A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC

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Based on https://arxiv.org/pdf/2108.03199v2.pdf

Theory Introduction

SM tested with unprecedented accuracy with LHC Run II statistics.
Recent evidence for tensions...
There are known SM shortcomings $\rightarrow$ the SM is thought to be a low level manifestation of a UV-complete theory at large scale.

EFT interpretation can shed light on NP

SMEFT

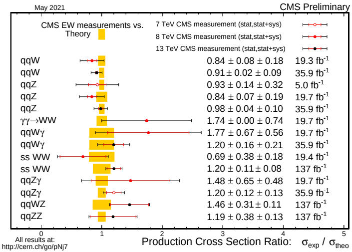
- Built upon SM fields
- $SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant
- Higgs-like in $SU(2)$ doublet. Linear realization of EWSB
- Describe $\sim$ all UV-complete theories

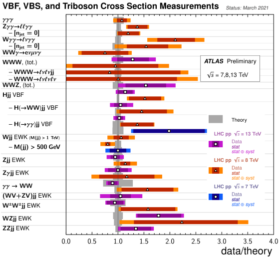
Neglecting B/L violating dim-5 and dim-7 operators

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} + \frac{c_i}{\Lambda^4} O_i^{(8)} + \dots$$

c_i Wilson coefficients

Λ unknown NP energy scale

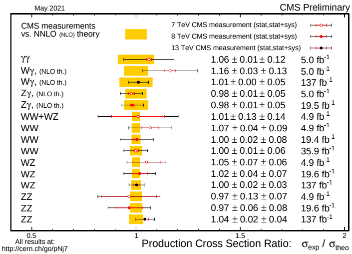


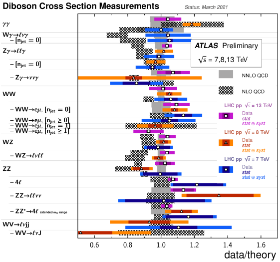


VBS

- $L \sim 137\ \text{fb}^{-1}$ allows new measurements.
- Statistically dominated.
- BSM in aQGC or EFT dim-8.
- dim-6 can be important (and should be considered)

[arXiv:1809.04189]





Diboson

- Well known processes.
- High cross-section, syst. dominated.
- BSM in aTGC or EFT dim-6.
- Limited operators studied.

The case for a LHE study

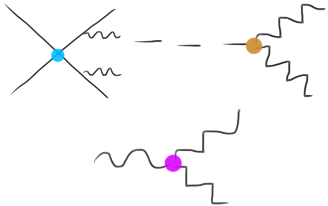
The case for a LHE study:

- LHC **VBS** results usually interpreted in terms of dim-8 operators. But **dim-6** should be considered
- Global EFT fit will be needed, **combination is key**: top + Higgs + EW + non-LHC (LEP, Tevatron,...), ... What's the sensitivity reach / interplay of VBS and WW?
- **Ranking of common observables** based on the operator-by-operator sensitivity
- A study of the **impact of Λ^{-4}** dim-6 terms
- Analysis of the **EFT contributions from the major background**
- First exercise with a **new statistical model for EFT fits** and combinations within CMS.

SMEFT Monte Carlo Generations

- 15 dim-6 SMEFT operators with various field content from Warsaw basis [arXiv:1008.4884v3].
- Generated at LO with SMEFTsim [arXiv: 2012.11343] + `MadGraph5_aMC@NLO` (2.6.5).
- Insertion of one operator per diagram in production/decay.
- $U(3)^5$ flavour symmetry, $\{m_W, m_Z, G_F\}$ input scheme, CP-even, $\Lambda = 1$ TeV.

$Q_{Hl}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_p)$	$Q_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p \tau^i \gamma^\mu l_p)$
$Q_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_p)$	$Q_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p \tau^i \gamma^\mu q_p)$
$Q_{qq}^{(1)} = (\bar{q}_p \gamma_\mu q_p)(\bar{q}_r \gamma^\mu q_r)$	$Q_{qq}^{(1,1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_r \gamma^\mu q_p)$
$Q_{qq}^{(3)} = (\bar{q}_p \gamma^i_\mu q_p)(\bar{q}_r \gamma^{\mu i} q_r)$	$Q_{qq}^{(3,1)} = (\bar{q}_p \gamma^i_\mu q_r)(\bar{q}_r \gamma^{\mu i} q_p)$
$Q_{HD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H)$	$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$
$Q_{HWB} = (H^\dagger \tau^i H) W^i_{\mu\nu} B^{\mu\nu}$	$Q_{HW} = (H^\dagger H) W^i_{\mu\nu} W^{i\mu\nu}$
$Q_W = \varepsilon^{ijk} W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$	$Q_{ll}^{(1)} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_r \gamma^\mu l_p)$



$$N \propto \overbrace{|\mathcal{A}_{SM}|^2}^{\text{SM}} + \sum_\alpha \frac{c_\alpha}{\Lambda^2} \cdot \underbrace{2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}^\dagger_{Q_\alpha})}_{\text{Lin}} + \frac{c_\alpha^2}{\Lambda^4} \cdot \overbrace{|\mathcal{A}_{Q_\alpha}|^2}^{\text{Quad}} + \sum_{\alpha,\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot \underbrace{\mathrm{Re}(\mathcal{A}_{Q_\alpha}\mathcal{A}^\dagger_{Q_\beta})}_{\text{Mix}}$$

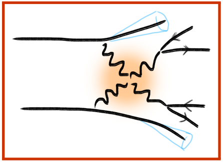
Two complementary approaches employed:

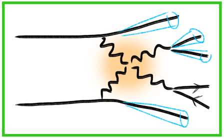
- Generate single components, $c_\alpha = 1$: $n(n+3)/2 = 135$ $\forall$ processes
- Generate events once, LO MG re-weight to different Wilson coeff. Algebra to extract components.

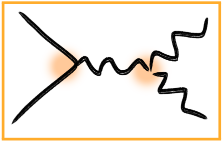
Processes of interest

Where appropriate, background contributions ($\alpha_s^2\alpha_{EW}^4$) generated for both SM and EFT.
Fully-leptonic and semi-leptonic final states investigated.
LHC-like selections performed (slides 23,24,25).
Full 2 $\to$ 6(4) VBS (diboson) processes including non-resonant diagrams.

- **Same-sign WW**: $\mathrm{p\,p\,>\,e^+\,\nu_e\,\mu^+\,\nu_\mu\,j\,j}$
- **Opposite-sign WW (QCD)**: $\mathrm{p\,p\,>\,e^+\,\nu_e\,\mu^-\,\bar{\nu_\mu}\,j\,j}$
- **WZ+2j(QCD)**: $\mathrm{p\,p\,>\,e^+\,e^-\,\mu^+\,\nu_\mu\,j\,j}$
- **ZZ+2j(QCD)**: $\mathrm{p\,p\,>\,e^+\,e^-\,\mu^+\,\mu^-}$
- **ZV+2j(QCD)**: $\mathrm{p\,p\,>\,z\,w^+(w^-,\,z)\,>\,l^+\,l^-\,j\,j\,j\,j}$
- **WW**: $\mathrm{p\,p\,>\,e^+\,\nu_e\,\mu^-\,\bar{\nu_\mu}}$







An integrated luminosity of **100 fb^{-1}** is assumed. Projection of constraints on slide 31

Processes of interest - EFT sensitivity

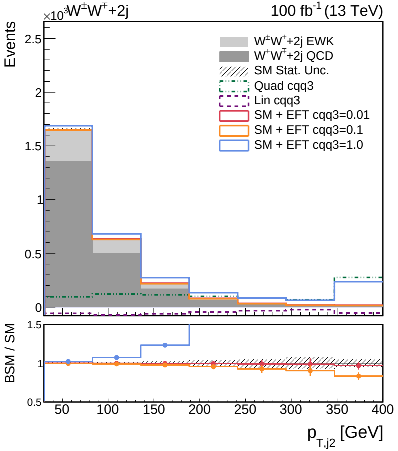
Summary of the sensitivity of each process to the operator subset. Empty cells = impossible to insert EFT vertices in diagrams.

proc / op	Q_{HD}	$Q_{H\Box}$	Q_{HWB}	$Q_{Hq}^{(1)}$	$Q_{Hq}^{(3)}$	Q_{HW}	Q_W	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	$Q_{ll}^{(1)}$	$Q_{qq}^{(3)}$	$Q_{qq}^{(3,1)}$	$Q_{qq}^{(1,1)}$	$Q_{qq}^{(1)}$	Q_{ll}
SSWW-EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
OSWW-EW	✓	✓	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	✓	(✓)
WZ-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZZ-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(✓)
ZV-EW	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
WW	✓		✓	✓	✓		✓	(✓)	✓	✓					
ZV-QCD	✓		✓	✓	✓		✓	✓	✓	✓					
OSWW-QCD	✓		✓	✓	✓		✓	✓	✓	✓					
WZ-QCD	✓		✓	✓	✓		✓	✓	✓	✓					(✓)
ZZ-QCD	✓		✓	✓	✓			✓	✓	✓					(✓)

- EW VBS phenomenology richer than diboson
- EFT contributions from QCD induced VBS backgrounds can enhance / mitigate the purely EW sensitivity

Introduction to shape analysis

$$N \propto SM^{EWK} + SM^{QCD} + \frac{c_\alpha}{\Lambda^2}\left(Lin^{EWK} + Lin^{QCD}\right) + \frac{c_\alpha^2}{\Lambda^4}\left(Quad^{EWK} + Quad^{QCD}\right)$$



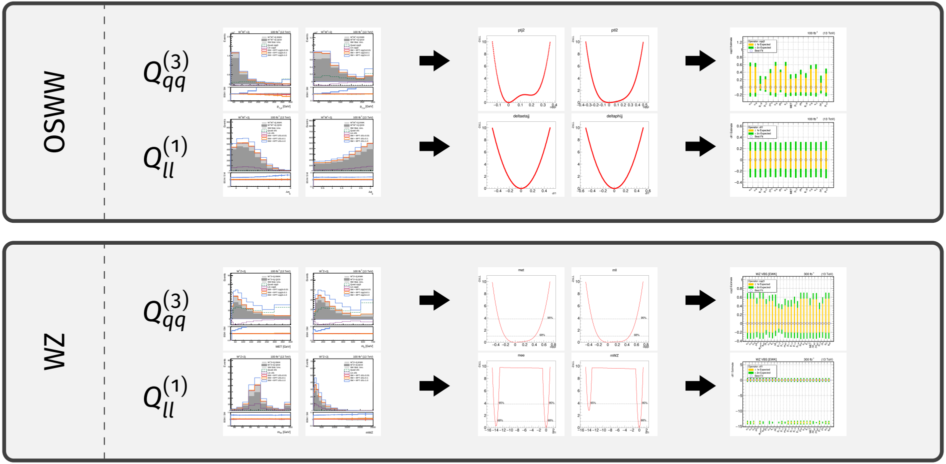
Likelihood

$$\mathcal{L}(\mathbf{c}) = \underbrace{\prod_{bin=k} \frac{(N_k(\mathbf{c}))^{n_k}}{n_k!} e^{-N_k(\mathbf{c})}}_{Poisson} \times \overbrace{\prod_{syst=j} \pi(\tilde{\theta}|\theta)}^{Nuisances}$$

- $N(\mathbf{c}) = SM + \sum_{c_\alpha} c_\alpha \cdot Lin_\alpha + c_\alpha^2 \cdot Quad_\alpha + \sum_{\alpha\beta} c_\alpha c_\beta Mix_{\alpha\beta}$
- $n = N(\mathbf{o}) \rightarrow$ assume SM

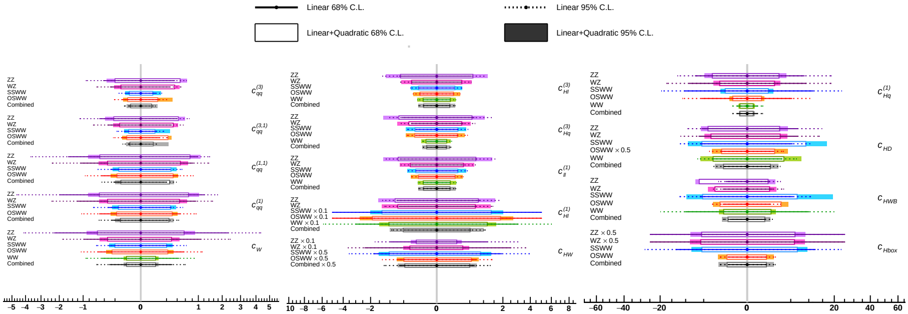
- Only one nuisance: correlated 2% between all yields, samples, and bins (proxy LHC lumi). Flat prior
- under SM, sensitivity estimated as $-2\Delta \log \mathcal{L} < 1\,(2.30)$ and $-2\Delta \log \mathcal{L} < 3.84\,(5.99)$ for 1(2) W.C.

Analysis strategy



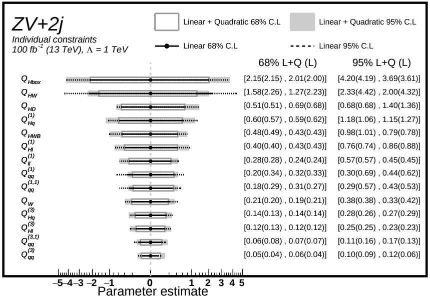
- **Parametrize EFT** dependence on c_i for observables of interest
- **Fit** each variable for each operator/s **rank** variables based on 1σ range (1σ area in 2D).
- $\forall$ operator/s extract best variable for **combination**

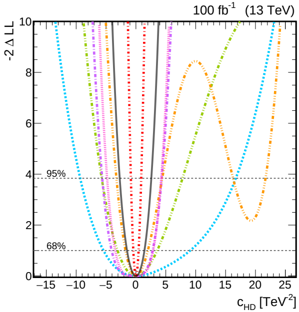
Individual constraints - VBS+WW Combination



- Most stringent constraints from VBS to **4-fermion ops**, agrees with previous studies [arXiv:1809.04189]
- **Strong impact of fits including** $O(\Lambda^{-4})$ **terms** for $\frac{1}{2}$ operators. For the remaining, no difference observed.
- Among VBS, **SSWW, OSWW** $>$ **WZ, ZZ** due to higher x-sec
- $Q_{Hl}^{(1)}$, Q_{HW}, $Q_{H\Box}$, Q_{HD} only constrained by VBS.
- $Q_{Hl}^{(1)}$ mostly constrained by VBS WZ/ZZ

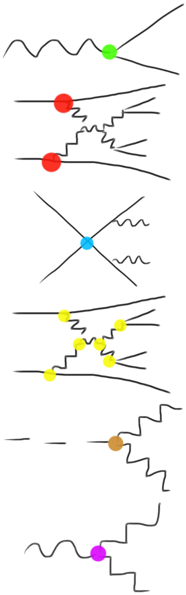
- Lack of Z+jets background $\alpha_s^4\alpha_{EW}^2$ (dominant in ZV semi-leptonic) $\rightarrow$ not included in the combination.
- **Constraints competitive with diboson** W^+W^- and slightly better than any other VBS channel considered, especially for $Q_{Hl}^{(1)}$.
- Impact of $O(\Lambda^{-4})$ less prominent w.r.t. other channels.





Individual contraints - Best variables

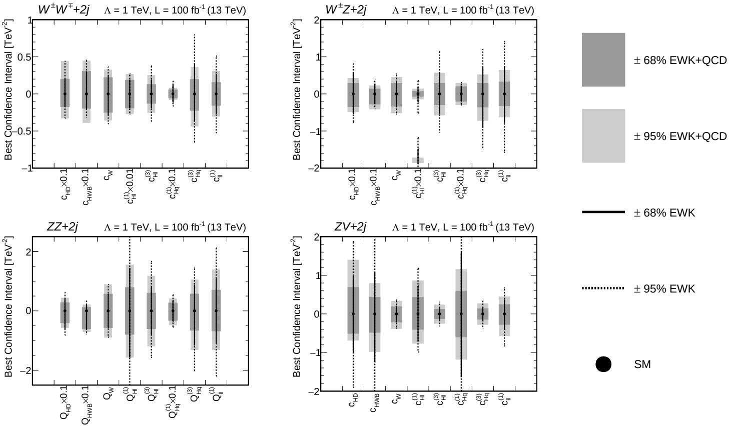
Op.	SSWW+2j		OSWW+2j		WZ+2j		ZZ+2j		ZV+2j		WW	
	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q
$c_{Hl}^{(1)}$	-	m_{ll}	-	MET	$m_{ee}{}^{\dagger}$	m_{WZ}	$p_{T,e^-\mu^-}{}^{\dagger}$	$p_{T,e^-\mu^-}{}^{\dagger}$	p^V_{T,j_1}	p^V_{T,j_1}	p_{T,l^1}	MET
$c_{Hq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	m_{jj}	m_{ll}	m_{jj}	p_{T,j^1}	m_{jj}	p_{T,j^1}	m_{jj}^{VBS}	m_{jj}^{VBS}	MET	MET
$c_{Hq}^{(3)}$	$\Delta\phi_{jj}$	$\Delta\phi_{jj}$	m_{ll}	m_{ll}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^1}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^4}	p^{VBS}_{T,j_2}	p^{VBS}_{T,j_2}	p_{T,l^1}	p_{T,l^1}
$c_{qq}^{(3)}$	$m_{ll}{}^{\dagger}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$p_{T,l^1}{}^{\dagger}$	$\Delta\phi_{jj}^{VBS}$	-	-
$c_{qq}^{(3,1)}$	$\Delta\phi_{jj}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$\Delta\eta_{jj}^{V\dagger}$	$\Delta\phi_{jj}^{VBS}$	-	-
$c_{qq}^{(1,1)}$	$\Delta\phi_{jj}$	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi_{jj}^{VBS}$	p^{VBS}_{T,j_1}	-	-
$c_{qq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi_{jj}^{VBS}$	p^{VBS}_{T,j_1}	-	-
$c_{Hl}^{(3)}$	$\Delta\eta_{jj}{}^{\dagger}$	$\Delta\eta_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta_{jj}^{V}$	$\Delta\eta_{jj}^{V}$	$m_{ll}{}^{\dagger}$	$m_{ll}{}^{\dagger}$
c_{HD}	p_{T,j^1}	m_{ll}	$\Delta\eta_{jj}$	$\Delta\eta_{jj}$	m_{ee}	$\Delta\eta_{jj}{}^{\dagger}$	$p_{T,e^+\mu^+}$	$p_{T,e^+\mu^+}{}^{\dagger}$	p_{T,l^2}	p_{T,l^2}	p_{T,l^1}	p_{T,l^1}
$c_{ll}^{(1)}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta_{jj}^{V\dagger}$	$\Delta\eta_{jj}^{V\dagger}$	$p_{T,ll}{}^{\dagger}$	p_{T,l^2}
c_{HWB}	p_{T,j^1}	p_{T,j^1}	$\Delta\eta_{jj}$	m_{ll}	m_{ee}	m_{WZ}	$m_{\mu\mu}{}^{\dagger}$	$\Delta\eta_{jj}$	$\Delta\eta_{jj}^{V}$	$\Delta\eta_{jj}^{V}$	p_{T,l^1}	MET
$c_{H\Box}$	p_{T,j^1}	m_{ll}	m_{ll}	m_{ll}	-	m_{WZ}	-	$\Delta\eta_{jj}$	p^V_{T,j_2}	p^V_{T,j_2}	-	-
c_{HW}	$\Delta\phi_{jj}$	m_{ll}	$\Delta\phi_{jj}$	m_{ll}	$\eta_{l^3}{}^{\dagger}$	m_{WZ}	m_{jj}	m_{4l}	p^{VBS}_{T,j_1}	p^V_{T,j_2}	-	-
c_W	$\Delta\phi_{jj}$	$p_{T,ll}$	$\Delta\phi_{jj}$	m_{ll}	p_{T,l^1}	m_{WZ}	$\Delta\phi_{jj}$	p_{T,l^4}	$\Delta\phi_{jj}^{VBS\dagger}$	$\Delta\phi_{jj}^{VBS\dagger}$	MET	MET



Observables ranking change from Lin to Lin+Quad.
Best observable group usually match prior knowledge about the operator.

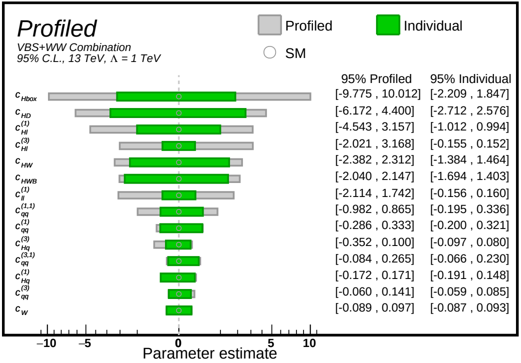
$$N(\mathrm{EWK{+}QCD}) \propto SM^{EWK} + SM^{QCD} + \frac{c_\alpha}{\Lambda^2}\left(Lin^{EWK} + Lin^{QCD}\right) + \frac{c_\alpha^2}{\Lambda^4}\left(Quad^{EWK} + Quad^{QCD}\right)$$

$$N(\mathrm{EWK}) \propto SM^{EWK} + SM^{QCD} + \frac{c_\alpha}{\Lambda^2} Lin^{EWK} + \frac{c_\alpha^2}{\Lambda^4} Quad^{EWK}$$



including the background QCD dependence never weakens the sensitivity reach of all analyses.

Profiled constraints - VBS+WW Combination



Global fit guarantees SMEFT model and basis independence. VBS + WW profiled constraints including all Λ^{-4} terms.

- All parameters free to float in likelihood maximisation
- Individual limits on operators obtained by **profiling** uninteresting W.C (free to float in the fit)
- **Profiled $\sim$ 1 − 20 $\times$ Individual**

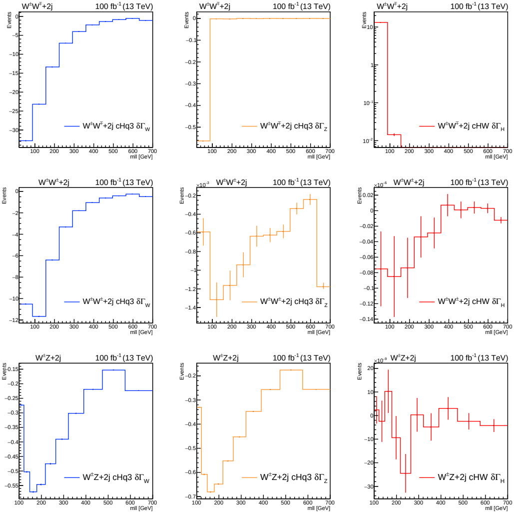
SMEFT corrections in propagators

Mass terms and decay widths of the SM particles generally **receive corrections** from $\mathcal{L}_6$ operators. Currently available simulation tools only allow their consistent estimate at linear order (excluded up to now).

$$\{m_W, m_Z, G_F\} \to \delta m_W = 0, \delta m_Z = 0$$

Corrections for different ops share the same shape except for normalization.
Simulate for $Q^{(3)}_{Hq}$ $\forall$ proc. and scale (W,Z) and Q_{HW} (H) only significant in OSWW

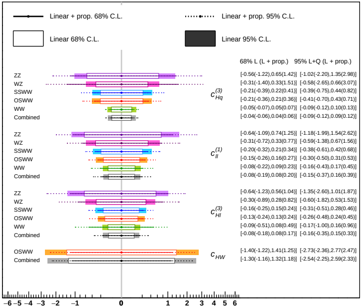
$$\delta\Gamma_W/\Gamma_W^{SM} = \frac{4}{3}c^{(3)}_{Hq} - \frac{4}{3}c^{(3)}_{Hl} - c^{(1)}_{ll}$$

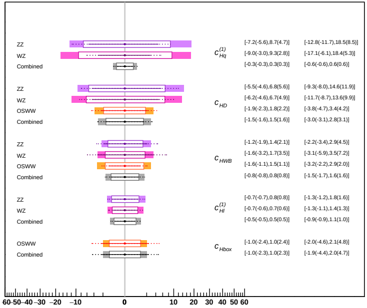


Γ_W correction Γ_Z correction Γ_H

SMEFT corrections in propagators

Comparing at linear only limits obtained with vertex+prop insertions ($\delta\Gamma$)
$N^{int}_{\alpha} = N^{int}_{\alpha,\mathrm{vert.}} + N^{int}_{\alpha,\delta\Gamma_W} + N^{int}_{\alpha,\delta\Gamma_Z} + N^{int}_{,\delta\Gamma_H}$ with previous linear only fits $N^{int}_{\alpha} = N^{int}_{\alpha,\mathrm{vert.}}$.
Apple to apple: same variables obtained with ranking w/o prop. corrections.
Non-trivial results: **limits may change up to a factor ~ 5**





$$\delta\Gamma_W/\Gamma_W^{SM} = \frac{4}{3}c_{Hq}^{(3)} - \frac{4}{3}c_{Hl}^{(3)} - c_{ll}^{(1)}\,, \tag{1}$$

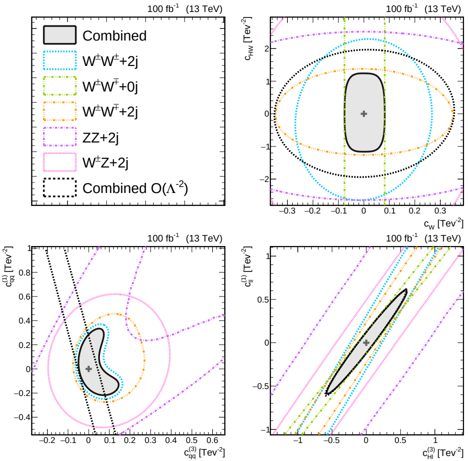
$$\delta\Gamma_Z/\Gamma_Z^{SM} = 1.61c_{Hq}^{(3)} - 1.37c_{Hl}^{(3)} + c_{ll}^{(1)} + 0.47c_{Hq}^{(1)} - 0.18c_{Hl}^{(1)} - 0.07c_{HD} + 0.46c_{HWB}\,, \tag{2}$$

$$\delta\Gamma_H/\Gamma_H^{SM} = 0.36c_{Hq}^{(3)} - 2.62c_{Hl}^{(3)} + 1.40c_{ll}^{(1)} + 1.83c_{H\Box} - 0.46c_{HD} - 1.26c_{HW} + 1.23c_{HWB}\,. \tag{3}$$

2D constraints - VBS+WW Combination

Complementarity of VBS and diboson measurements:

- Q_{qq} operators only constrained by VBS
- $Q_{H\Box}$, Q_{HW} operators only constrained by VBS
- Degeneracy on $Q_{Hl}^{(1)}$ resolved by VBS ZZ/WZ
- Flat directions resolved thanks to combination.



Impact of $O(\Lambda^{-4})$ terms non negligible:

- Distorts the linear elliptic c.l. in a non-trivial way
- Linear-only sometimes better (differently from 1D): Mixed interference between dim-6 amplitudes can mitigate deviations

Summary

In this work we presented **a comprehensive study at parton level of EFT dimension-6 effects on VBS and diboson W^+W^-**

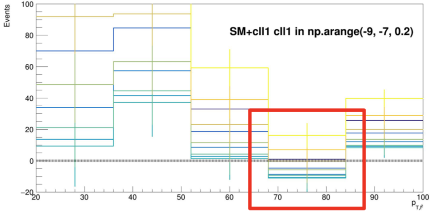
- VBS $2 \to 6$ simulated for all channels ($2 \to 4$ diboson)
- Individual sensitivity does not decrease at $\mathcal{O}(\Lambda^{-4})$
- $\mathcal{O}(\Lambda^{-4})$ terms help in reducing flat directions
- Propagator corrections at $\mathcal{O}(\Lambda^{-2})$ provide sensitive contributions
- EFT dependence of the QCD induced sample ($\alpha_s^2 \alpha_{EW}^4$) never weakens the sensitivity
- Addressed sensitivity reach of ZV+2j (semileptonic)
- Orthogonality of VBS and diboson measurements in more dimensions

BACKUP

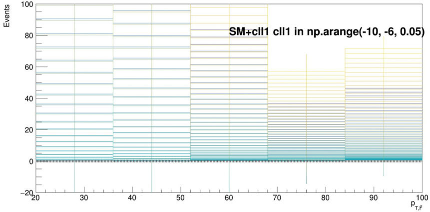
Amplitude decomposition

While the advantage of **amplitude decomposition** while generating EFT contributions at fixed orders in E/Λ is a better PS sampling, it has the disadvantage that the nominal value for $\boldsymbol{N \propto \|\mathcal{A}_{SM} + \mathcal{A}_6|^2}$ **can be negative** due to the fact that each contribution is evaluated on a different PS.
$\rightarrow$ **The reweighting method** (LO $w^N = w^O|\mathcal{M}_h^N|^2/|\mathcal{M}_h^O|^2$) computes weights for new hypothesis fixing the PS and **guarantees positive definiteness.**. Handy when working with pdfs.
Closure tests performed between standalone components and reweighted one, agreement within statistical error.

SINGLE COMPONENTS



REWEIGHTING



[Technical Details](#)

Impact of QCD EFT dependence

The fact that adding QCD often makes the bounds stronger can be understood intuitively as following from the fact that, in most cases, adding QCD corresponds to adding a positive number of signal events (independently of the value of the Wilson coefficient), which improves the bounds. in the paper for the case of one Wilson coefficient C, the statistical analysis results into a constraint of the form

$$|N^{lin} C + N^{quad} C^2| \leq X \tag{4}$$

where $X > 0$ is some numerical quantity and the N pre-factors decompose additively into EW and QCD components, because the interference between them is negligible for both SM and EFT, that is:

$$N^{lin}_{EW+QCD} = N^{lin}_{EW} + N^{lin}_{QCD}\,, \qquad N^{quad}_{EW+QCD} = N^{quad}_{EW} + N^{quad}_{QCD}\,. \tag{5}$$

If the constraint is dominated by the quadratic term, it takes approximately the form $|C| < \sqrt{X/N^{quad}}$ and, because $N^{quad}_i > 0$, necessarily

$$\sqrt{\frac{X}{N^{quad}_{EW} + N^{quad}_{QCD}}} < \sqrt{\frac{X}{N^{quad}_{EW}}} \tag{6}$$

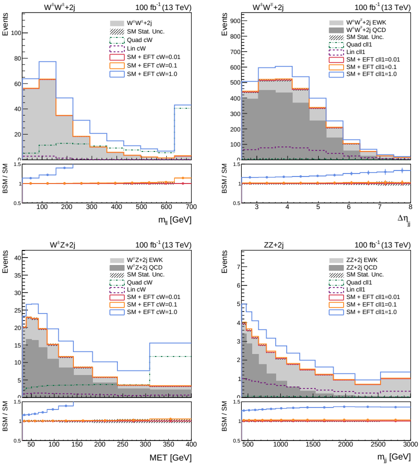
i.e. the EW+QCD bound is always stronger. If linear terms are dominant, the constraint scales as $|C| < X/|N^{lin}|$, so again the EW+QCD is stronger than the EW one, unless N^{lin}_{EW} and N^{lin}_{QCD} partially cancel against each other, i.e. $|N^{lin}_{EW+QCD}| < |N^{lin}_{EW}|$, which, however, is unlikely to occur systematically across all bins of a distribution.

To get a further handle on this aspect, we ran fits to the fully-leptonic QCD-induced processes alone. All cases where EW and EW+QCD bounds are very close, correspond to situations where the EW constraint is much stronger than the QCD one.

	OSWW		WZ		ZZ	
	EW + QCD	QCD	EW + QCD	QCD	EW + QCD	QCD
c_{HD}	[−3.3, 4.4]	[−57, 27]	[−4.8, 4.2]	[−5.5, 4.4]	[−5.6, 4.]	[−6.3, 5.4]
c_{HWB}	[−3.1, 4.5]	[−11.5, 11.0]	[−4.1, 2.2]	[−7.2, 2.3]	[−7.0, 2.1]	[−7.9, 3.0]
c_W	[−0.4, 0.3]	[−0.7, 0.6]	[−0.5, 0.5]	[−1.1, 0.8]	—	—
$c_{Hl}^{(1)}$	[−27.0, 26.6]	$>$ 100	[−1.4, 1.3]	[−1.6, 1.6]	[−1.6, 1.6]	[−13.4, 9.1]
$c_{Hl}^{(3)}$	[−0.3, 0.3]	[−0.5, 0.5]	[−0.6, 0.6]	[−0.9, 0.9]	[−1.2, 1.2]	[−2.5, 2.7]
$c_{Hq}^{(1)}$	[−0.8, 0.8]	[−0.8, 0.8]	[−2.9, 2.9]	[−19.7, 16.6]	[−4.8, 4.1]	[−6.2, 4.6]
$c_{Hq}^{(3)}$	[−0.4, 0.4]	[−0.5, 0.4]	[−0.7, 0.5]	[−0.9, 0.6]	[−1.3, 1.1]	[−1.8, 1.9]
$c_{ll}^{(1)}$	[−0.3, 0.3]	[−0.5, 0.5]	[−0.6, 0.6]	[−0.8, 0.9]	[−1.3, 1.4]	[−2.4, 2.4]

VBS fully-leptonic

Standard VBS LHC cuts searching for two forward jets with high invariant mass and large η gap, Central leptons and MET. ZZ+2j implements VBS enriched and inclusive selections.

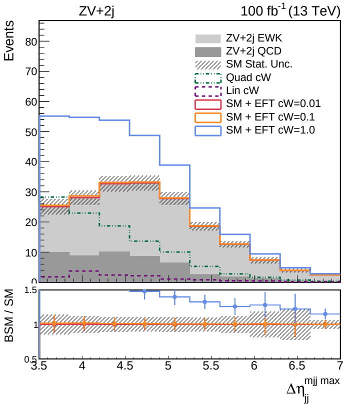


Process	**Variables of interest**	**Selections**
$W^{\pm}W^{\pm}+2j$ $(pp \to 2l2\nu jj)$	MET, m_{jj}, m_{ll}, ϕ_{j^i}, p_{T,j^i} p_{T,l^i}, $p_{T,ll}$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, η_{j^i}, η_{l^i}	$MET > 30$ GeV $m_{jj} > 500$ GeV $m_{ll} > 20$ GeV $p_{T,l^1} > 25$ GeV $p_{T,l^2} > 20$ GeV $p_{T,j^i} > 30$ GeV $\Delta\eta_{jj} > 2.5$ $\lvert\eta_{j^i}\rvert < 5$ $\lvert\eta_{l^i}\rvert < 2.5$
$W^{+}W^{-}+2j$ $(pp \to 2l2\nu jj)$		
$W^{\pm}Z+2j$ $(pp \to 3l\nu jj)$	MET, m_{jj}, m_{ll}, ϕ_{j^i}, p_{T,j^i}, p_{T,l^i} $p_{T,ll}$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, η_{j^i}, η_{l^i}, m_{3l} $p_{T,3l}$, m_{WZ}, $\delta\eta_{WZ}$, $\delta\phi_{WZ}$, Φ_{planes} θ_{lW}, θ_{lZ}, θ^*	
$ZZ+2j$ $(pp \to 4l2j)$	m_{jj}, $m_{l^1l^2}$, m_{ll}, m_{4l}, ϕ_{j^i}, p_{T,j^i}, p_{T,l^i}, p_{T,l^1l^2}, $p_{T,l^{\pm}l^{\pm}}$ $\Delta\phi_{jj}$, $\Delta\eta_{jj}$, η_{j^i}, η_{l^i}	$m_{jj} > 400$ GeV $60 < m_{ll} < 120$ GeV $m_{4l} > 180$ GeV $p_{T,l^1} > 20$ GeV $p_{T,l^2} > 10$ GeV $p_{T,l^i} > 5$ GeV $p_{T,j^{1,2}} > 30$ GeV $\Delta\eta_{jj} > 2.4$ $\lvert\eta_{j^i}\rvert < 4.7$ $\lvert\eta_{l^i}\rvert < 2.5$ $\Delta R(l^i, j^k) > 0.4$

Same Sign WW distributions: .
Opposite Sign WW distributions: .
VBS ZZ distributions: .
VBS WZ distributions: .

VBS semi-leptonic

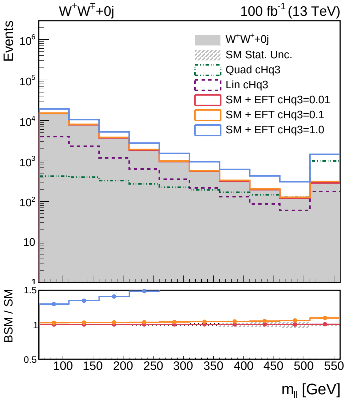
- First evidence for semi-leptonic VBS this year CMS-PAS-SMP-20-013
- $W \to q\bar{q}$: **more statistics, more backgrounds**.
- Major background: **Z+jets, not simulated** $\to$ separate treatment.
- Highest m_{jj} partons tagged as VBS jets ($\epsilon \sim$ 75%).



VBS ZV distributions: .

Process	Variables of interest	Selections
$ZV + 2j$ $(pp \to 2ljjjj)$	m_{jj}, m_{ll}, ϕ_{j^i}, p_{T,j^i}, p_{T,l^i} $p_{T,ll}$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, η_{j^i} η_{l^i}	$m_{jj} > 1500$ GeV $60 < m_{jj}^{V} < 110$ GeV $85 < m_{ll} < 95$ GeV $p_{T,l^1} > 25$ GeV $p_{T,l^2} > 20$ GeV $p_{T,j^i} > 100$ GeV $\Delta\eta_{jj} > 3.5$ $\lvert\eta_{j^i}\rvert < 5$

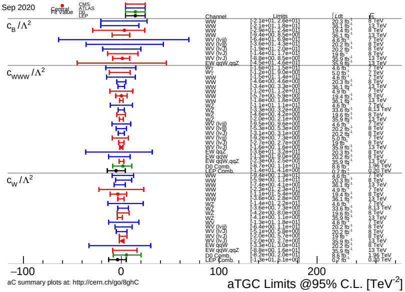
Diboson W^+W^-



Diboson WW distributions:

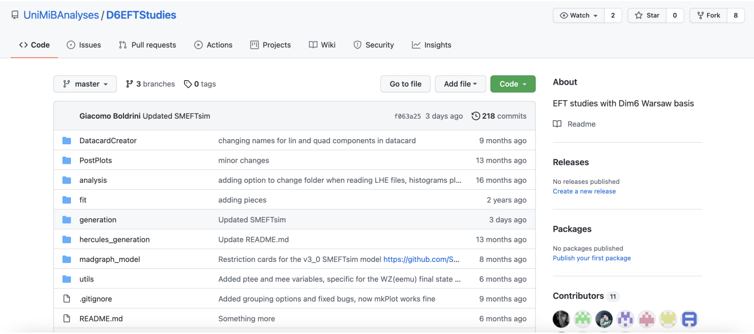
Process	Variables	Selections
$W^+W^- + 0j$ ($pp \to 2l2\nu$)	MET, m_{ll}, p_{T,l^i}, $p_{T,ll}$, η_{l^i}	$MET > 30$ GeV $m_{ll} > 60$ GeV $p_{T,l^1} > 25$ GeV $p_{T,l^2} > 20$ GeV $\lvert\eta_{l^i}\rvert < 2.5$

- Highest cross section
- Historically main playground for aTGC and dim-6 EFT
- usually **few operators studied**: Q_W, Q_{WWW}, Q_B and CP violating (HISZ basis)
- DF 0-jet category **high purity** (main backgrounds $t\bar{t}$, non-prompt, DY)

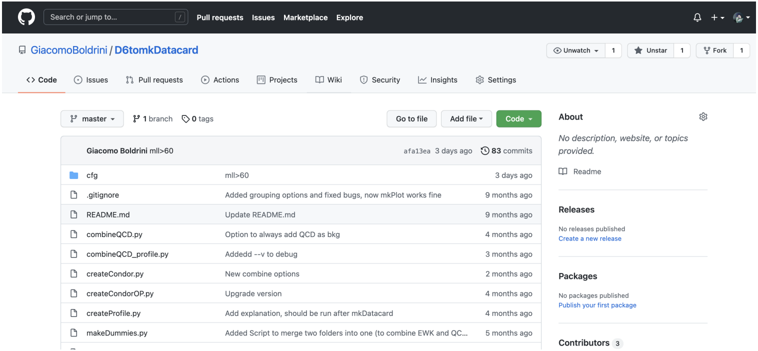


Analysis setup

Ntuples and LHE generation framework
[https://github.com/UniMiBAnalyses/D6EFTStudies]



Post-processing, QCD merging, and shape maker based on
https://github.com/GiacomoBoldrini/D6tomkDatacard



Tailored to latinos framework datacard maker
https://github.com/latinos/LatinoAnalysis

Analysis setup

EFT analysis inside CMS problematic. The fitting tool Combine does not allow negative shapes (such as linear and mixed interference). Workaround: **redefine each component as positive-definite**.

Combine model for EFT studies with up to $O(\Lambda^{-4})$ and possibility to add dim-8 operators: AnalyticAnomalousCoupling

More details in CMS internal note.

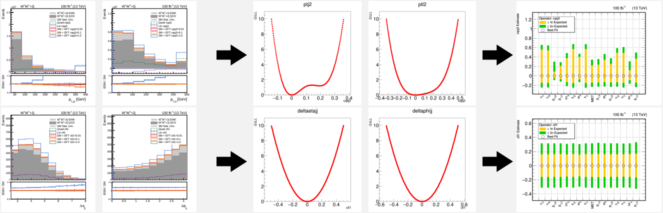
$$
\begin{aligned}
N = {} & S \cdot \Big(1 - \sum_i k_i + \sum_{i,i<j} \sum_j k_i \cdot k_j\Big) \\
& + \Big[\sum_i k_i - \sum_{i \neq j} k_i \cdot k_j\Big] \cdot (S + L_i + Q_i) \\
& + \sum_i \left(k_i^2 - k_i\right) \cdot Q_i \\
& + \sum_{i,i<j} \sum_j k_i \cdot k_j \cdot \left[S + L_i + L_j + Q_i + Q_j + 2 \cdot M_{ij}\right]
\end{aligned}
$$

Analysis strategy

OSWW

$Q_{qq}^{(3)}$

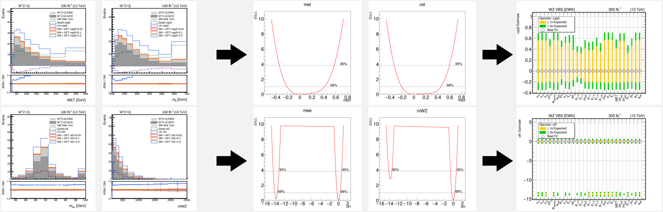
$Q_{ll}^{(1)}$



WZ

$Q_{qq}^{(3)}$

$Q_{ll}^{(1)}$



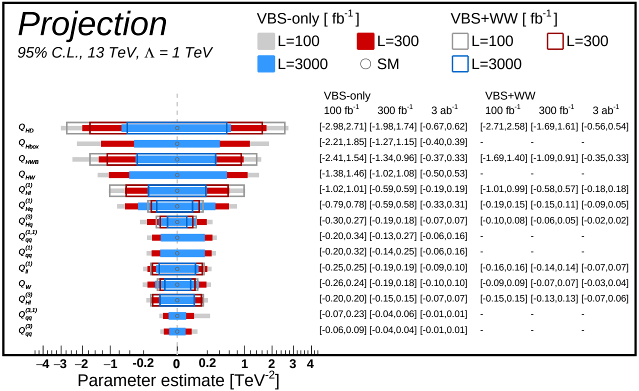
Generations

SMEFTsim newest version: [https://github.com/SMEFTsim/SMEFTsim]

SSWW-EW	`generate p p > e+ ve mu+ vm j j QCD=0 SMHLOOP=0`
OSWW-EW	`generate p p > e+ ve mu- vm j j QCD=0 SMHLOOP=0`
WZ-EW	`generate p p > e+ e- mu+ vm j j QCD=0 SMHLOOP=0`
ZZ-EW	`generate p p > e+ e- mu+ mu- j j QCD=0 SMHLOOP=0`
ZV-EW	`generate p p > z w+(w-,z) j j QCD=0 SMHLOOP=0, z > l+ l-, w+(w-,z) > j j`
WW	`generate p p > e+ ve mu- vm SMHLOOP=0`
ZV-QCD	`generate p p > z w+(w-,z) j j QCD==2 SMHLOOP=0, z > l+ l-, w+(w-,z) > j j`
OSWW-QCD	`generate p p > e+ ve mu- vm j j QCD==2 SMHLOOP=0`
WZ-QCD	`generate p p > e+ e- mu+ vm j j QCD==2 SMHLOOP=0`
ZZ-QCD	`generate p p > e+ e- mu+ mu- j j QCD==2 SMHLOOP=0`

$\sqrt{s} = 13$ TeV, NNLO pdfs from NNPDF $\alpha_s = 0.118$ (lhaid=325500) and 4-flavour scheme. $U(3)^5$ symmetry group and $\{m_W, m_Z, G_F\}$ input scheme. $\Lambda = 1$ TeV

Expected constraints at future colliders



	VBS-only			VBS+WW		
	100 fb^{-1}	300 fb^{-1}	3 ab^{-1}	100 fb^{-1}	300 fb^{-1}	3 ab^{-1}
Q_{HD}	[-2.98,2.71]	[-1.98,1.74]	[-0.67,0.62]	[-2.71,2.58]	[-1.69,1.61]	[-0.56,0.54]
$Q_{H\square}$	[-2.21,1.85]	[-1.27,1.15]	[-0.40,0.39]	-	-	-
Q_{HWB}	[-2.41,1.54]	[-1.34,0.96]	[-0.37,0.33]	[-1.69,1.40]	[-1.09,0.91]	[-0.35,0.33]
Q_{HW}	[-1.38,1.46]	[-1.02,1.08]	[-0.50,0.53]	-	-	-
$Q_{Hl}^{(1)}$	[-1.02,1.01]	[-0.59,0.59]	[-0.19,0.19]	[-1.01,0.99]	[-0.58,0.57]	[-0.18,0.18]
$Q_{Hq}^{(1)}$	[-0.79,0.78]	[-0.59,0.58]	[-0.33,0.31]	[-0.19,0.15]	[-0.15,0.11]	[-0.09,0.05]
$Q_{Hq}^{(3)}$	[-0.30,0.27]	[-0.19,0.18]	[-0.07,0.07]	[-0.10,0.08]	[-0.06,0.05]	[-0.02,0.02]
$Q_{qq}^{(1,1)}$	[-0.20,0.34]	[-0.13,0.27]	[-0.06,0.16]	-	-	-
$Q_{qq}^{(1)}$	[-0.20,0.32]	[-0.14,0.25]	[-0.06,0.16]	-	-	-
$Q_{ll}^{(1)}$	[-0.25,0.25]	[-0.19,0.19]	[-0.09,0.10]	[-0.16,0.16]	[-0.14,0.14]	[-0.07,0.07]
Q_{W}	[-0.26,0.24]	[-0.19,0.18]	[-0.10,0.10]	[-0.09,0.09]	[-0.07,0.07]	[-0.03,0.04]
$Q_{Hl}^{(3)}$	[-0.20,0.20]	[-0.15,0.15]	[-0.07,0.07]	[-0.15,0.15]	[-0.13,0.13]	[-0.07,0.06]
$Q_{qq}^{(3,1)}$	[-0.07,0.23]	[-0.04,0.06]	[-0.01,0.01]	-	-	-
$Q_{qq}^{(3)}$	[-0.06,0.09]	[-0.04,0.04]	[-0.01,0.01]	-	-	-

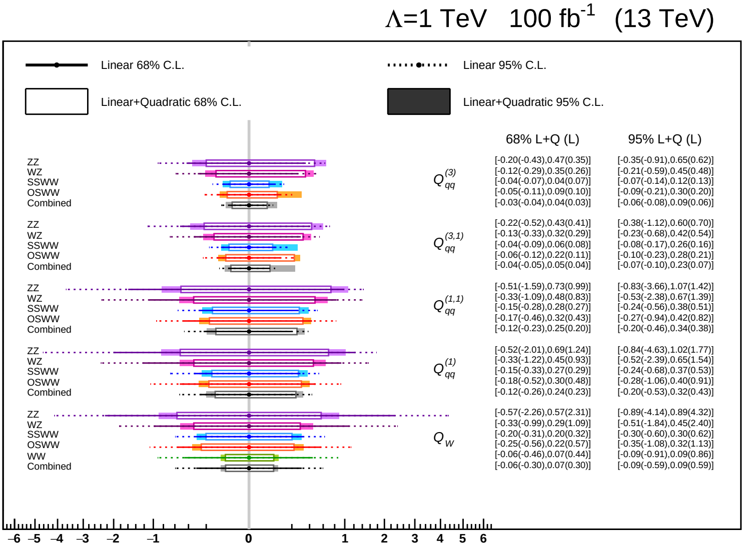
Projection of individual constraints to future LHC phases Integrated luminosities: LHC Run II $\sim$ 100fb^{-1}, LHC Run III $>$ 300fb^{-1}, HL-LHC $\sim$ 3 ab^{-1}. No scaling of the nuisance constraint involved.

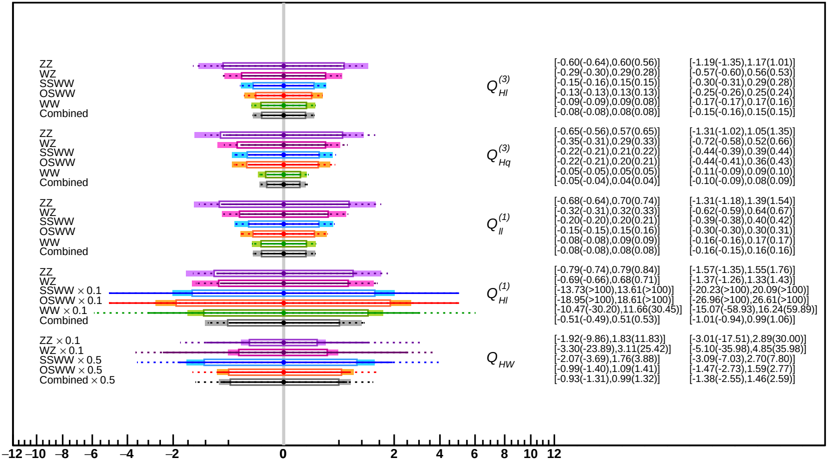
At the HL-LHC, the VBS-only combination is expected to constrain all operators to less than [-1,1], including diboson lowers the range to [-0.5,0.5]. Roughly a factor $\sim$ 5 improvement expected from LHC Run II to HL-LHC.

SMEFT corrections in propagators

Op.	SSWW+2j		OSWW+2j		WZ+2j		ZZ+2j		ZV+2j		WW	
	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q	L	L+Q
$c_{Hl}^{(1)}$	-	m_{ll}	-	MET	$m_{ee}{}^{\dagger}$	m_{WZ}	$p_{T,e^-\mu^-}{}^{\dagger}$	$p_{T,e^-\mu^-}{}^{\dagger}$	p^V_{T,j_1}	p^V_{T,j_1}	p_{T,l^1}	MET
$c_{Hl}^{(3)}$	$\Delta\eta_{jj}{}^{\dagger}$	$\Delta\eta_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta^V_{jj}$	$\Delta\eta^V_{jj}$	$m_{ll}{}^{\dagger}$	$m_{ll}{}^{\dagger}$
$c_{Hq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	m_{jj}	m_{ll}	m_{jj}	p_{T,j^1}	m_{jj}	p_{T,j^1}	m^{VBS}_{jj}	m^{VBS}_{jj}	MET	MET
$c_{Hq}^{(3)}$	$\Delta\phi_{jj}$	$\Delta\phi_{jj}$	m_{ll}	m_{ll}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^1}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^4}	p^{VBS}_{T,j_2}	p^{VBS}_{T,j_2}	p_{T,l^1}	p_{T,l^1}
$c_{qq}^{(3)}$	$m_{ll}{}^{\dagger}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$p_{T,l^1}{}^{\dagger}$	$\Delta\phi^{VBS}_{jj}$	-	-
$c_{qq}^{(3,1)}$	$\Delta\phi_{jj}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$\Delta\eta^{V\dagger}_{jj}$	$\Delta\phi^{VBS}_{jj}$	-	-
$c_{qq}^{(1,1)}$	$\Delta\phi_{jj}$	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi^{VBS}_{jj}$	p^{VBS}_{T,j_1}	-	-
$c_{qq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi^{VBS}_{jj}$	p^{VBS}_{T,j_1}	-	-
c_{HD}	p_{T,j^1}	m_{ll}	$\Delta\eta_{jj}$	$\Delta\eta_{jj}$	m_{ee}	$\Delta\eta_{jj}{}^{\dagger}$	$p_{T,e^+\mu^+}$	$p_{T,e^+\mu^+}{}^{\dagger}$	p_{T,l^2}	p_{T,l^2}	p_{T,l^1}	p_{T,l^1}
$c_{H\square}$	p_{T,j^1}	m_{ll}	m_{ll}	m_{ll}	-	m_{WZ}	-	$\Delta\eta_{jj}$	p^V_{T,j_2}	p^V_{T,j_2}	-	-
c_{HW}	$\Delta\phi_{jj}$	m_{ll}	$\Delta\phi_{jj}$	m_{ll}	$\eta_{l^3}{}^{\dagger}$	m_{WZ}	m_{jj}	m_{4l}	p^{VBS}_{T,j_1}	p^V_{T,j_2}	-	-
c_{HWB}	p_{T,j^1}	p_{T,j^1}	$\Delta\eta_{jj}$	m_{ll}	m_{ee}	m_{WZ}	$m_{\mu\mu}{}^{\dagger}$	$\Delta\eta_{jj}$	$\Delta\eta^V_{jj}$	$\Delta\eta^V_{jj}$	p_{T,l^1}	MET
c_W	$\Delta\phi_{jj}$	$p_{T,ll}$	$\Delta\phi_{jj}$	m_{ll}	p_{T,l^1}	m_{WZ}	$\Delta\phi_{jj}$	p_{T,l^4}	$\Delta\phi^{VBS\dagger}_{jj}$	$\Delta\phi^{VBS\dagger}_{jj}$	MET	MET
$c_{ll}^{(1)}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta^{V\dagger}_{jj}$	$\Delta\eta^{V\dagger}_{jj}$	$p_{T,ll}{}^{\dagger}$	p_{T,l^2}

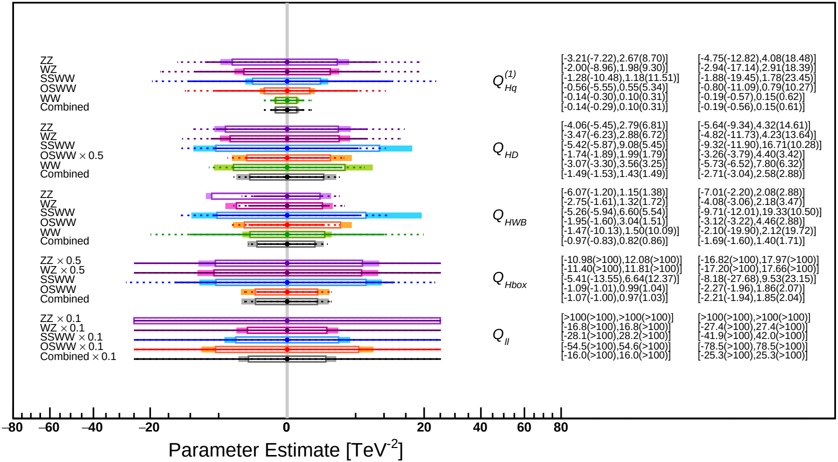
Individual constraints - VBS+WW Combination



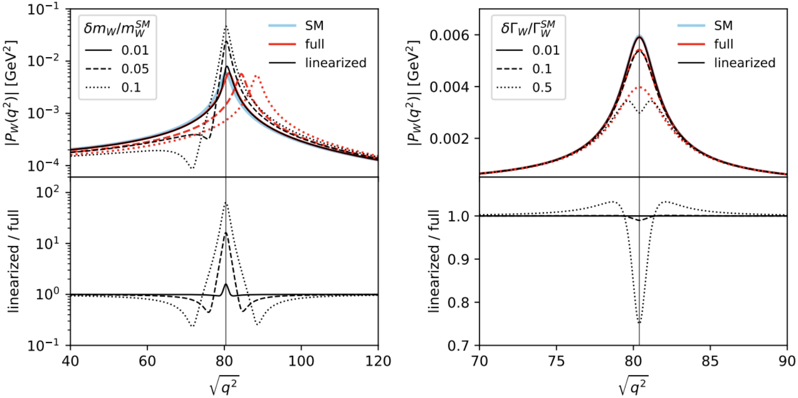


ZZ
WZ
SSWW
OSWW
WW
Combined
$Q^{(3)}_{Hl}$
[-0.60(-0.64),0.60(0.56)]
[-0.29(-0.30),0.29(0.28)]
[-0.15(-0.16),0.15(0.15)]
[-0.13(-0.13),0.13(0.13)]
[-0.09(-0.09),0.09(0.08)]
[-0.08(-0.08),0.08(0.08)]
[-1.19(-1.35),1.17(1.01)]
[-0.57(-0.60),0.56(0.53)]
[-0.30(-0.31),0.29(0.28)]
[-0.25(-0.26),0.25(0.24)]
[-0.17(-0.17),0.17(0.16)]
[-0.15(-0.16),0.15(0.15)]
ZZ
WZ
SSWW
OSWW
WW
Combined
$Q^{(3)}_{Hq}$
[-0.65(-0.56),0.57(0.65)]
[-0.35(-0.31),0.29(0.33)]
[-0.22(-0.21),0.21(0.22)]
[-0.22(-0.21),0.20(0.21)]
[-0.05(-0.05),0.05(0.05)]
[-0.05(-0.04),0.04(0.04)]
[-1.31(-1.02),1.05(1.35)]
[-0.72(-0.58),0.52(0.66)]
[-0.44(-0.39),0.39(0.44)]
[-0.44(-0.41),0.36(0.43)]
[-0.11(-0.09),0.09(0.10)]
[-0.10(-0.09),0.08(0.09)]
ZZ
WZ
SSWW
OSWW
WW
Combined
$Q^{(1)}_{ll}$
[-0.68(-0.64),0.70(0.74)]
[-0.32(-0.31),0.32(0.33)]
[-0.20(-0.20),0.20(0.21)]
[-0.15(-0.15),0.15(0.16)]
[-0.08(-0.08),0.09(0.09)]
[-0.08(-0.08),0.08(0.08)]
[-1.31(-1.18),1.39(1.54)]
[-0.62(-0.59),0.64(0.67)]
[-0.39(-0.38),0.40(0.42)]
[-0.30(-0.30),0.30(0.31)]
[-0.16(-0.16),0.17(0.17)]
[-0.16(-0.15),0.16(0.16)]
ZZ
WZ
SSWW × 0.1
OSWW × 0.1
WW × 0.1
Combined
$Q^{(1)}_{Hl}$
[-0.79(-0.74),0.79(0.84)]
[-0.69(-0.66),0.68(0.71)]
[-13.73(>100),13.61(>100)]
[-18.95(>100),18.61(>100)]
[-10.47(-30.20),11.66(30.45)]
[-0.51(-0.49),0.51(0.53)]
[-1.57(-1.35),1.55(1.76)]
[-1.37(-1.26),1.33(1.43)]
[-20.23(>100),20.09(>100)]
[-26.96(>100),26.61(>100)]
[-15.07(-58.93),16.24(59.89)]
[-1.01(-0.94),0.99(1.06)]
ZZ × 0.1
WZ × 0.1
SSWW × 0.5
OSWW × 0.5
Combined × 0.5
Q_{HW}
[-1.92(-9.86),1.83(11.83)]
[-3.30(-23.89),3.11(25.42)]
[-2.07(-3.69),1.76(3.88)]
[-0.99(-1.40),1.09(1.41)]
[-0.93(-1.31),0.99(1.32)]
[-3.01(-17.51),2.89(30.00)]
[-5.10(-35.98),4.85(35.98)]
[-3.09(-7.03),2.70(7.80)]
[-1.47(-2.73),1.59(2.77)]
[-1.38(-2.55),1.46(2.59)]
−12 −10 −8 −6 −4 −2 0 2 4 6 8 10 12

Individual constraints - VBS+WW Combination



Individual constraints - VBS+WW Combination



$$\{\alpha_{em}, m_Z, G_F\}$$

scheme