jets**.

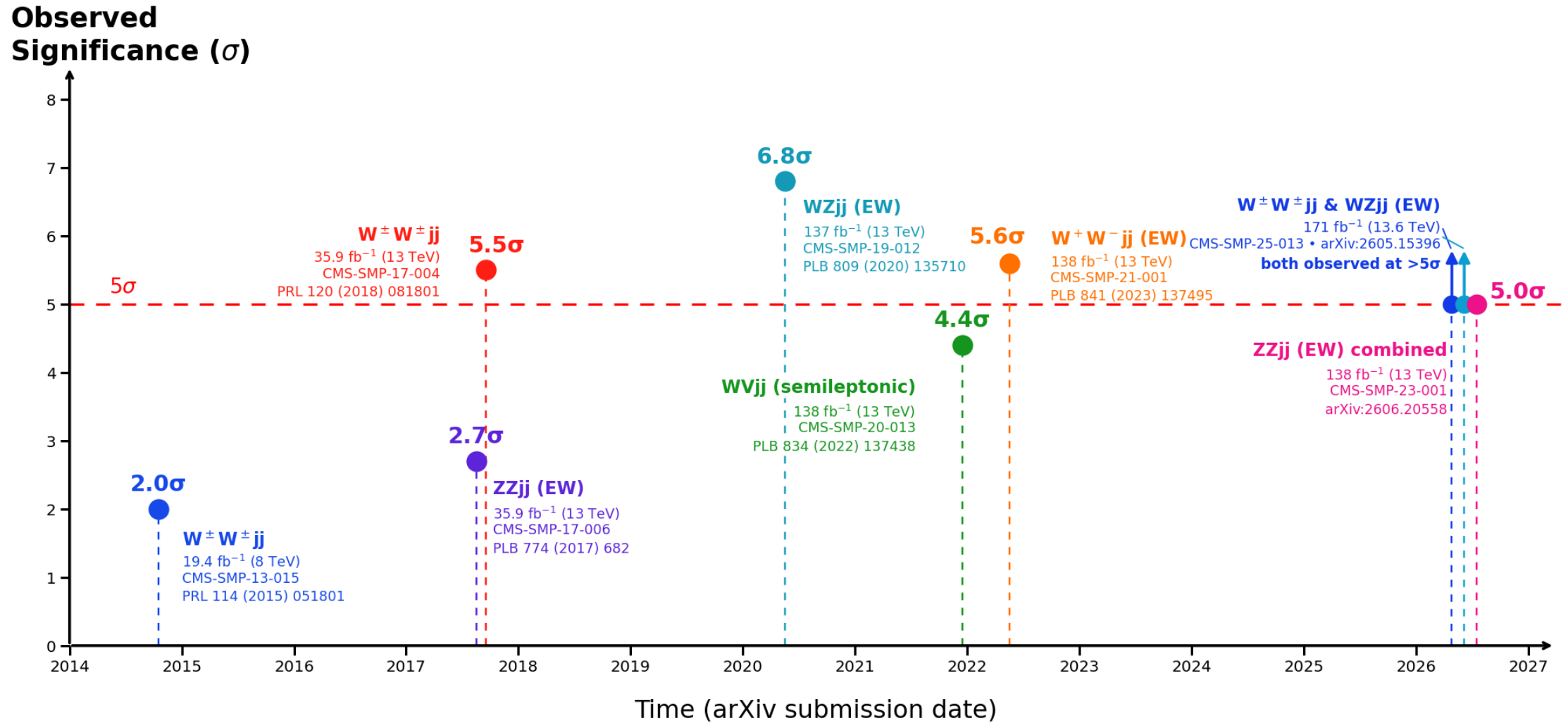


VBS Decay Channels



	Leptonic	Semileptonic	Hadronic
 Overview	Both bosons decay to leptons or neutrinos → large missing energy	One bosons decays leptonically, the other hadronically → one lepton + jets	Both bosons decay hadronically → fully hadronic final state
 Advantages	• Clean signature • Smallest background	• Good balance of statistics and clean signature • One fully reconstructed boson	• Highest statistics • Complete reconstruction of the final state
 Limitations	• Lowest statistics • Limited information from kinematics	• Still limited by lepton reconstruction	• Large QCD background and pileup

Landscape and content



Landscape and content

Observed
Significance (σ)

8
7

CMS VBS results

- ❖ Same sign WW and WZ measurements with Run3 [[SMP-25-013](#)]
- ❖ First evidence of VBS ZZ $\ell\ell\nu\nu$ with Run2 [[SMP-23-001](#)]
- ❖ Results of VBS combination with Run2 [[SMP-24-013](#)]
- ❖ ZV and WV EFT combination with Run2 [[SMP-22-011](#)]

2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

EW = Electroweak Production
VBS topology selection
All results from CMS

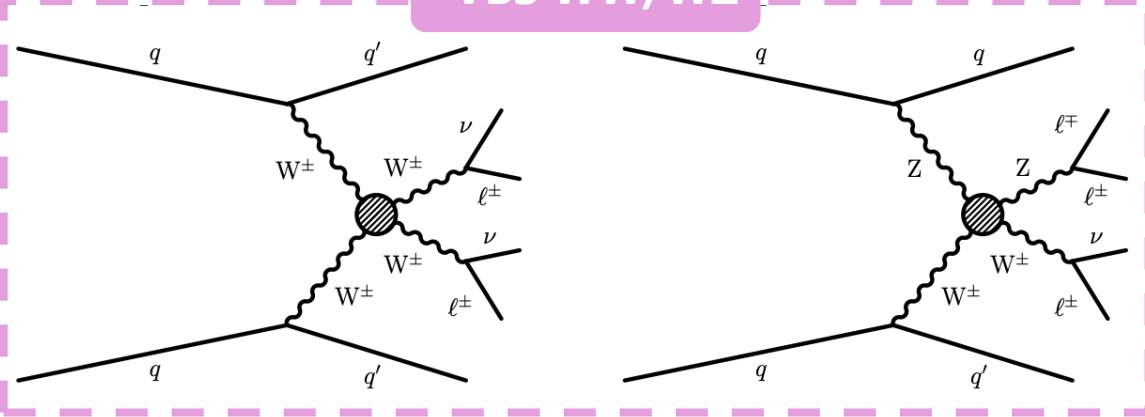
Time (Publication / Public-Result Year)

† Latest Run-3 result as of
Sep 2, 2026 (not yet published)

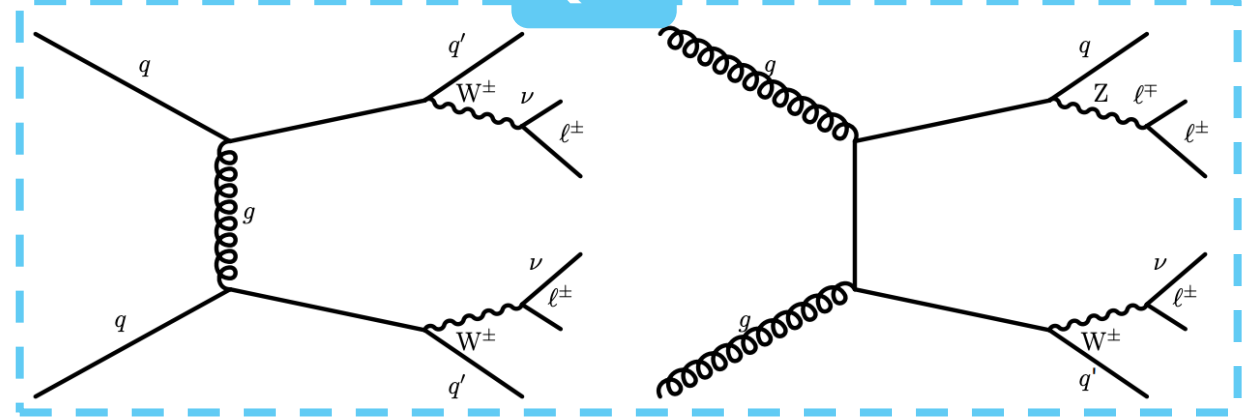
Same sign WW and WZ measurements with Run3

Submitted to JHEP: [arXiv:2605.15396](https://arxiv.org/abs/2605.15396)

VBS WW/WZ



QCD



- ❖ VBS directly probes the electroweak sector and quartic gauge couplings, using same-sign $W^\pm W^\pm$ and WZ leptonic final states.
- ❖ Run 2 established VBS with $>5\sigma$ observations, motivating a shift from discovery to precision measurements.
- ❖ Run 3 uses 171 fb^{-1} of 2022-2024 data to measure inclusive and differential VBS cross sections. Key improvements:
 - larger dataset
 - refined signal extraction
 - more robust non-prompt background estimation

Same sign WW and WZ measurements with Run3---Analysis strategy

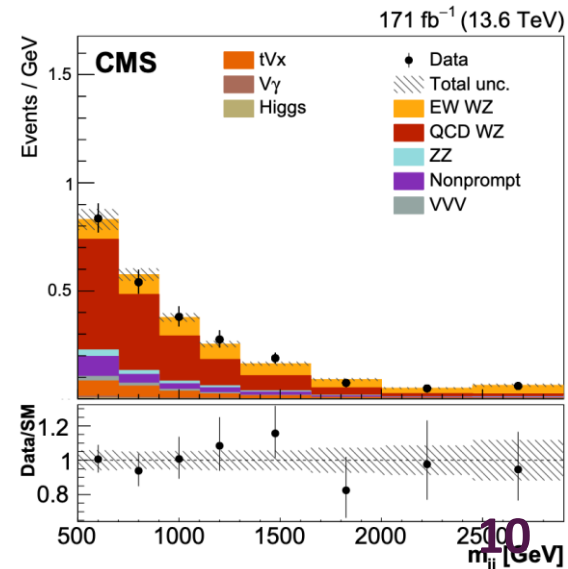
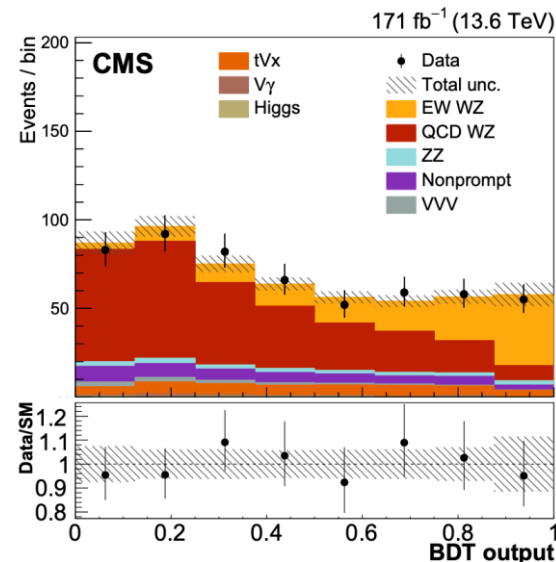
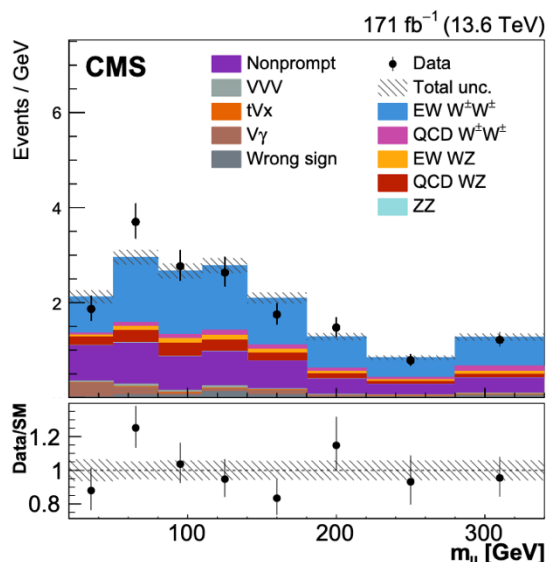
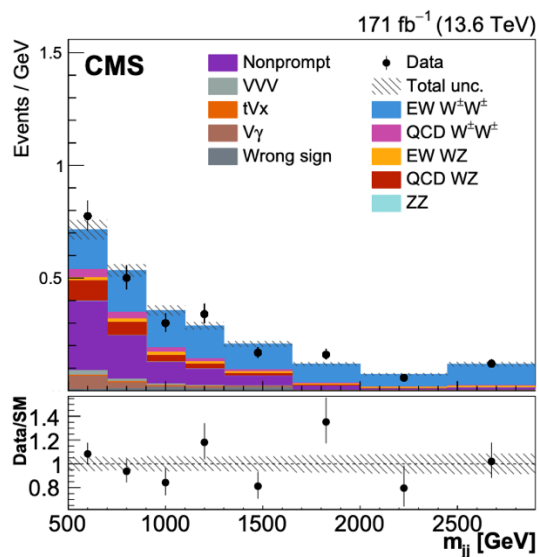
- **Exploit the characteristic VBS topology:** two energetic forward tagging jets with large M_{jj} and $|\Delta\eta_{jj}|$ together with central leptons and p_T^{miss} .
- **Control the dominant backgrounds with dedicated data control regions,** especially non-prompt leptons and top-related backgrounds, and constrain them simultaneously with the signal regions.

$$W^\pm W^\pm jj \rightarrow \ell^\pm \nu \ell^\pm \nu jj$$

- ❖ **Signature:** 2 same-sign leptons + p_T^{miss} + two VBS tagging jets; **b-jet veto** suppresses top.
- ❖ **Backgrounds:** **non-prompt leptons dominate**, estimated with data-driven methods; charge mis-ID is subleading.
- ❖ **Signal extraction:** **2D kinematic fit** using m_{jj} , $m_{\ell\ell}$, N_{jets} , $\Delta\eta_{jj}$, $\Delta\phi_{jj}$.

$$W^\pm Zjj \rightarrow \ell^\pm \nu \ell \ell jj$$

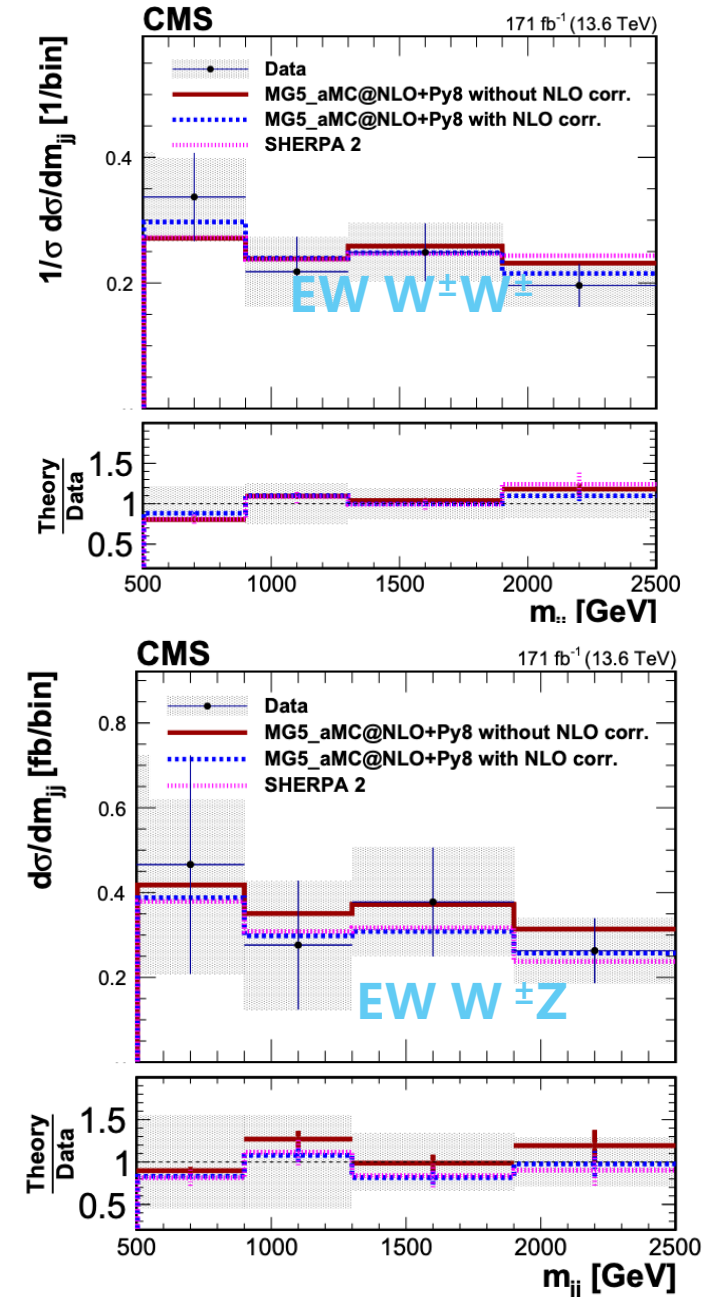
- ❖ **Signature:** 3 leptons + p_T^{miss} + 2 VBS tagging jets.
- ❖ **Backgrounds:** QCD WZ dominates; tZq, non-prompt and diboson backgrounds constrained in CRs.
- ❖ **Signal extraction:** gradient BDT + Zeppenfeld variable separate EW WZ from QCD WZ.



Same sign WW and WZ measurements with Run3---Results

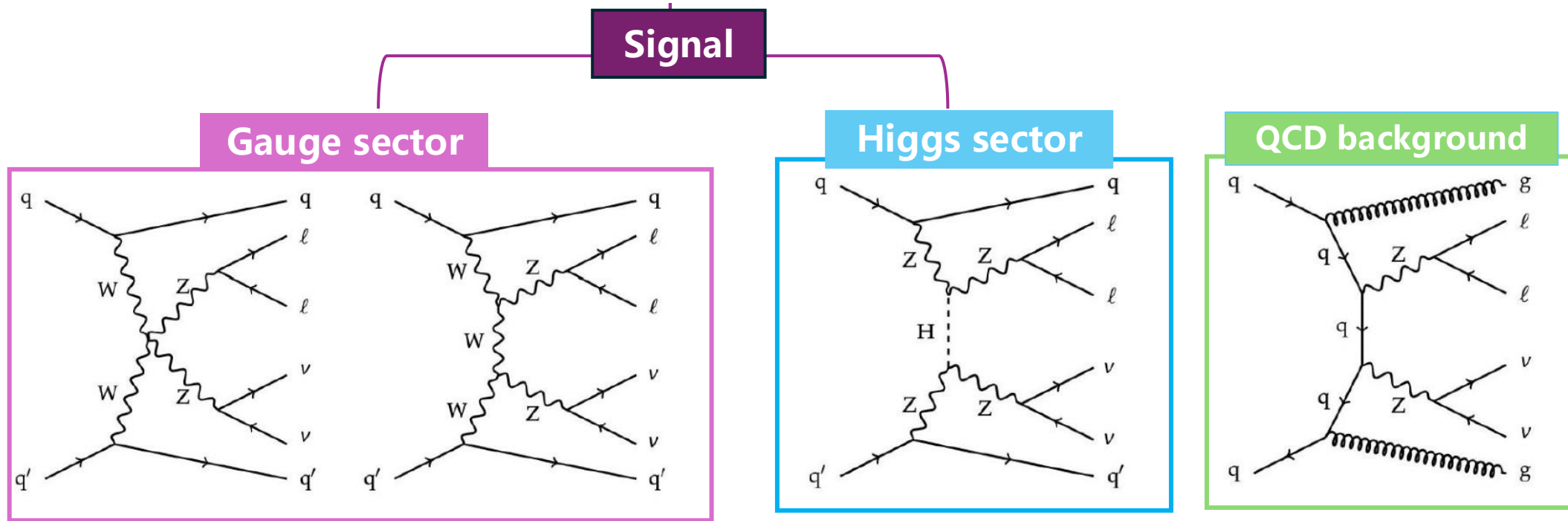
- **First Run 3 (2022–24) VBS measurement:** EW ssWW and WZ production both observed at $>5\sigma$
- **Simultaneous binned profile-likelihood fit** of $W^\pm W^\pm + WZ$ SRs with CRs $\rightarrow$ inclusive and differential cross sections
- **Data consistent with MG5_aMC@NLO and Sherpa** within uncertainties; Sherpa central values tend lower
- **Precision: 10% ($W^\pm W^\pm$), 18% (WZ)**
- **vs Run 2:** smaller non-prompt bkg. and its uncertainty, improved lepton and lumi unc.; still statistics-limited

Process	$\sigma \mathcal{B}$ (fb)	Predictions (fb)		
		MADGRAPH5_aMC@NLO without NLO corrections	MADGRAPH5_aMC@NLO with NLO corrections	SHERPA without NLO corrections
EW $W^\pm W^\pm$	3.81 ± 0.38 $0.33 \text{ (stat)} \pm 0.18 \text{ (syst)}$	4.27 ± 0.38	3.51 ± 0.31	3.37 ± 0.50
EW+QCD $W^\pm W^\pm$	4.32 ± 0.40 $0.36 \text{ (stat)} \pm 0.18 \text{ (syst)}$	4.75 ± 0.52	3.99 ± 0.44	—
EW WZ	1.43 ± 0.26 $0.23 \text{ (stat)} \pm 0.12 \text{ (syst)}$	1.45 ± 0.13	1.25 ± 0.11	1.24 ± 0.19
EW+QCD WZ	4.75 ± 0.35 $0.27 \text{ (stat)} \pm 0.22 \text{ (syst)}$	4.59 ± 1.07	4.39 ± 1.05	—



First evidence of VBS $ZZ \ell\ell\nu\nu$ @ 138 fb^{-1}

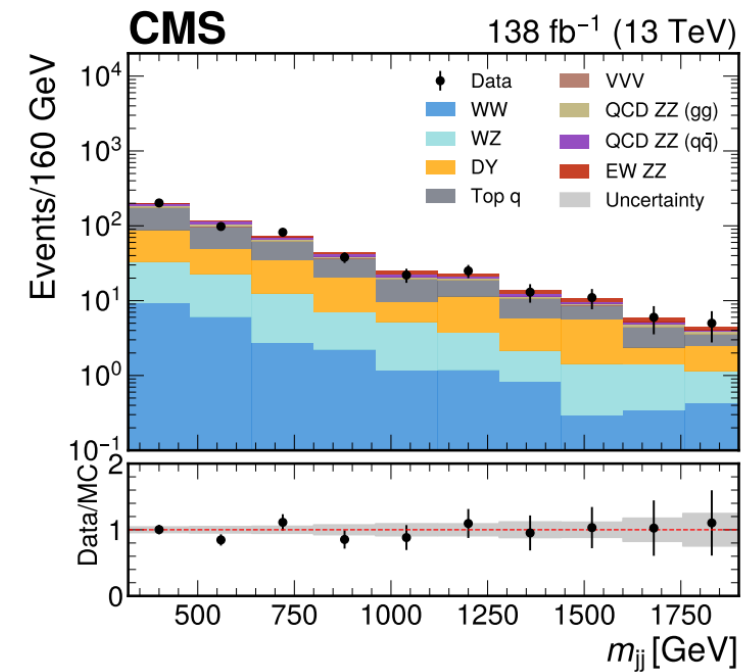
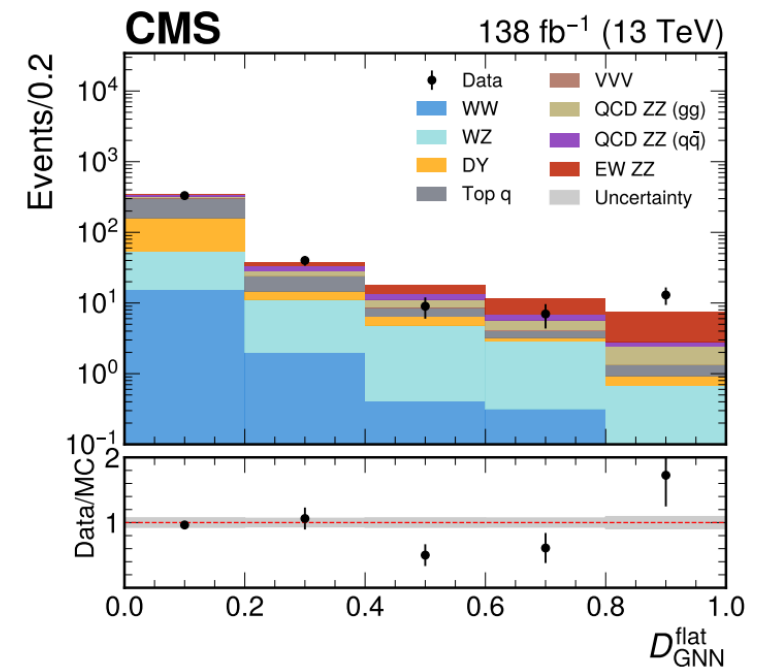
Submitted to PRL: [arXiv:2606.20558](https://arxiv.org/abs/2606.20558)



- **Final state:** $ZZ \rightarrow \ell\ell\nu\nu$, with two opposite-sign same-flavour leptons compatible with a Z boson, large p_T^{miss} , and two VBS like jets.
- **Signal topology:** EW $ZZjj$ receives contributions from **quartic gauge interactions**, **gauge-boson exchange**, and **Higgs-mediated scattering**, while QCD-induced $ZZjj$ forms the main irreducible background.
- **Physics goals:** establish evidence for EW $ZZjj$ production and measure its fiducial cross section; constrain anomalous quartic gauge couplings in the dimension-8 EFT framework.

First evidence of VBS ZZ $\ell\ell\nu\nu$ @138 fb^{-1} --- analysis strategy

- **VBS selection:** OSSF $Z \rightarrow \ell\ell$ + large p_T^{miss} + two high M_{jj} and large $|\Delta\eta_{jj}|$ jets, with extra-lepton τ, b jets veto.
- **background estimation:**
 - **Background constraints:** WZ from a 3ℓ CR and WW/top from an $e\mu$ CR.
 - **DY background:** data-driven γ +jets method to model fake p_T^{miss} in Z+jets.
- **Signal discrimination:** GNN built from lepton, jet and event-level kinematics to separate EW ZZjj from QCD ZZjj.
- **Signal extraction:** simultaneous likelihood fit to the GNN output in SR and CRs.



First evidence of VBS ZZ $\ell\ell\nu\nu$ @138 fb⁻¹ ---analysis Results

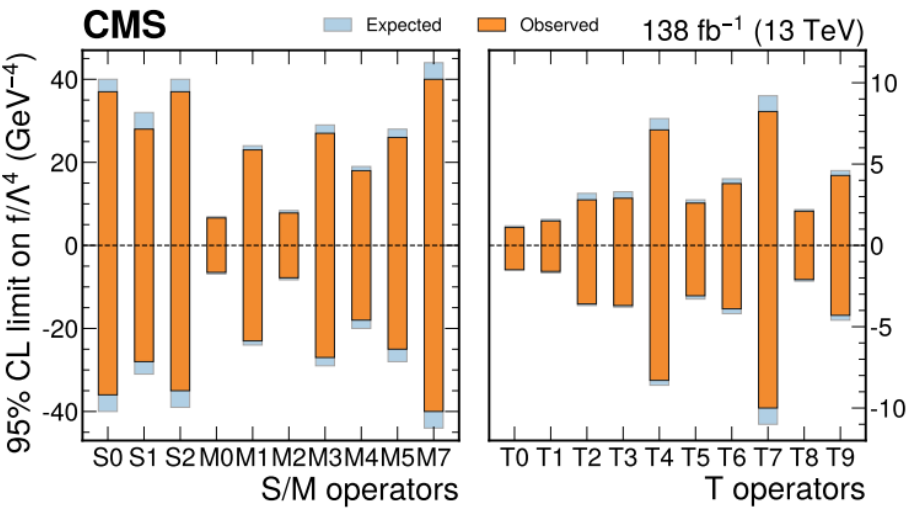
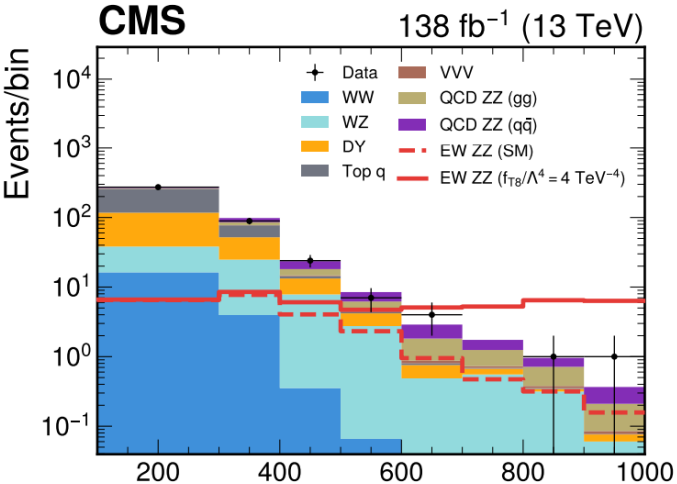
- **First evidence for EW $ZZjj \rightarrow \ell\ell\nu\nu jj$ production**, with a significance of **3.1 σ** .
- The measured **fiducial cross section is consistent with the SM prediction**.
- **Combined with the $ZZ \rightarrow 4\ell$ channel**, the significance reaches **5.0 σ** .

$$\sigma_{EW}^{fid}(pp \rightarrow ZZjj \rightarrow \ell\ell\nu\nu jj) = 0.37^{+0.14}_{-0.12} \text{ (stat)}^{+0.06}_{-0.06} \text{ (syst)} \text{ fb}$$

Channel	Expected	Observed
$\ell\ell\ell'\ell'$	3.5 σ	4.0 σ
$\ell\ell\nu\nu$	2.8 σ	3.1 σ
$\ell\ell\ell'\ell' + \ell\ell\nu\nu$	4.5 σ	5.0 σ

EFT interpretation

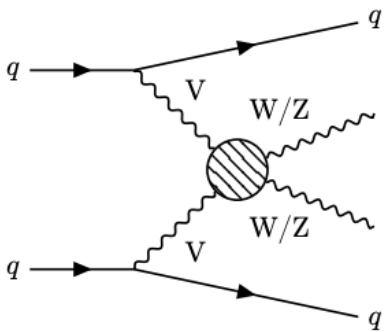
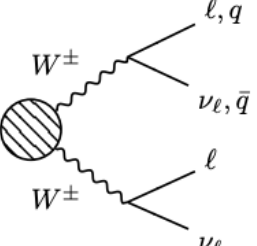
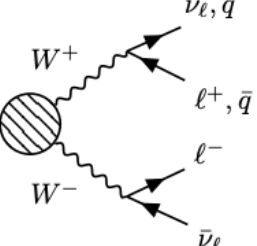
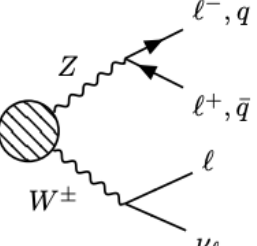
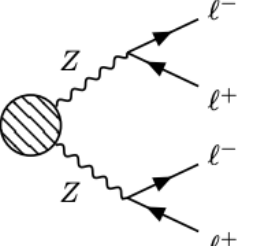
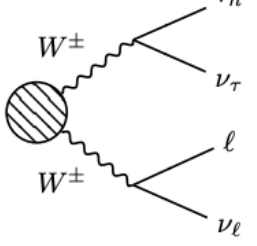
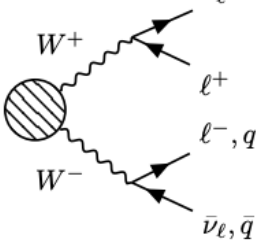
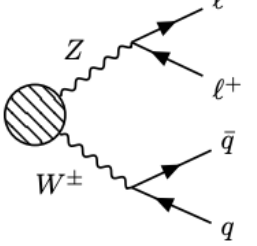
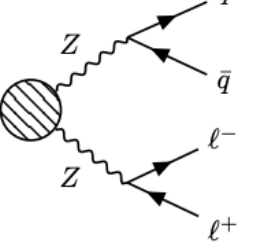
- **95% CL limits on dim-8 SMEFT operators** are derived using m_T as the sensitive observable.
- Constraints are set on **longitudinal, transverse, and mixed aQGC operators**, with no significant deviation from the SM.



Results of VBS combination with Run2

Submitted to Physics Letters B: [arXiv:2608.01289](https://arxiv.org/abs/2608.01289)

Combine analyses targeting multiple production modes

EW production through VBS	Final states				Shorthand name	Final state
	SSWW	OSWW	WZ	ZZ		
					SSWW (e, μ)	$\ell^\pm \ell^\pm 2\nu jj$
					SSWW (τ_h)	$\ell^\pm \tau_h^\pm 2\nu jj$
					OSWW	$\ell^\pm \ell^\mp 2\nu jj$
					WV	$\ell \nu jjjj$
					WZ	$3\ell \nu jj$
					ZV	$2\ell jjjj$
					ZZ (4ℓ)	$4\ell jj$

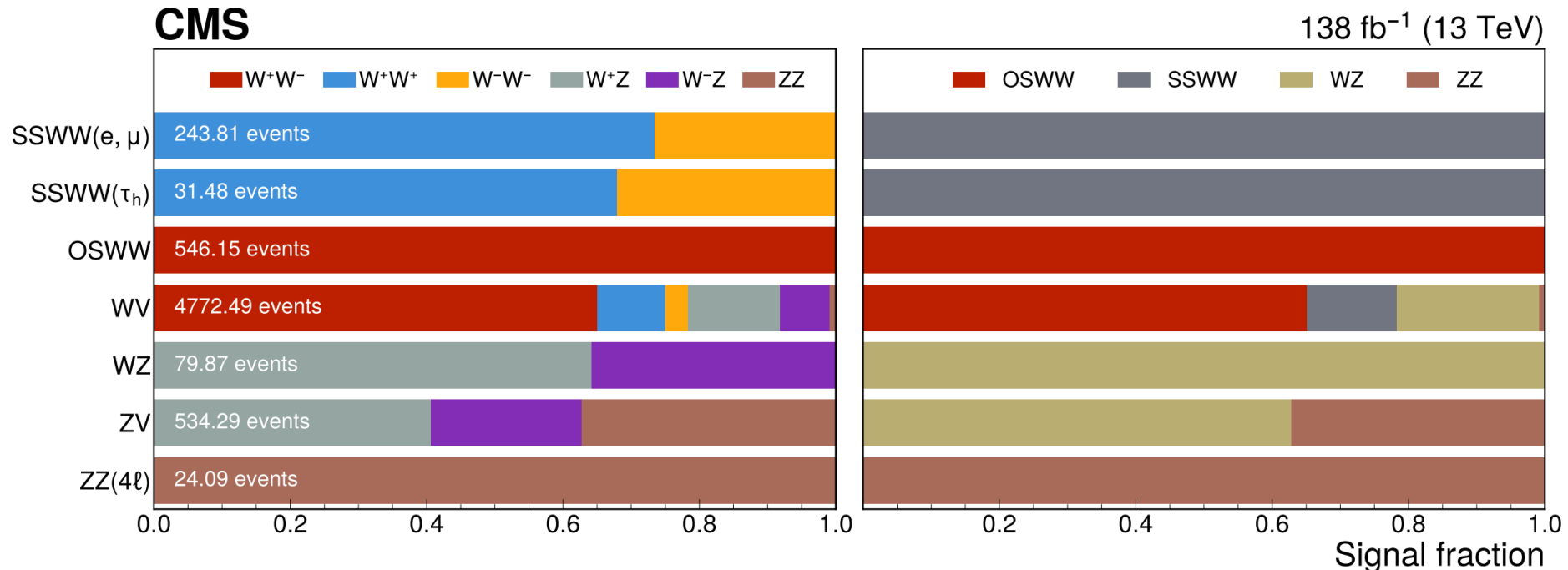
- **Seven analyses** mapped onto **four production modes** (SSWW, OSWW, WZ, ZZ): fully leptonic channels give the sensitivity; semileptonic ones (WV, ZV) add complementary kinematics but cannot separate individual modes.
- **Most comprehensive CMS VBS combination to date**, treating all modes coherently including their correlations ->a global test of the EW gauge structure not accessible channel by channel.
- Improves precision over the best single-channel results.

Results of VBS combination with Run2---analysis strategy

➤ Two signal-strength models:

- **4-POI:** SSWW, OSWW, WZ, ZZ $\rightarrow$ global VBS measurement
- **6-POI:** W^+W^+ , W^-W^- , W^+W^- , W^+Z , W^-Z , ZZ $\rightarrow$ probe charge asymmetry

- **WV:** largest yield ($\sim 4.8k$ events) but mixes all WW/WZ modes $\rightarrow$ constrains several POIs at once.
- **ZZ (4ℓ):** only ~ 24 expected events $\rightarrow$ statistics-limited, consistent with ZZ reaching 4.0σ (not 5σ).
- **W^+ vs W^- :** $\sim 70/30$ in SSWW, $\sim 65/35$ in WZ $\rightarrow$ the charge asymmetry the 6-POI model is built to probe.



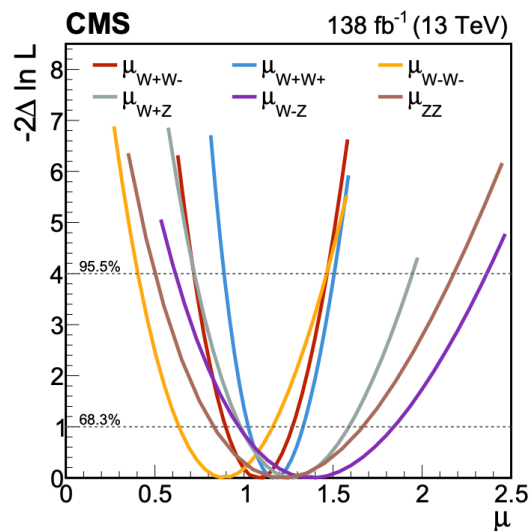
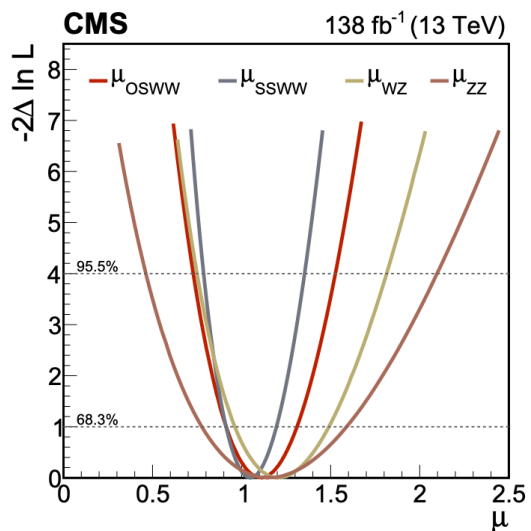
Results of VBS combination with Run2---analysis strategy

Channel	Final state	Discriminant in fit
SSWW (e, μ)	$\ell^\pm \ell^\pm 2\nu jj$	2D: $m_{jj} : m_{ee}$
SSWW (τ_h)	$\ell^\pm \tau_h \pm 2\nu jj$	DNN
OSWW	$\ell^\pm \ell^\mp 2\nu jj$	DNN (e μ) ; $m_{jj} : \Delta\eta_{jj}$ (ee, $\mu\mu$)
WZ	$3\ell\nu jj$	BDT
ZZ (4 ℓ)	$4\ell jj$	Matrix-element KD
WV	$\ell\nu jjjj$	DNN (resolved / merged)
ZV	$2\ell jjjj$	DNN (resolved / merged, b-tag / b-veto)

- **Orthogonality:** exclusive charged-lepton multiplicity + extra-lepton veto as the first layer; refined by τ_h , total charge, SF/DF pairs, mass windows, resolved/boosted jets and b tagging.
- **Backgrounds:** nonprompt leptons, charge mis-ID, W/Z+jets, $t\bar{t}$ and DY constrained in dedicated CRs, fitted together with the SRs.
- **Uncertainties:** theory (scales, PDF+ α_s , parton shower) correlated across analyses and between signal and background where appropriate; experimental ones correlated where justified. Results are robust against variations of the correlation scheme.
- **Fit:** 48 regions $\times$ 3 years, 1525 bins in a binned profile-likelihood fit (COMBINE).

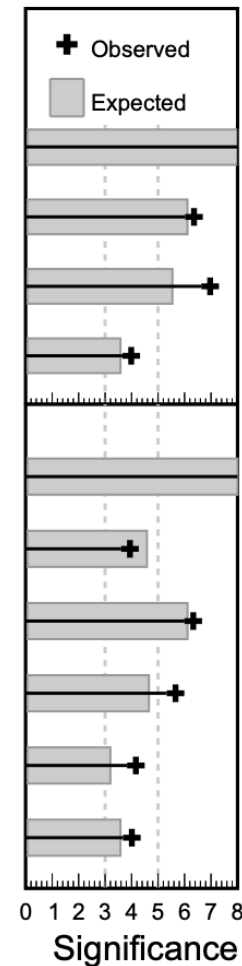
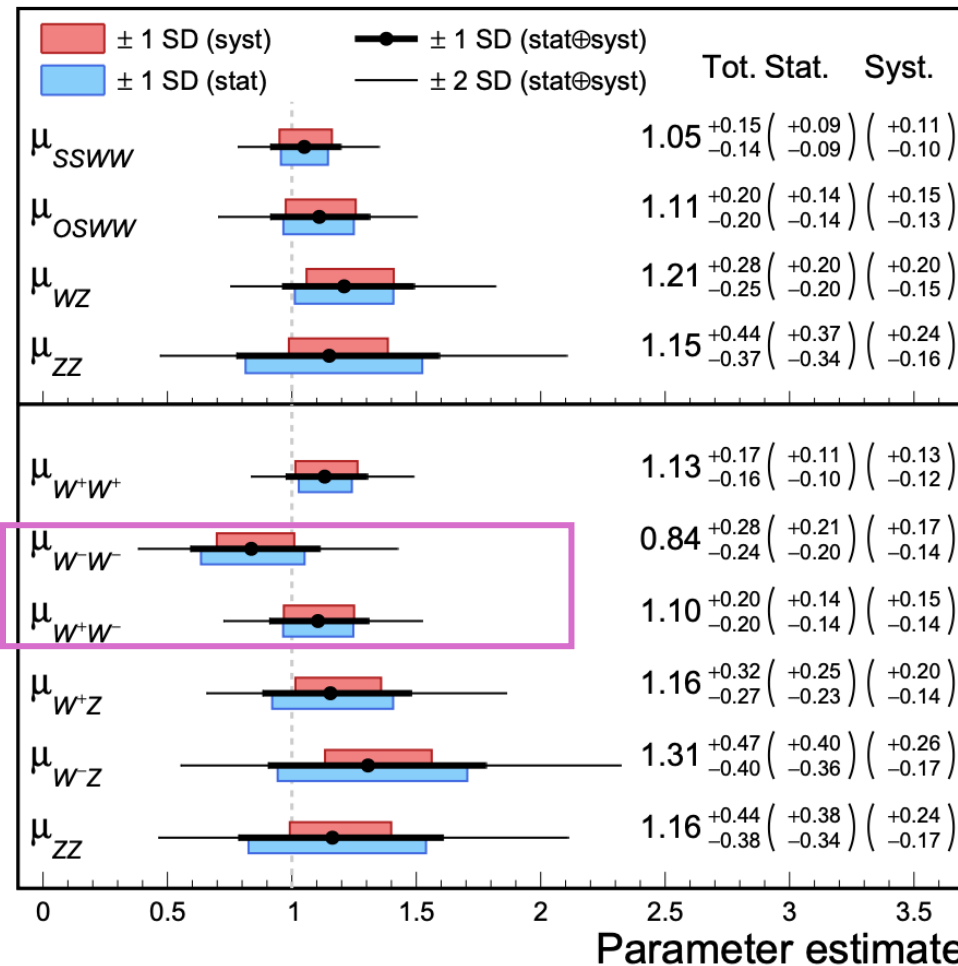
Results of VBS combination with Run2---analysis results

- All signal strengths consistent with the SM within 1σ
- Simultaneous observation: SSWW $> 5\sigma$, OSWW 6.4σ , WZ 7.0σ , (ZZ 4.0σ)
- Up to 15% improvement in precision for OSWW and WZ over the best individual CMS measurements
- Charge-separated results agree with SM expectations, probing the PDF-driven charge asymmetry

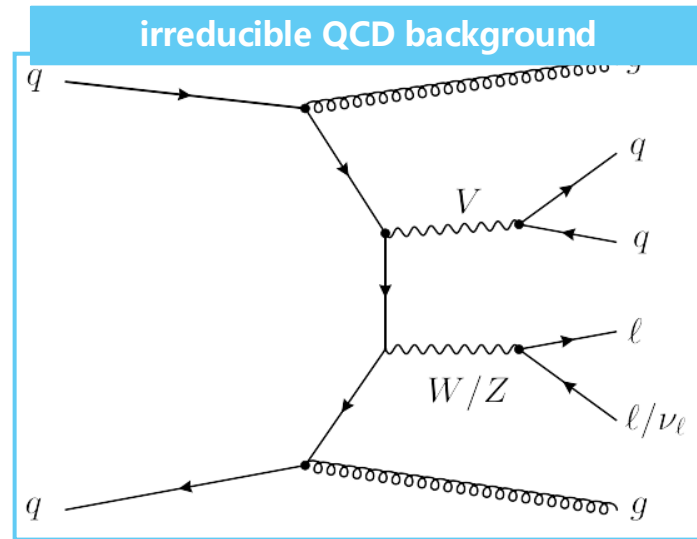
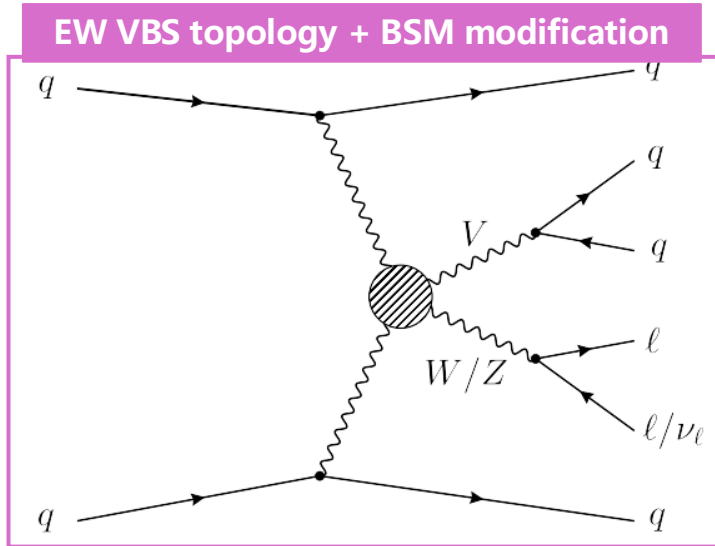


CMS

138 fb⁻¹ (13 TeV)



ZV and WV EFT combination with Run2



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{D_i > 4} \sum_i \frac{c_i^{(D_i)}}{\Lambda_{\text{BSM}}^{D_i-4}} \mathcal{O}_i^{(D_i)},$$

Effective Lagrangian

Standard Model Lagrangian

Wilson coefficient (coupling strength)

Higher-dimensional operator of dimension D_i

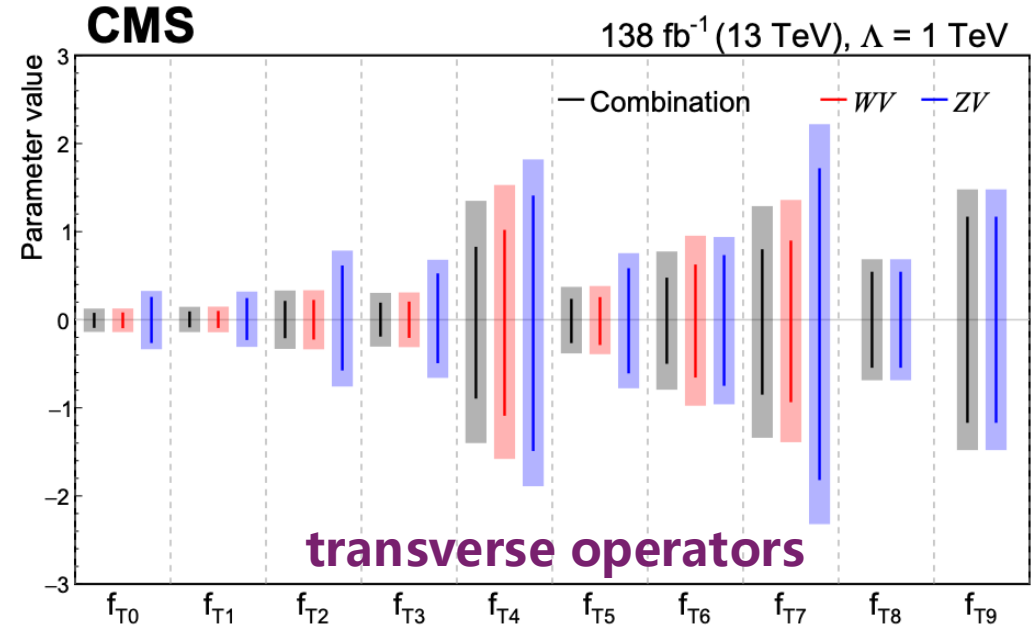
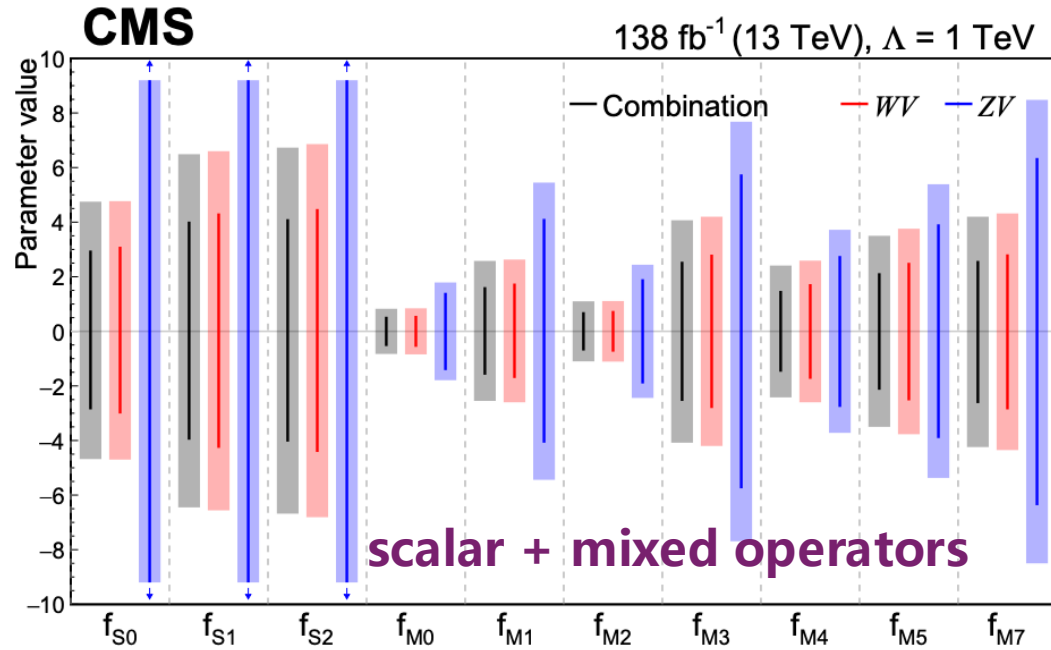
BSM scale

Operator dimension

EFT: parameterizing new-physics effects at low energy using higher-dimensional operators

- **Combine semileptonic VBS channels:**
WV→ $\ell\nu qq$ and ZV→ $\ell\ell qq$, targeting EW WW, WZ, and ZZ scattering.
- The **hadronic decay of one vector boson** gives a larger branching fraction and access to the high energy regime, complementary to fully leptonic VBS measurements.
- Interpret the high-energy tails in **dimension-8 SMEFT**, targeting anomalous quartic gauge couplings (**aQGCs**) with **20 operator structures**.

ZV and WV EFT combination with Run2---analysis results



- **95% CL intervals** are derived for all **20 dimension-8 Wilson coefficients**, varying one coefficient at a time.
- The **combined WV + ZV fit improves the sensitivity** relative to the individual channels by exploiting their complementary dependence on the EFT operators.
- The analysis sets **several of the strongest constraints** on dimension-8 aQGC operators with Run-2 CMS data.
- **No significant deviation from the SM** is observed in either the ZV or WV high-mass distributions.

Summary

- **VBS provides a direct probe of electroweak symmetry breaking and quartic gauge interactions**, with sensitivity to new physics in the high-energy regime.
- **Run 3 ssWW and WZ measurements move VBS into the precision era**
 - both processes are observed above 5σ and inclusive/differential cross sections measured.
- **EW ZZjj production is observed at 5.0σ** by combining the $ZZ \rightarrow \ell\ell\nu\nu$ and $ZZ \rightarrow 4\ell$ channels, extending the established VBS program to the neutral-boson sector.
- **Run 2 global combinations provide a coherent picture of SSWW, OSWW, WZ and ZZ scattering**, including charge-separated measurements.
- **Global combinations and EFT interpretations strengthen sensitivity to BSM effects**
 - setting stringent constraints on dimension-8 aQGC operators, with no significant deviation from the SM observed.

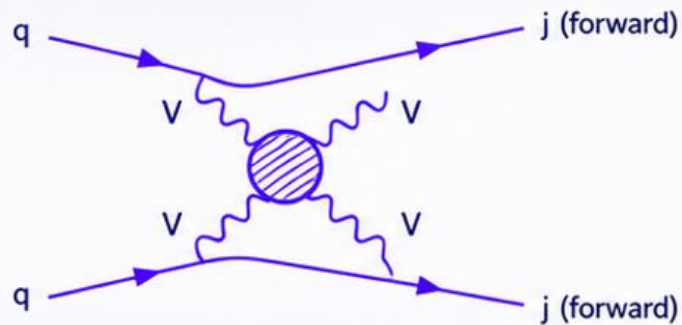
Outlook: Vector Boson Scattering and Beyond

From precision measurements to new physics sensitivity

More precision
A deeper understanding
A broader search

Vector Boson Scattering (VBS, VV+jj)

Core program: direct probe of electroweak symmetry breaking and quartic gauge interactions



- ✓ Same-sign and opposite-sign channels
- ✓ Sensitive to EWSB and quartic gauge couplings
- ✓ Unique kinematic signatures (e.g. forward jets, large m_{jj})
- ✓ Growing precision with Run 3 and HL-LHC



Run 3 & HL-LHC → precision tests of electroweak dynamics

Higher statistics, improved techniques, extended phase space

Related electroweak and multiboson measurements

WW WZ ZZ Z γ W γ ...

Provide complementary information and inputs to the VBS program

Complementary probes

Other sectors



Higgs sector

Couplings, differential measurements



Top sector

Precision measurements, rare processes



multiboson

WWW, WWZ, WZZ, ZZZ, ...

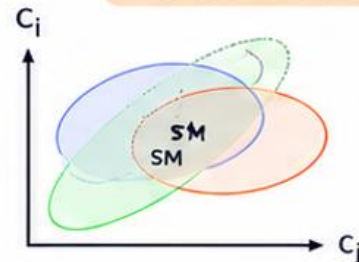


Other EW measurements

EW precision observables, α_{TGCs} , ...

Complementary information

Global interpretation & combinations



- Global combinations (SMEFT) link multiboson, VBS, and other sectors
- Combine Run 3 and HL-LHC measurements
- Constrain EFT operators and anomalous couplings
- Improve sensitivity to subtle BSM effects



Enhanced sensitivity to BSM physics

- Discover deviations, or
- Set the most stringent limits
- Guide the next generation

Precision inputs from VBS and diboson measurements

Run 3 → HL-LHC → Beyond

Same collisions
Bigger questions

Gauge bosons
Illuminate
What lies beyond

Looking to the Future

Higher energies
Brighter questions
A deeper understanding

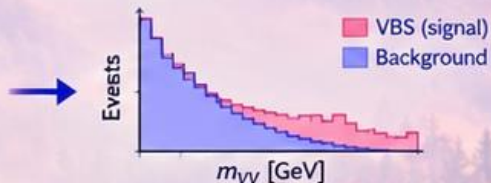
Vector Boson Scattering: precision tests of electroweak dynamics and beyond

The New Frontier

- VBS as a direct probe of EWSB
- Quartic gauge couplings and rare scattering channels
- Precision VBS + SMEFT + BSM sensitivity

Rare processes, high-energy tails,
and strong sensitivity to new physics.

AI + VBS



ML for event reconstruction and classification



Better separation of signal and backgrounds



Faster interpretation and anomaly detection

Run 3

- More data
- Improved analyses
- Differential measurements

SAME PARTICLES
NEW HORIZONS

HL-LHC

- Precision VBS program
- Extended phase space
- Stronger SMEFT reach

HIGHER ENERGY
DEEPER INSIGHTS

SAME QUESTIONS
A BRIGHTER TOMORROW

Synergy & Global Efforts



Theory and experiment
working together



Global SMEFT combinations



Links to Higgs, top, and
multiboson sectors



Toward a coherent picture
of the electroweak sector



Exploring the **VBS** landscape,
advancing precision tests of the Standard Model,
and searching for **new physics** at the energy frontier.



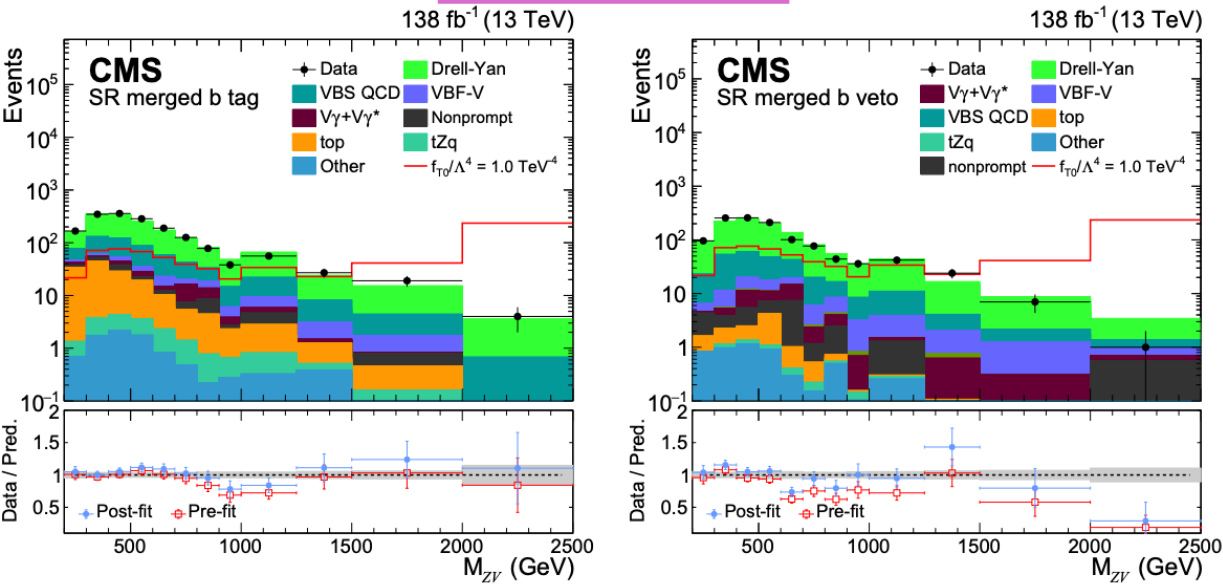
From scattering
to discovery

MORE DATA
SHARPER TOOLS
BOLDER DISCOVERIES

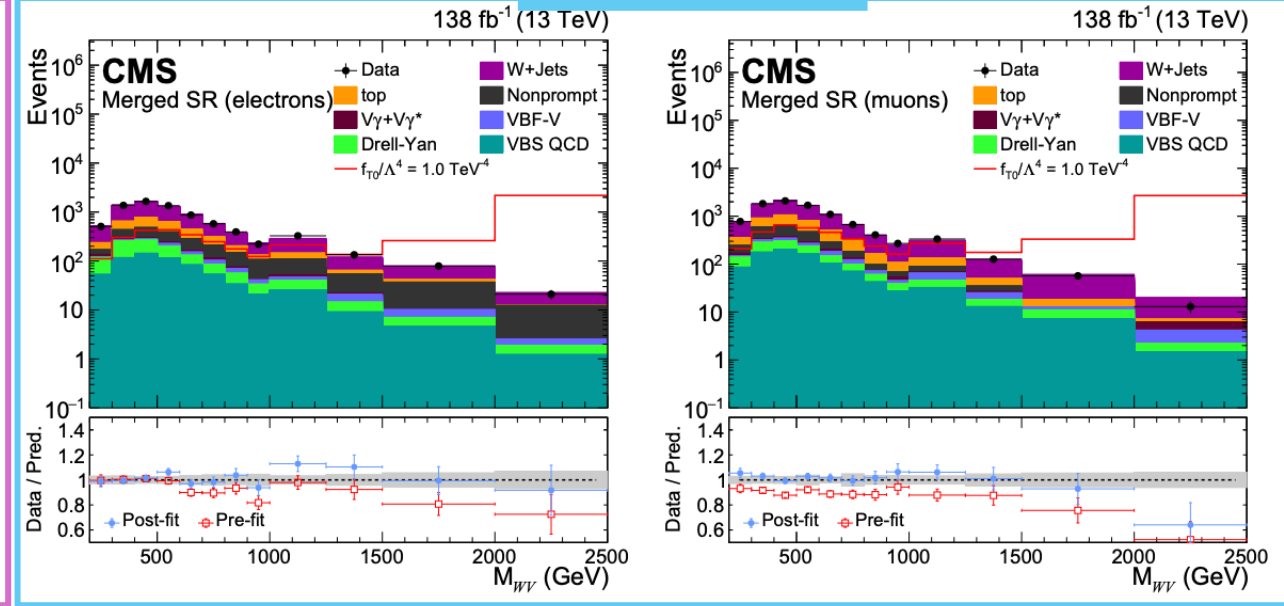
BACK UP

ZV and WV EFT combination with Run2---analysis strategy

ZV SR



WV SR



- **Boosted V topology:** reconstruct the hadronic $V \rightarrow qq$ decay as a large-R jet, targeting the energetic phase space with enhanced EFT sensitivity.
- **VBS topology:** require two forward tagging jets with $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 2.5$.
- **Combine ZV and WV signal regions**, together with dedicated control regions to constrain the dominant backgrounds.
- Use the **diboson invariant masses M_{ZV} and M_{WV}** as the EFT-sensitive observables
- Perform a **simultaneous profile-likelihood fit**, varying one dimension-8 Wilson coefficient at a time

$$N_{\text{exp}}^{\alpha} = N_{\text{SM}} + \frac{f_{\alpha}}{\Lambda^4} N_{\text{lin}}^{\alpha} + \frac{f_{\alpha}^2}{\Lambda^8} N_{\text{quad}}^{\alpha}$$