Multi-boson production sensitivity to dimension-6 EFT operators at the LHC

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Outline

- **Theoretical introduction: SMEFT**
- **Motivation** for **multi-boson measurements**
- **Experimental results** at **LHC**
- **Sensitivity LHE study** to constrain **dimension-6 SMEFT operators**
  - **Processes: VBS+WW di-boson** and **tri-boson**
  - **Analysis Strategy**
  - **Results: One and Two-dimensional operator constraints**
- **Summary and Outlook**

References

- R.Bellan et al. “A sensitivity study of **VBS** and **diboson WW** to dimension-6 EFT operators at the LHC” -published in JHEP05(2022)039

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

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- R.Bellan et al. “A sensitivity study of **triboson** production processes to dimension-6 EFT operators at the LHC” -published in JHEP08(2023)158

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A sensitivity study of triboson production processes to dimension-6 EFT operators at the LHC

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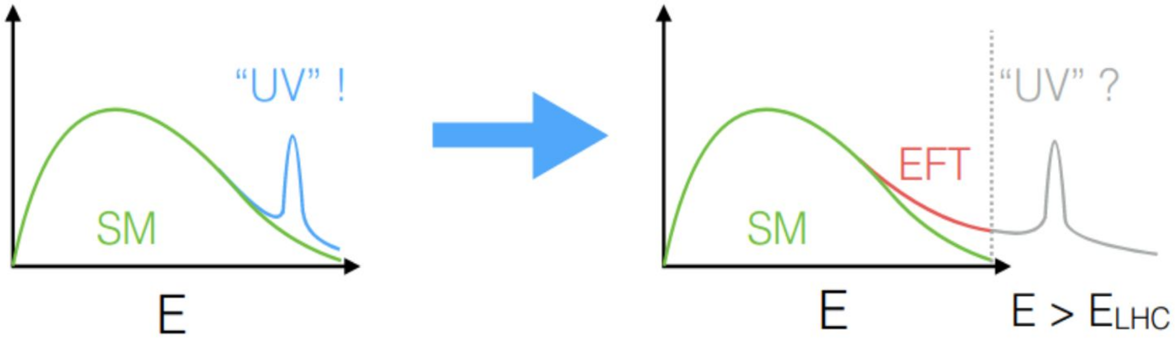
Theory introduction: SMEFT approach

- **Multi-boson processes** serve as a **test** of the **EW Symmetry Breaking**
- **EW sector still unexplored** since **several rare processes** not yet **observed**!
  - **Any deviation** in **kinematic observables** could point to **New Physics**



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- **SMEFT bottom-up approach:**
  - **Effective Lagrangian** with only light **SM** particles
  - **BSM effects** incorporated as a **momentum expansion**

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(4)} + \sum_{n,i} \frac{1}{\Lambda^{n-4}} c_i^{(n)} Q_i^{(n)}$$

$SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant

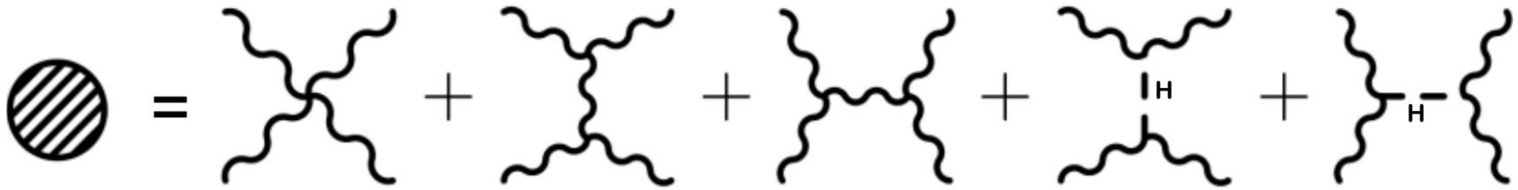
Λ unknown NP energy scale

Wilson coefficient

Dim. n operator.

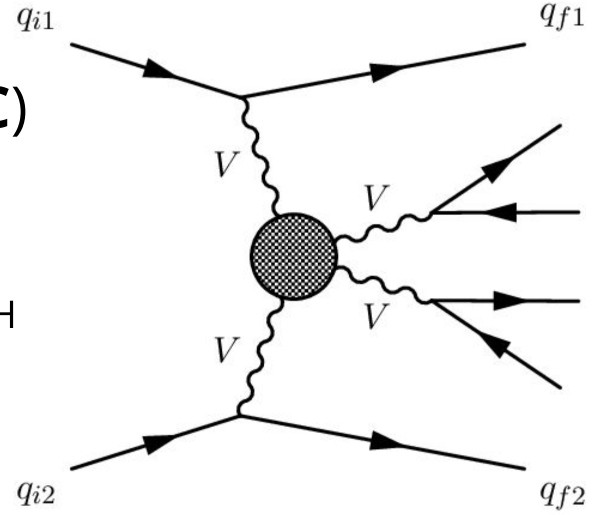
Motivation for multi-boson measurements

- **These processes probe** the **non-Abelian nature of SM:**
  - direct access to **triple**/**quartic gauge** couplings (**TGC/QGC**)
  - **sensitive** to **couplings** between **Higgs** and **gauge** bosons
    - complementary to **Higgs** measurements at scales > m_H

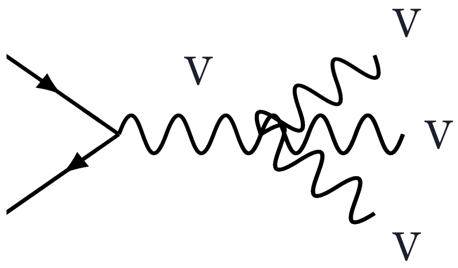


- **Portal to BSM physics:**
  - **model-independent** via **E**ffective **F**ield **T**heories (EFTs)
    - **18 bosonic** operators in **dim-8 EFT** tested (**aQGCs**)
    - **14 fermionic** and **bosonic dim-6 EFT** operators

VBS

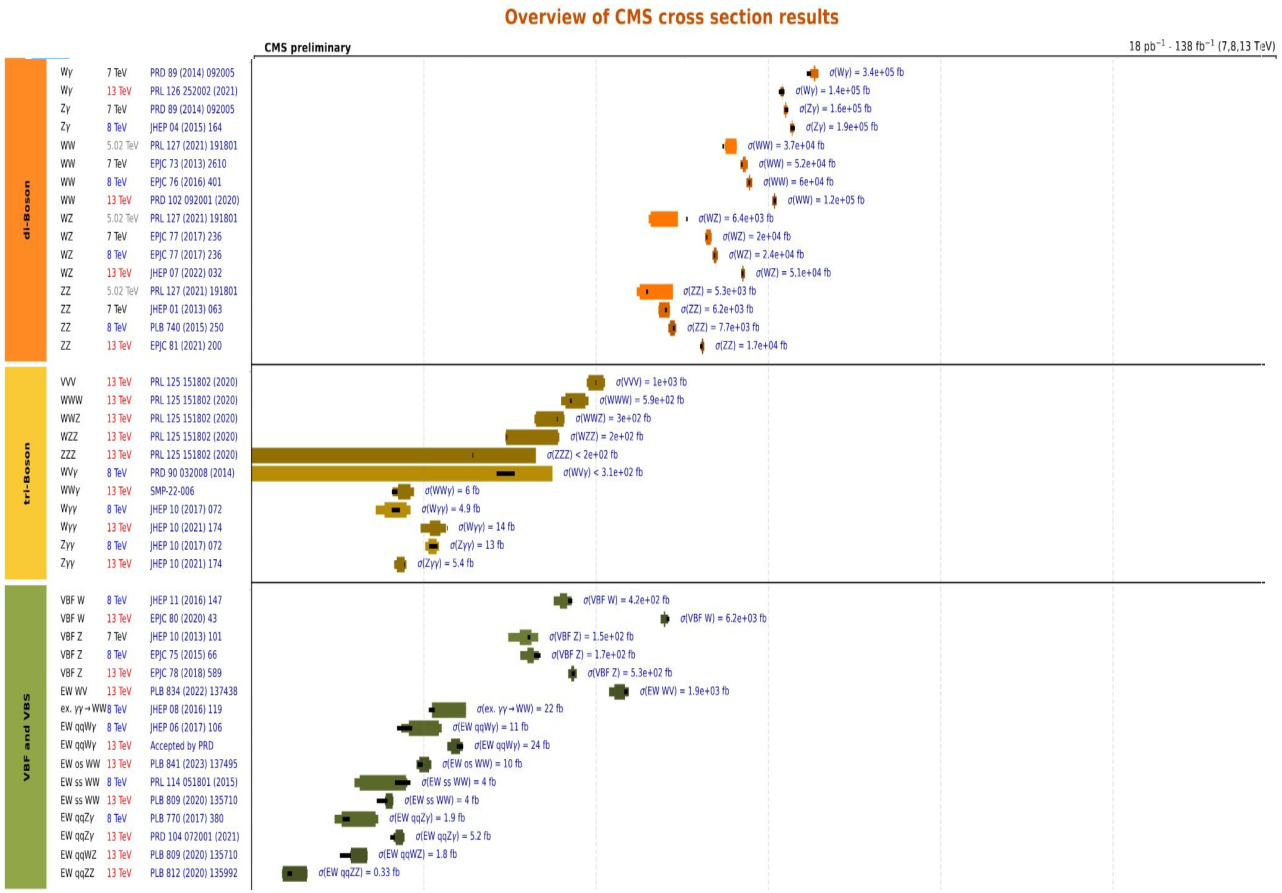


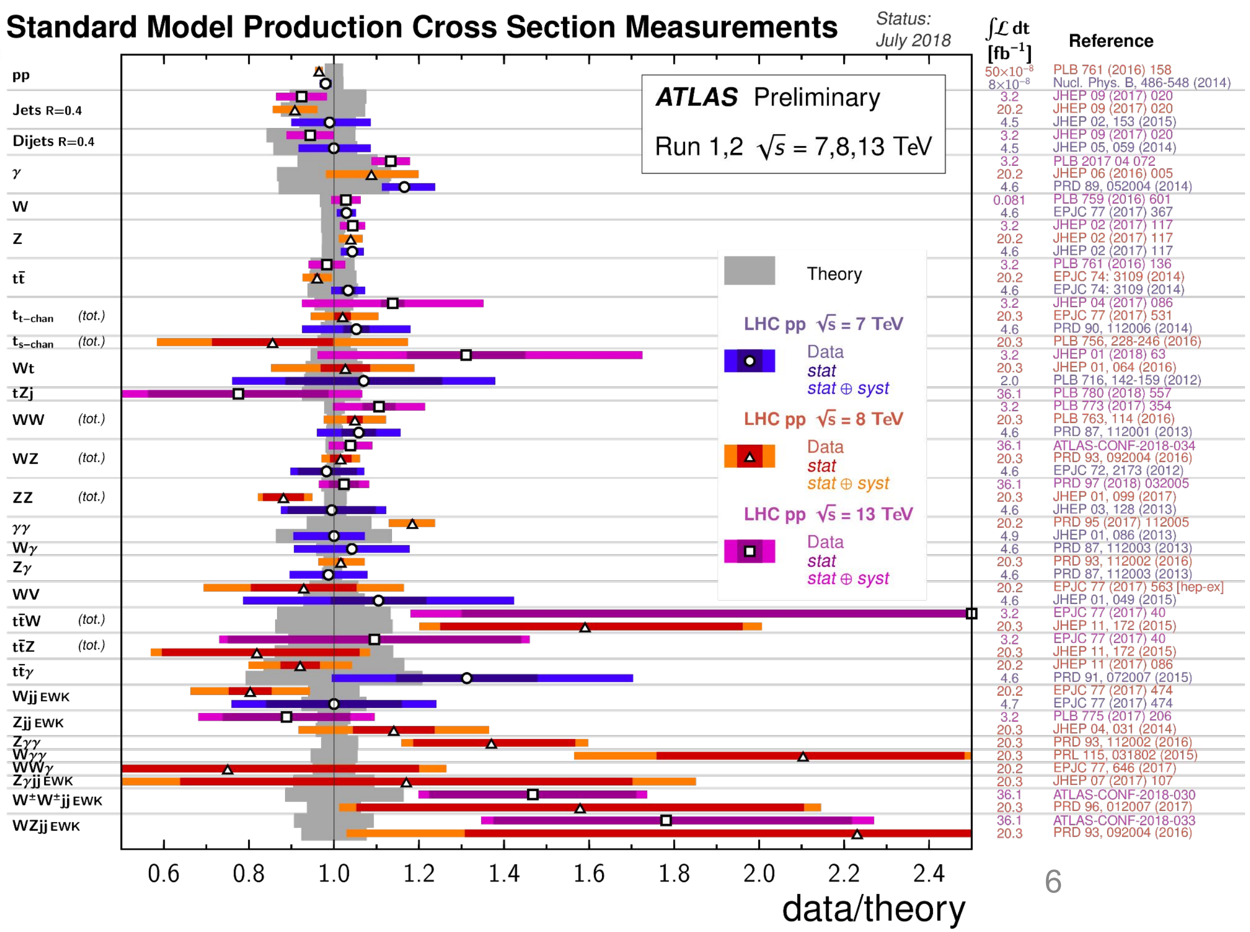
Triboson



Multi-boson measurements at LHC

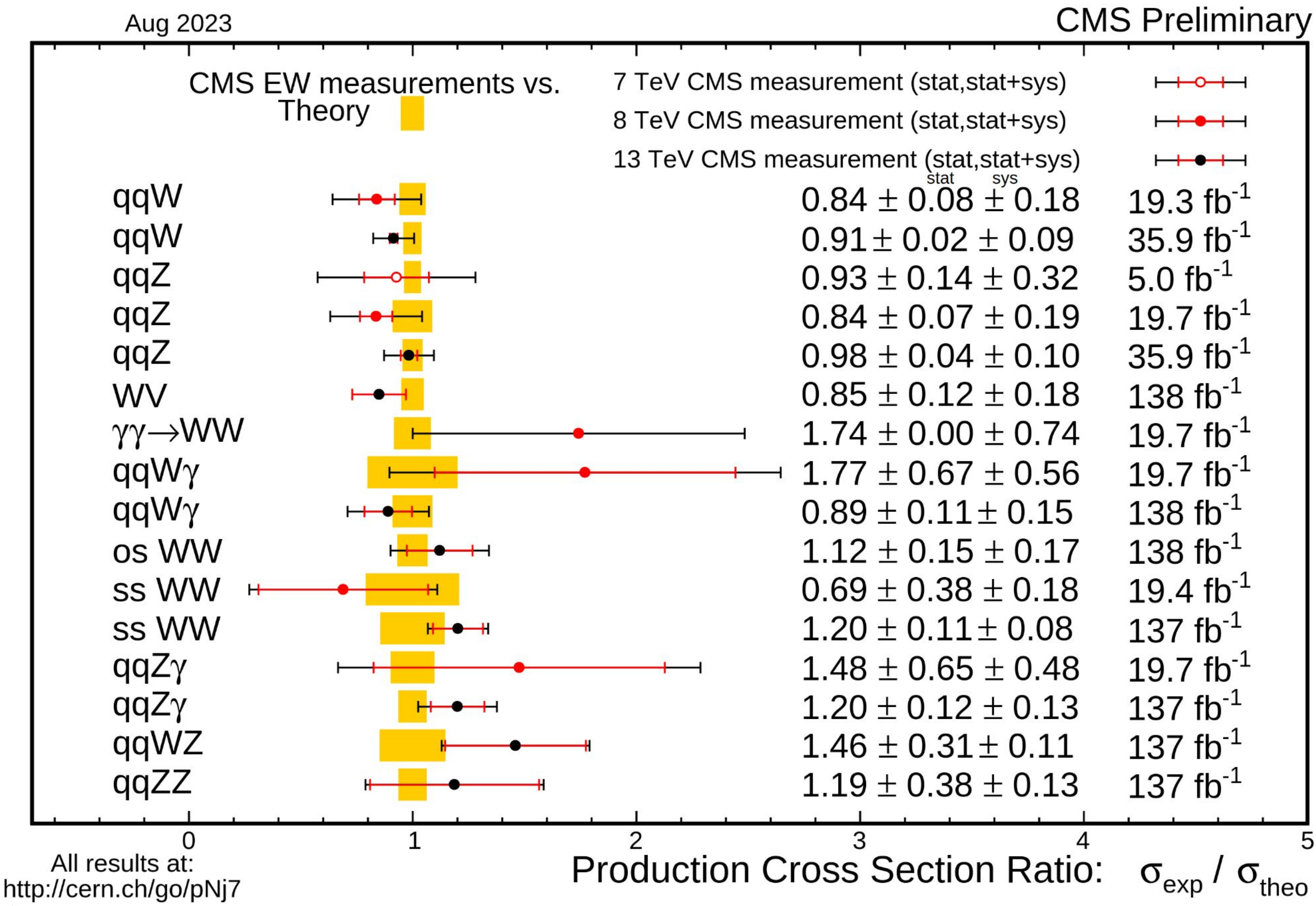
- The **ATLAS** and **CMS collaborations** have a **rich program** of **multi-boson** analyses
- **All diboson** and **VBS** processes have been **measured** in different decay modes
- Many **triboson** processes **have been studied** with at least a **photon** in final state





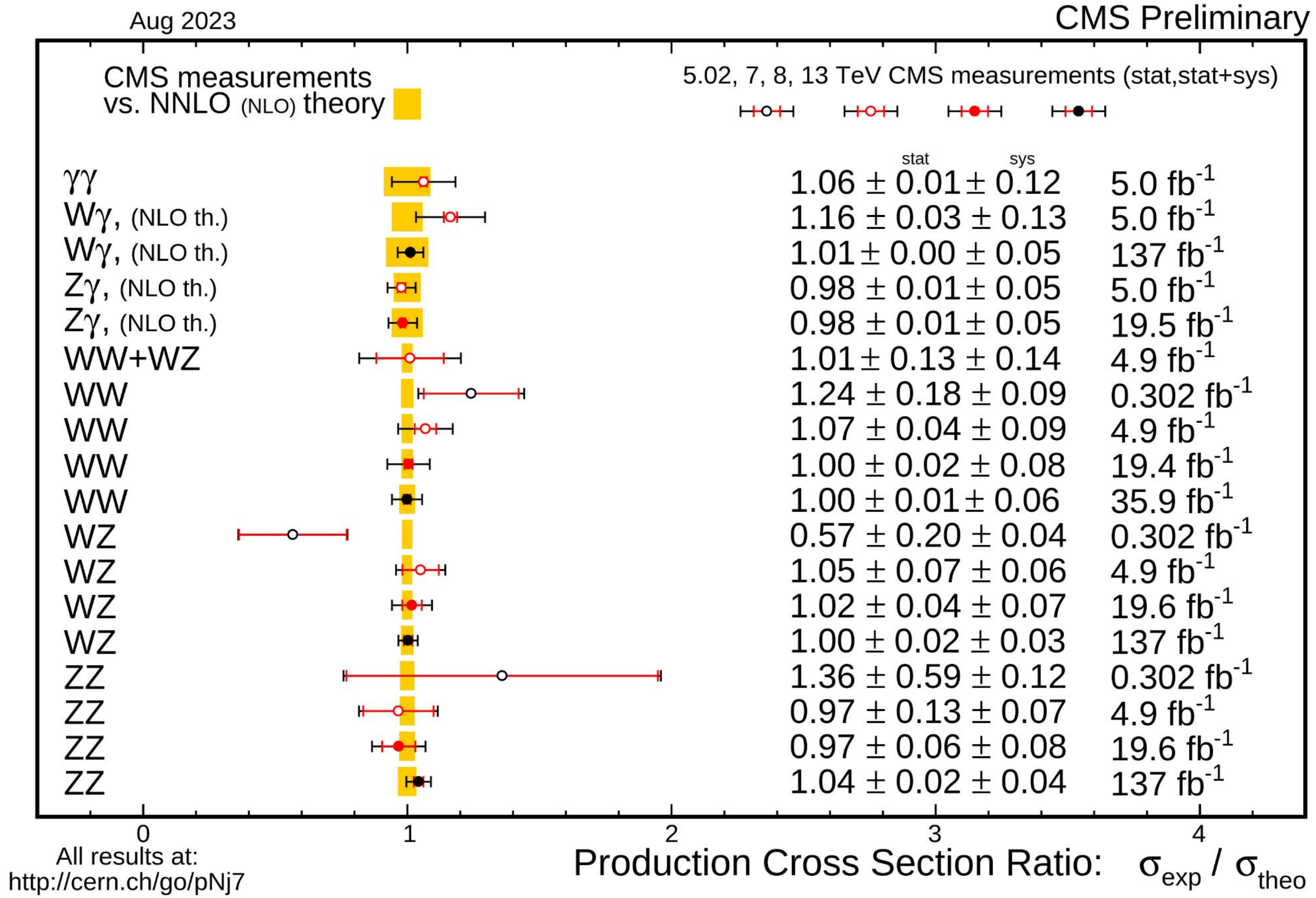
Vector boson scattering measurements

- **Statistically** limited, **L~137 fb^{-1}** allows new **measurements**
- Good **agreement** with SM: in some **VBS VV** scattering the EW measurements are ~1**σ** away from theory
- Accurate modelling of **VVjj non-VBS** contributions crucial
- BSM effects in **aQGC** (**EFT dim-8**) **dim-6** important and **should** not be neglected [arXiv:1809.04189]



Di-boson measurements

- Diboson: well-known processes, **differential x-sec** measurements
- **Large cross-section**: limited by **systematic** uncertainties
- In agreement with state-of-the-art **NNLO** theoretical calculations
- BSM effects manifest as **aTGC** (**EFT dim-6**)

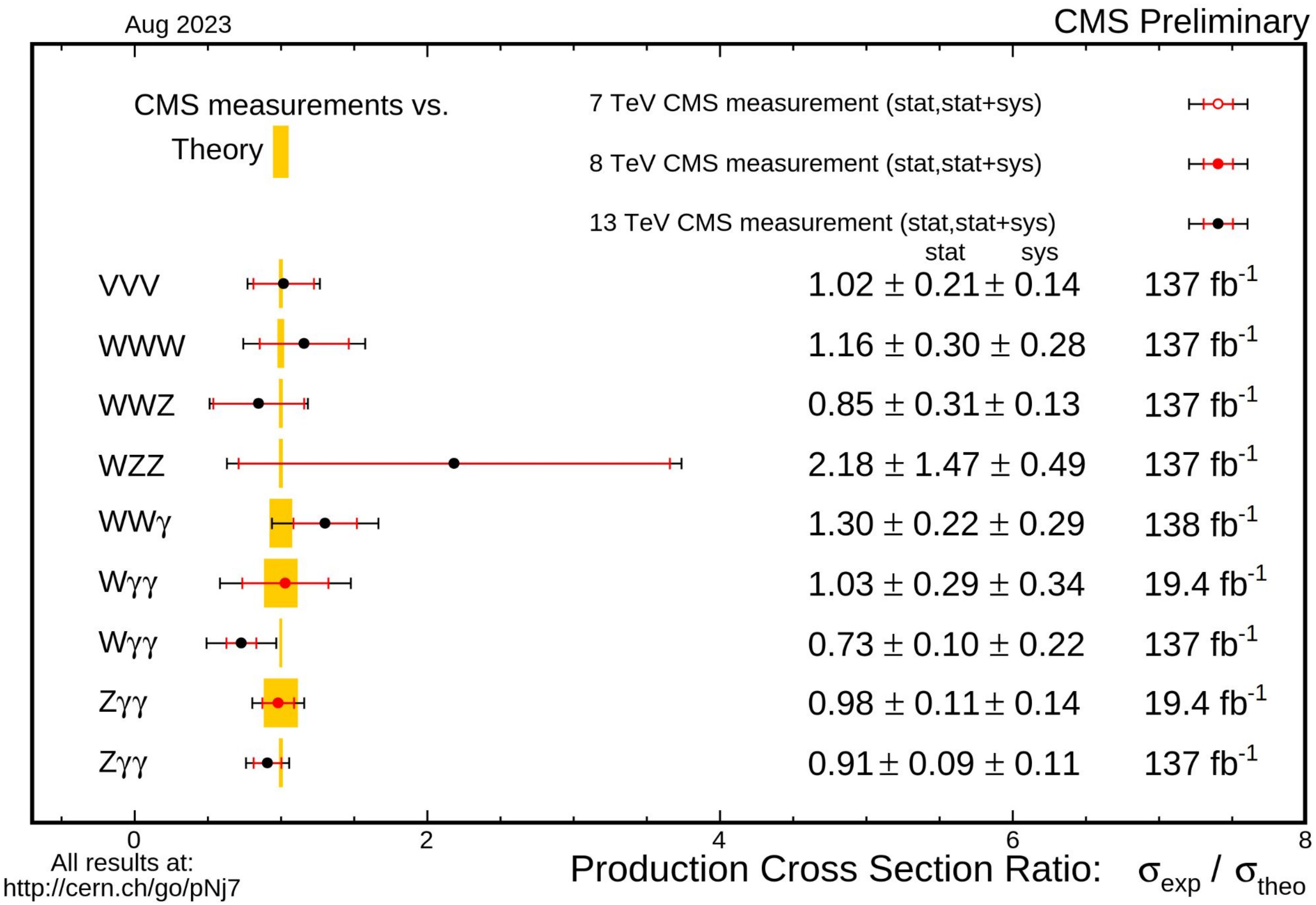


Tri-boson measurements

- **Extremely rare processes:**
  σ × BR(to leptons) ~O(1fb)

- **Observed three massive gauge** boson production and in **channel** with a **single VVγ** and **two photons Vγγ**

- **BSM effects** as both **aTGC/aQGC** and as anomalous **Higgs-gauge coupling**



Constraints to SMEFT operators

- Multi-boson processes can be a **tool** to **probe** BSM physics at the **TeV scale**, provided no **new light state** exists

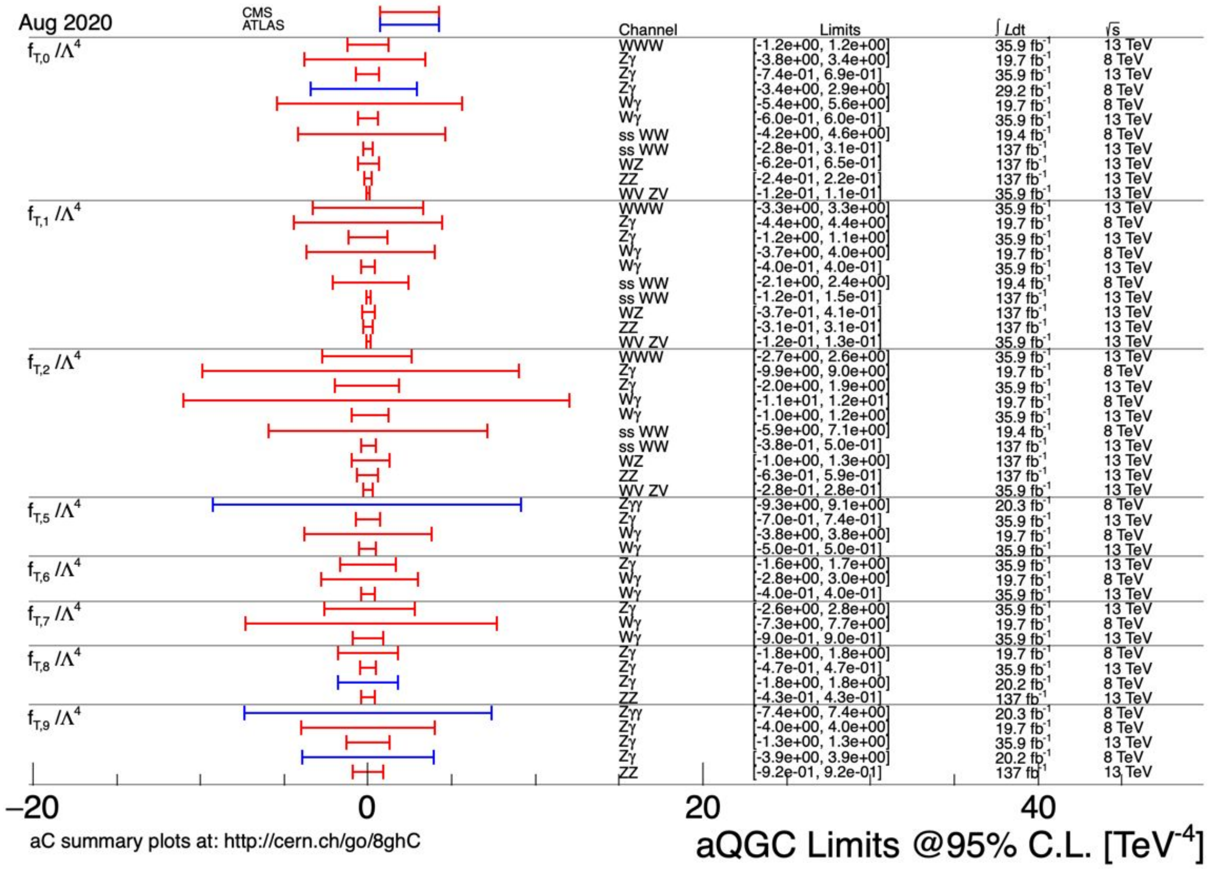
- Combination of **several analyses** is key to fit simultaneously all **59 independent SMEFT operators** to preserve **gauge invariance** and **UV-matching**
  - What is the sensitivity reach of a **VBS** and **tri-boson** combination?
  - What is the interplay with **WW** constraints?

- The first step towards **global SMEFT fit** is the **sensitivity study** at parton level of anomalies induced by **dimension-6** EFT operators

- **Assess sensitivity interplay** between **multi-boson analyses at LHC**
  - in the future **global EFT fit** will be necessary to provide the most stringent constraints to **SMEFT operators** (top, Higgs, EW, etc)

Motivation for dimension-6 EFT sensitivity study

- **Interpretation** of **VBS/tri-boson results** *traditionally* in terms of **dim-8 SMEFT operators (aQGCs)** at the LHC



- **However, dim-6 EFT operators** can also have an impact in VBS, e.g *pp→ZZjj*, **[arXiv:1809.04189]**

- **First LHE sensitivity** study **of VBS+WW** including **O(Λ^{-4}) dim-6** EFT terms extended to **triboson** production

- EFT analysis of both **EWK+QCD-induced** processes (**main** background)

SMEFT Monte Carlo Generations

- **Paramerisation** using **15 dim-6 SMEFT operators** from **Warsaw basis**
  - in **triboson** study focus on **bosonic** ops**,** for Yukawa sector see JHEP04(2021)023

- **Generated** at **LO** with **SMEFTsim interfaced** with **MadGraph5_aMC@NLO (2.6.5)**
  - **$U(3)^5$ flavour symmetry**
  - **$\{m_W, m_Z, G_F\}$ input scheme**
  - **CP-even**
  - **Λ = 1TeV**

- **Insertion** of **one operator** per **diagram** to generate directly **single components**

$$Q_{Hl}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_p) \qquad Q_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p\sigma^i\gamma^\mu l_p)$$

$$Q_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_p) \qquad Q_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p\sigma^i\gamma^\mu q_p)$$

$$Q_{qq}^{(1)} = (\bar{q}_p\gamma_\mu q_p)(\bar{q}_r\gamma^\mu q_r) \qquad Q_{qq}^{(1,1)} = (\bar{q}_p\gamma_\mu q_r)(\bar{q}_r\gamma^\mu q_p)$$

$$Q_{qq}^{(3)} = (\bar{q}_p\gamma_\mu\sigma^i q_p)(\bar{q}_r\gamma^\mu\sigma^i q_r) \qquad Q_{qq}^{(3,1)} = (\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_r\gamma^\mu\sigma^i q_p)$$

$$Q_{HD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H) \qquad Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$Q_{HWB} = (H^\dagger\sigma^i H)W^i_{\mu\nu}B^{\mu\nu} \qquad Q_{HW} = (H^\dagger H)W^i_{\mu\nu}W^{i\mu\nu}$$

$$Q_W = \varepsilon^{ijk}W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho \qquad Q_{HB} = (\phi^\dagger\phi)B_{\mu\nu}B^{\mu\nu}$$

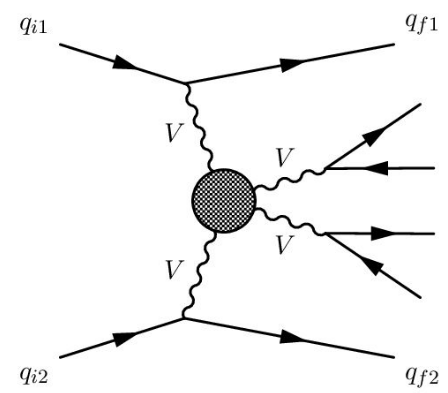
$$Q_{ll}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{l}_r\gamma^\mu l_p)$$

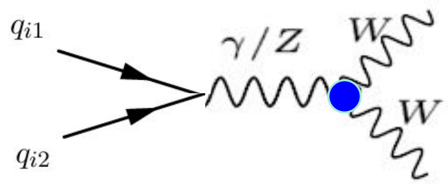
$$N \propto \overbrace{|\mathcal{A}_{SM}|^2}^{\textbf{SM}} + \sum_\alpha \frac{c_\alpha}{\Lambda^2}\cdot \underbrace{2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}^\dagger_{Q_\alpha})}_{\textbf{Lin}} + \frac{c_\alpha^2}{\Lambda^4}\cdot\overbrace{|\mathcal{A}_{Q_\alpha}|^2}^{\textbf{Quad}} + \sum_{\alpha,\beta}\frac{c_\alpha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

Processes of interest: VBS+WW

- **Modelling** of **2→6(4) processes** including non-resonant diagrams
  - both **EWK** and **QCD-induced** contributions for **SM** and **EFT processes**

- **Same-sign W±W±:** pp > $e^{\pm}\nu_e\mu^{\pm}\nu_\mu$ j j
- **Opposite-sign W±W (QCD)**: pp > $e^{\pm}\nu_e\mu\ \nu_\mu$ j j
- **W±Z+2j(QCD)**: pp > $e^+e^-\mu^{\pm}\nu_\mu$ j j
- **ZZ+2j(QCD)**: pp > $e^+e^-\mu^+\mu^-$j j
- **ZV+2j(QCD)**: pp > ZW^+ (W^-Z) > l^+l^- j j j j
- **WW: pp** > $e^+\nu_e\mu^-\nu_\mu$





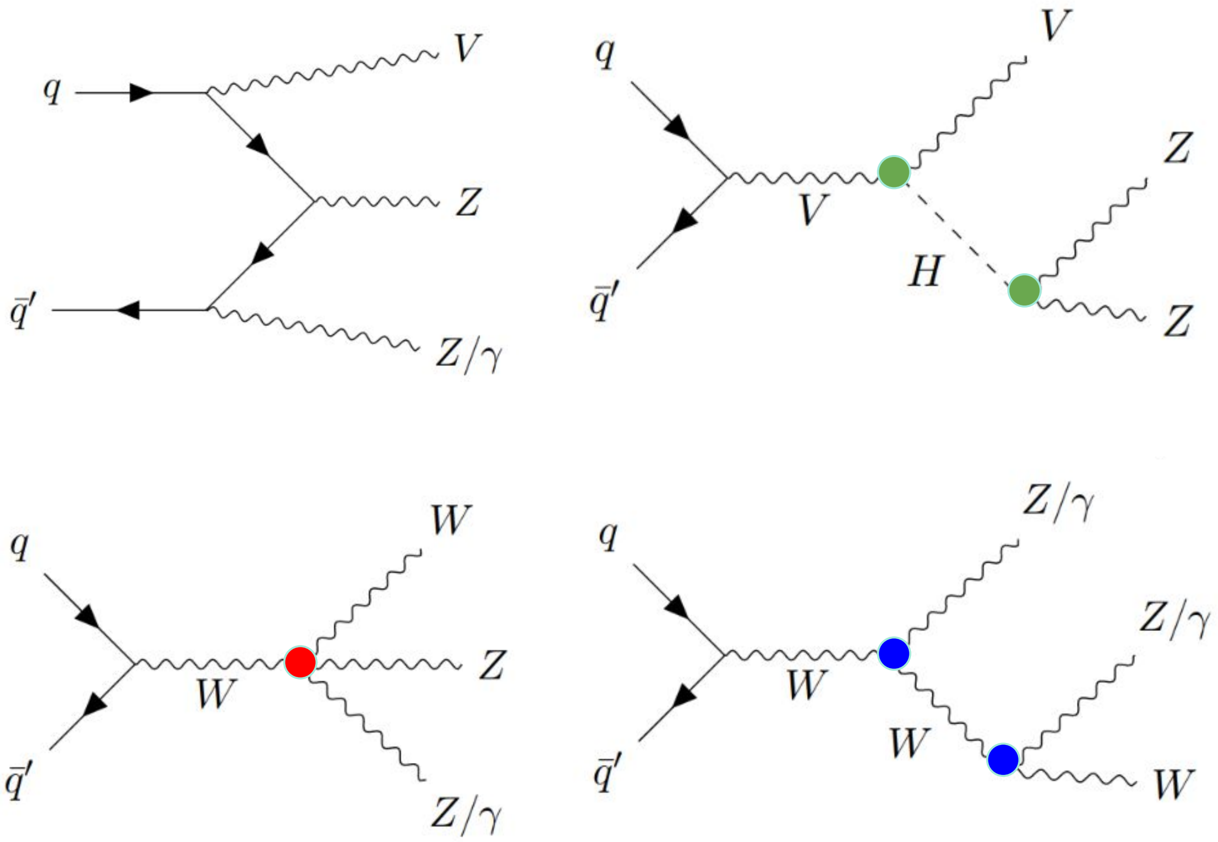
- **Integrated luminosity** of **100 fb^{-1}** is assumed for the **VBS+WW study**

Processes of interest: tri-boson

- **Modelling** of **2→6(4+γ) processes** including non-resonant diagrams
  - both **EWK** and **QCD-induced** contributions for **SM** and **EFT processes**

- **W±Zγ**: pp > $\mu^{\pm} \nu_{\mu} e^{+} e^{-} \gamma$
- **ZZγ**: pp > $e^{+} e^{-} \mu^{+} \mu^{-} \gamma$
- **VZγ(QCD)**: pp > $l^{+} l^{-}$ j j γ
- **VZZ(QCD)**: pp > $e^{+} e^{-} \mu^{+} \mu^{-}$ j

j



- **Integrated luminosity** of **300 fb^{-1}** is assumed for the **triboson study**

Processes of interest - EFT sensitivity

- **Summary** of the sensitivity of **each process** to the subset of operators
  - empty cells -> no EFT diagrams

VBS+ WW diboson

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	✓		✓	✓	✓			✓	✓	✓					(✓)

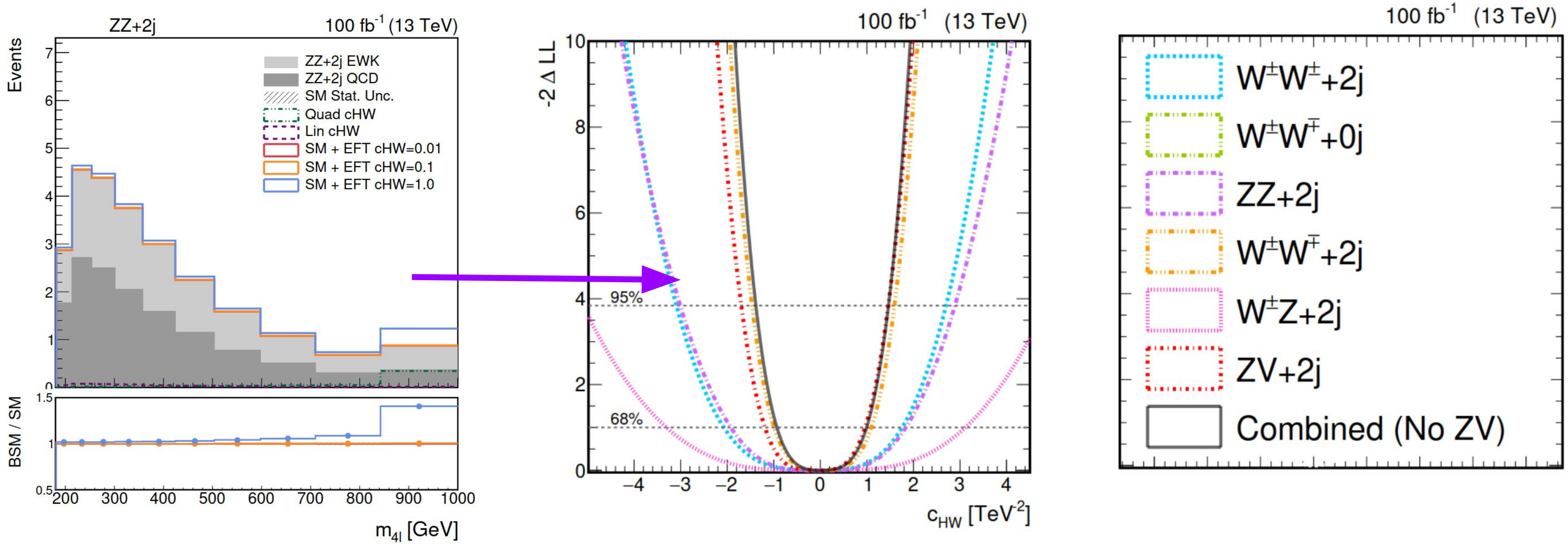
Triboson

Operators → ↳ Processes	Q_W	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HD}	$Q_{H\Box}$
WZγ	✓	✓	✓	✓	✓	
ZZγ		✓	✓	✓	✓	
VZγ	✓	✓	✓	✓	✓	
QCD-Zγjj				✓	✓	
VZZ	✓	(✓)	✓	✓	✓	(✓)
QCD-ZZjj				✓	✓	

- **Brackets** indicate only ops that enter **non-resonant** contributions or negligible

Template fit analysis

- **Dependence** of **EFT-**induced kinematic **anomalies** on **Wilson coefficients**
- **Likelihood fit** for each **variable** based on **1σ** range (**area** for **2D** fit)

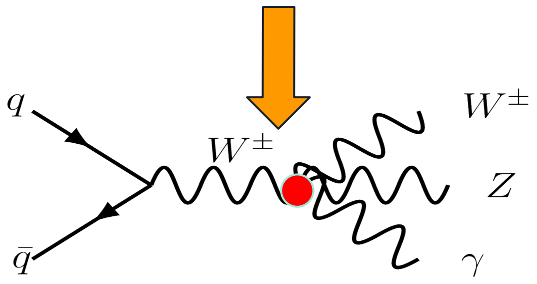


- **Optimal variable** extracted per **operator** used in **combination**

Tri-boson fully leptonic: WZγ

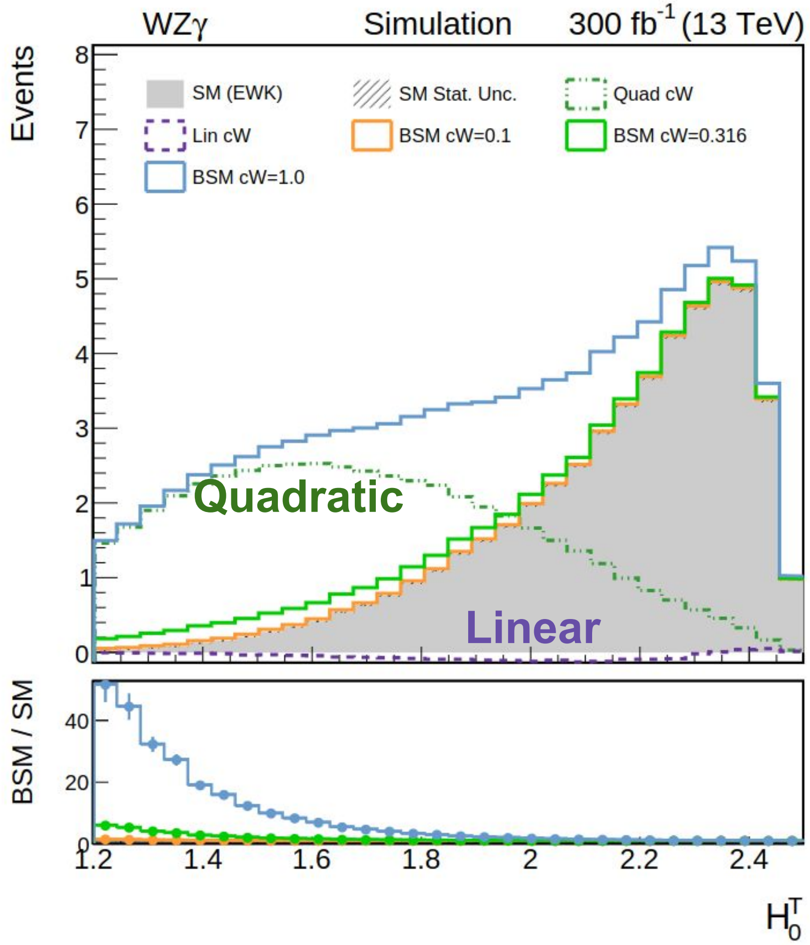
- **WZγ** production **extremely rare** process **~O(fb)** studied in **fully leptonic** channel
- In the SM, **WZγ** depends on **quartic gauge couplings (QGC)** at tree level unlike **ZZγ**

$$Q_W = \epsilon^{IJK} W_\mu^{I\,\nu} W_\nu^{J\,\rho} W_\rho^{K\,\mu}$$



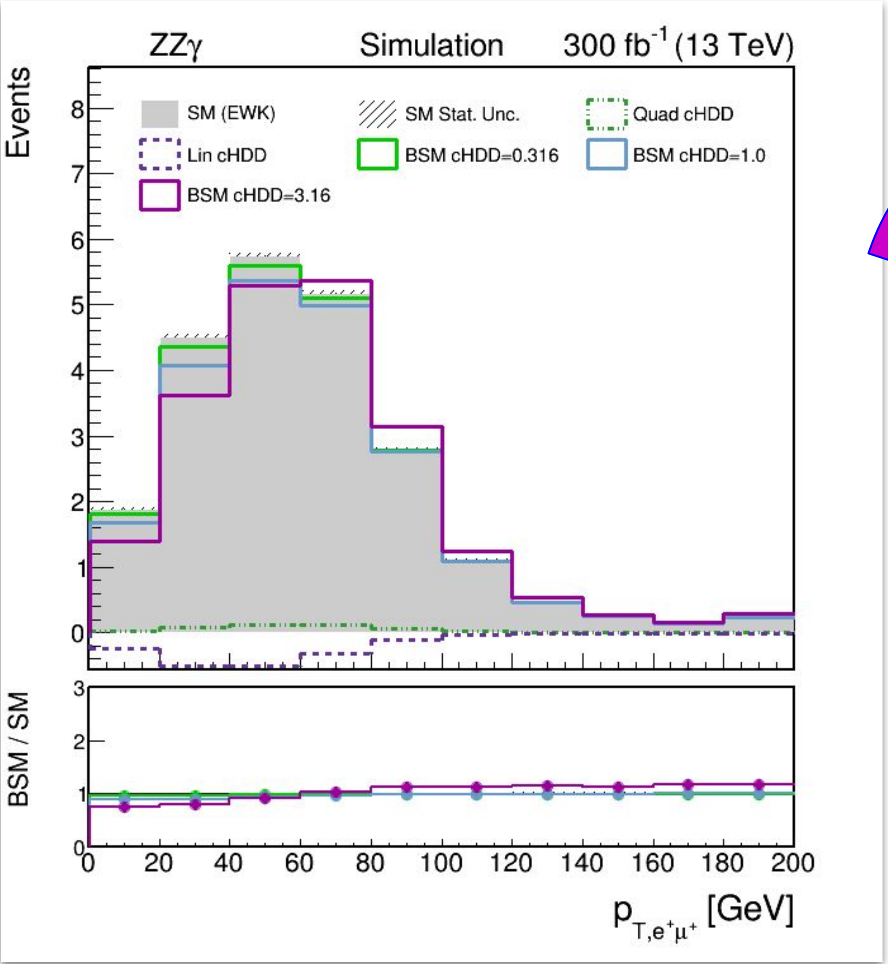
- **Fox-Wolfram variable** provides good discrimination between **O(Λ⁻⁴) dim-6** contribution and **SM**

$$H_0^T = \sum_{a\neq b}^{\text{fin.state}} \frac{p_T^a p_T^b}{(\sum_i p_T^i)^2}$$

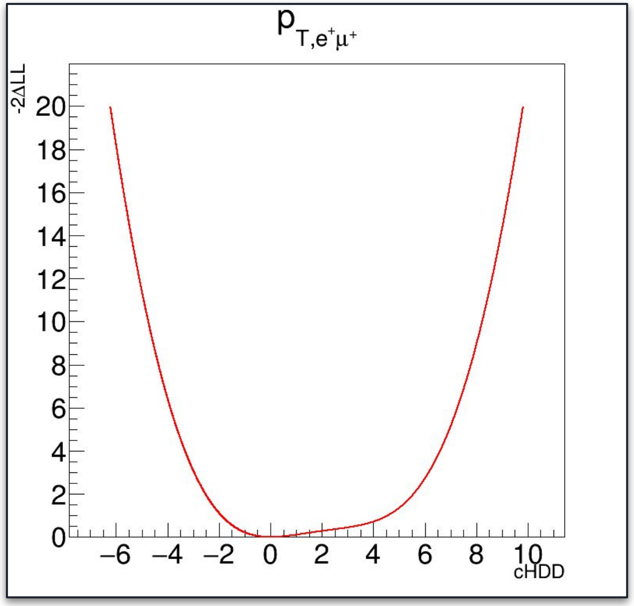


Tri-boson fully leptonic: ZZγ

- **Higgs-gauge boson** couplings affect the **electroweak** vertices in **ZZγ**
- **Best variable:** total $\mathbf{p_T}$ of same-sign **eμ** related to leptonic final state



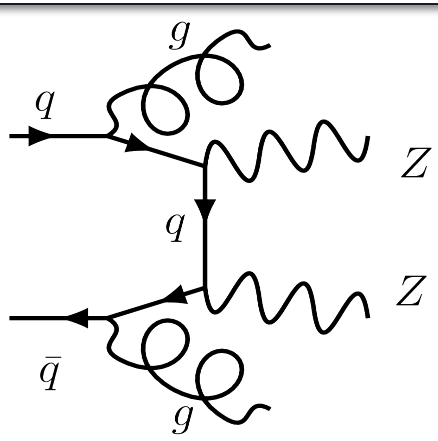
Consequence:
evident **asymmetry** in
the likelihood scan



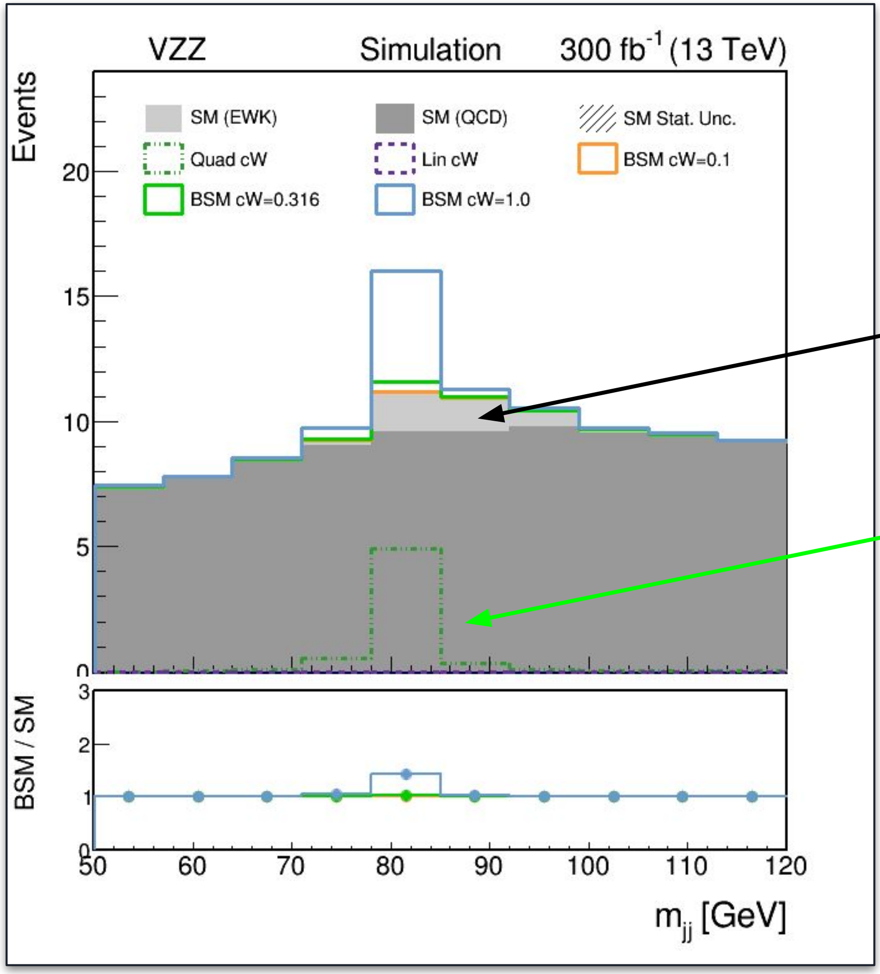
Triboson semi-leptonic: VZZ

- **Study** of inclusive **4ljj** production: **EWK VZZ**+**QCD-induced** background
- **Unique Q_W-sensitivity** of **WZZ** channel to **WWZZ quartic** couplings unlike **ZZZ** channel

Inclusion of the main **background** given by diagrams involving QCD-induced vertices.



$$\sigma_{\mathrm{SM}} = \sigma_{\mathrm{EWK}} + \sigma_{\mathrm{QCD}}$$

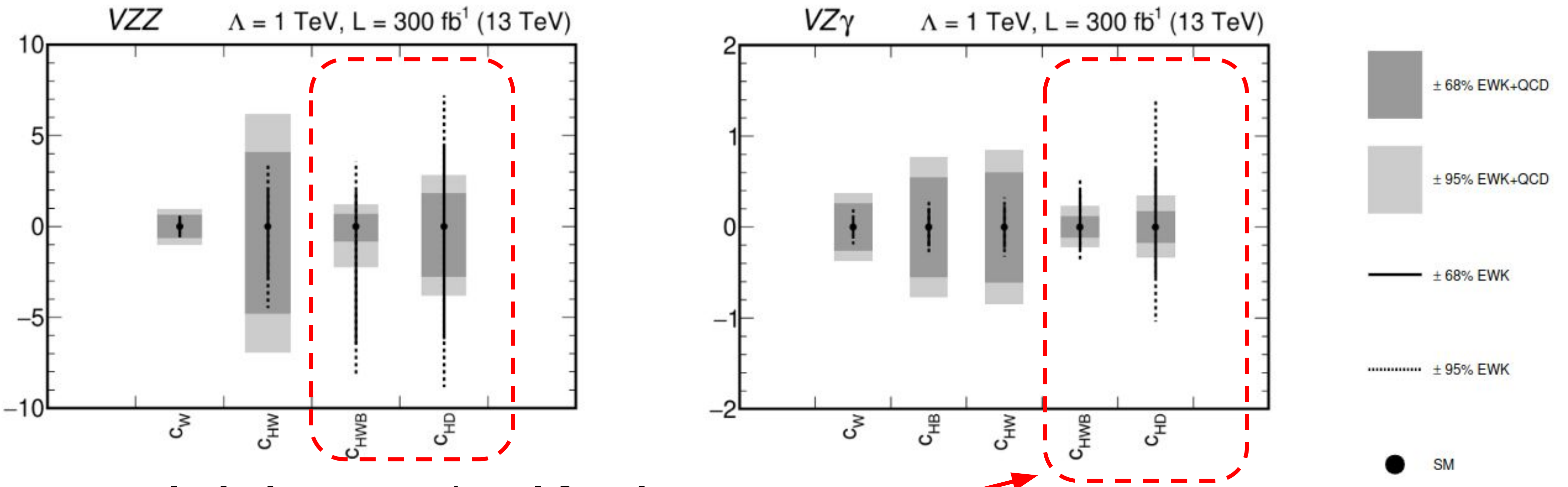


EWK SM term broad peak around $(m_W+m_Z)/2$

Quadratic term resonates at m_W

Triboson semi-leptonic: VZZ/VZγ

- **Impact of QCD** background on **semi-leptonic** channels **VZZ/VZγ sensitivity**
- $\mathbf{Q_{HWB}}$ and $\mathbf{Q_{HD}}$ **induce EWK anomalies** in **QCD** diagrams unlike other operators



- **Included as BSM signal for these operators**
  - enhances overall EFT-sensitivity despite larger background from QCD

Fit procedure

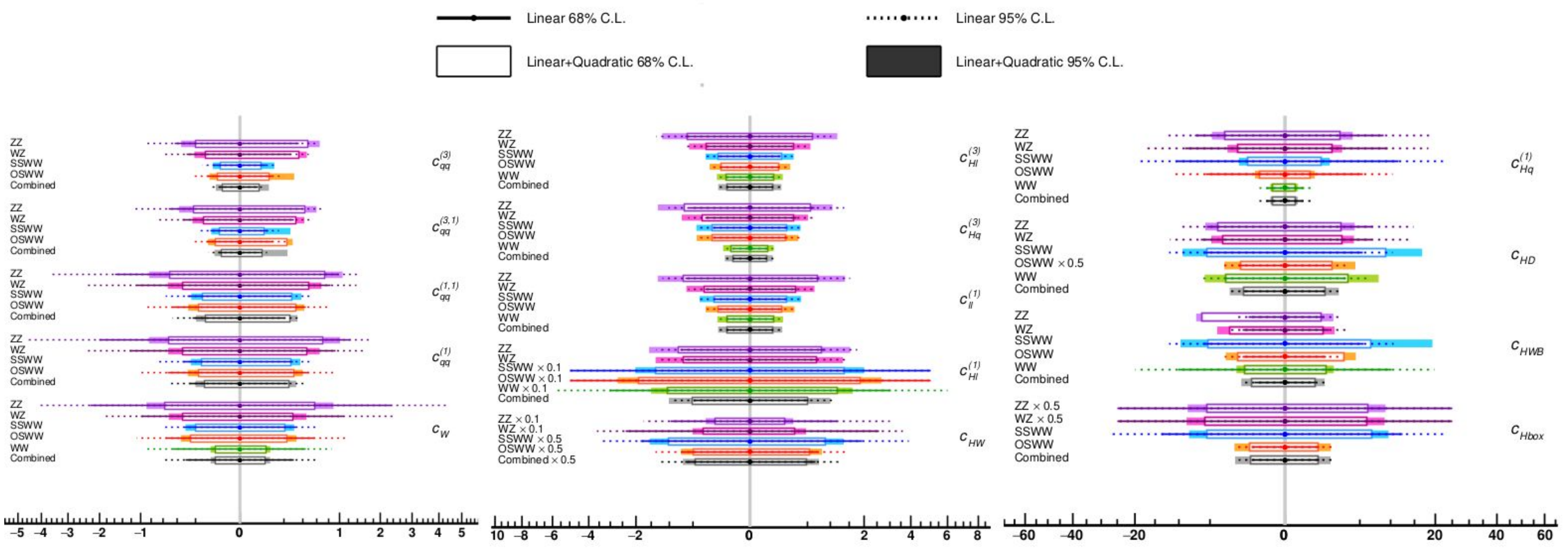
- **Likelihood scan** for each **variable** varying the **Wilson coefficient** in a fixed range

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

- **SM expectation** for **N(c=0)**
- **Total yield:** $N(\mathbf{c}) = SM + \sum_{c_\alpha} c_\alpha \cdot Lin_\alpha + c_\alpha^2 \cdot Quad_\alpha + \sum_{\alpha\beta} c_\alpha c_\beta Mix_{\alpha\beta}$
- **Single nuisance: proxy LHC luminosity** 2% correlated across all yields & samples **(flat prior)**
- **Sensitivity constraint** at **68(95%) CL** estimated as **-2ΔLL <1(2.30)** and **-2ΔLL <3.84(5.99)** for single (pair) Wilson coefficient

Individual constraints - VBS + WW combination

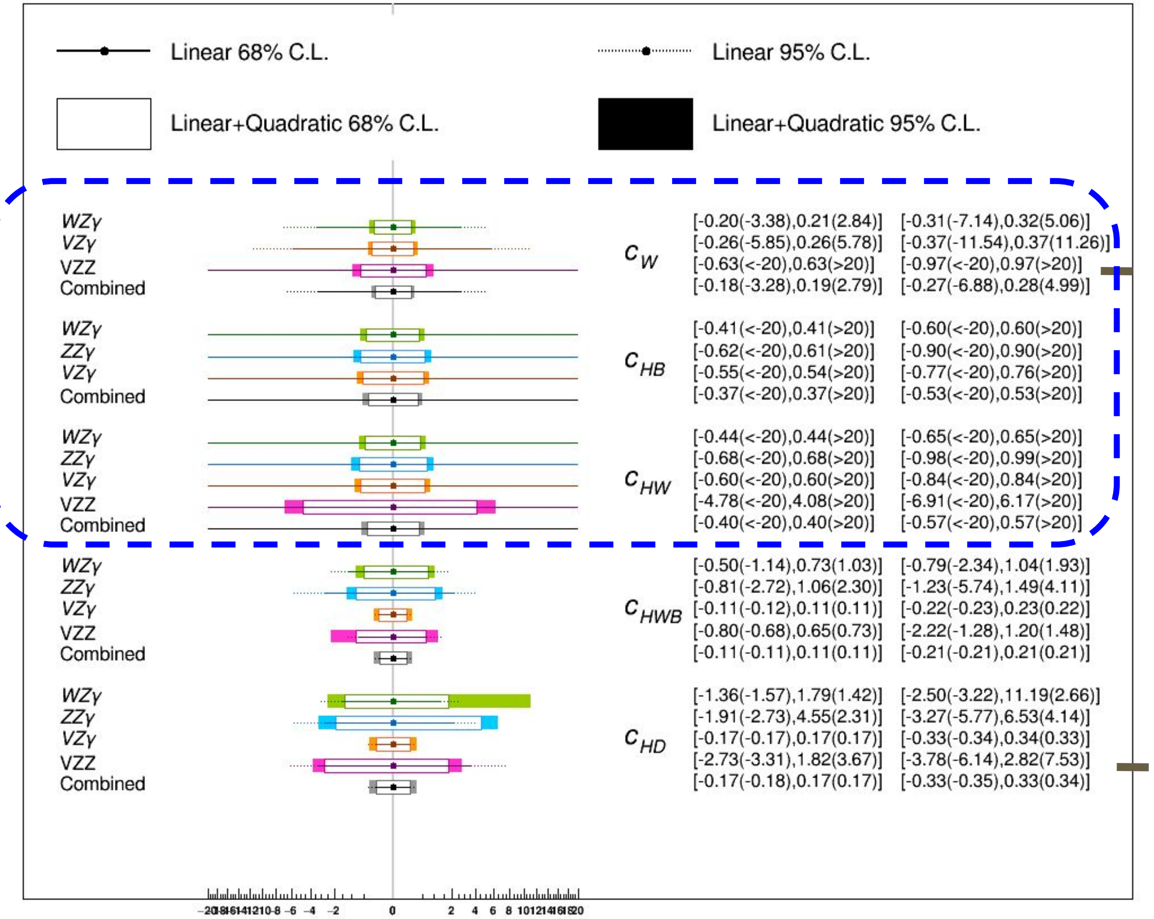
- **Individual operator constraints** with(without) **O(Λ^{-4})** quadratic **terms**

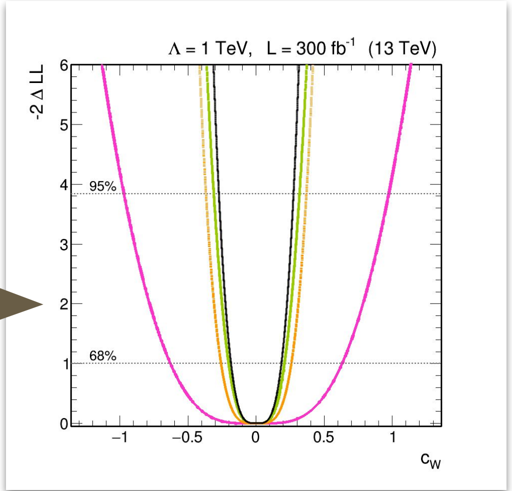


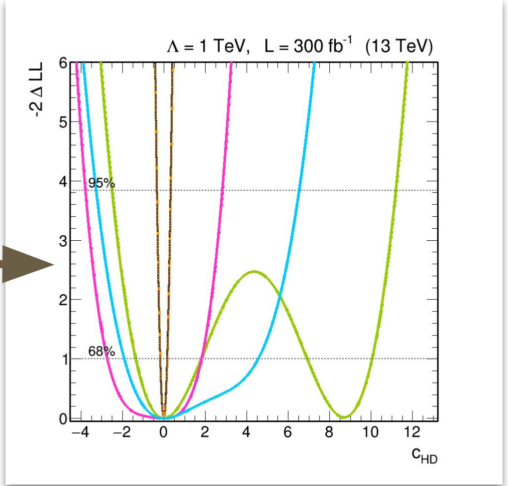
- **Large impact** of **quadratic terms** on **half** of the **single operator** constraints
- **Strongest constraints** on **four-fermion** coefficients as expected
- $\mathbf{Q_{HW}}$, $\mathbf{Q_{H\Box}}$, ops constrained solely by **VBS processes**

Individual constraints - Triboson

- **Individual operator constraints** with(without) **O(Λ^{-4})** quadratic **terms**





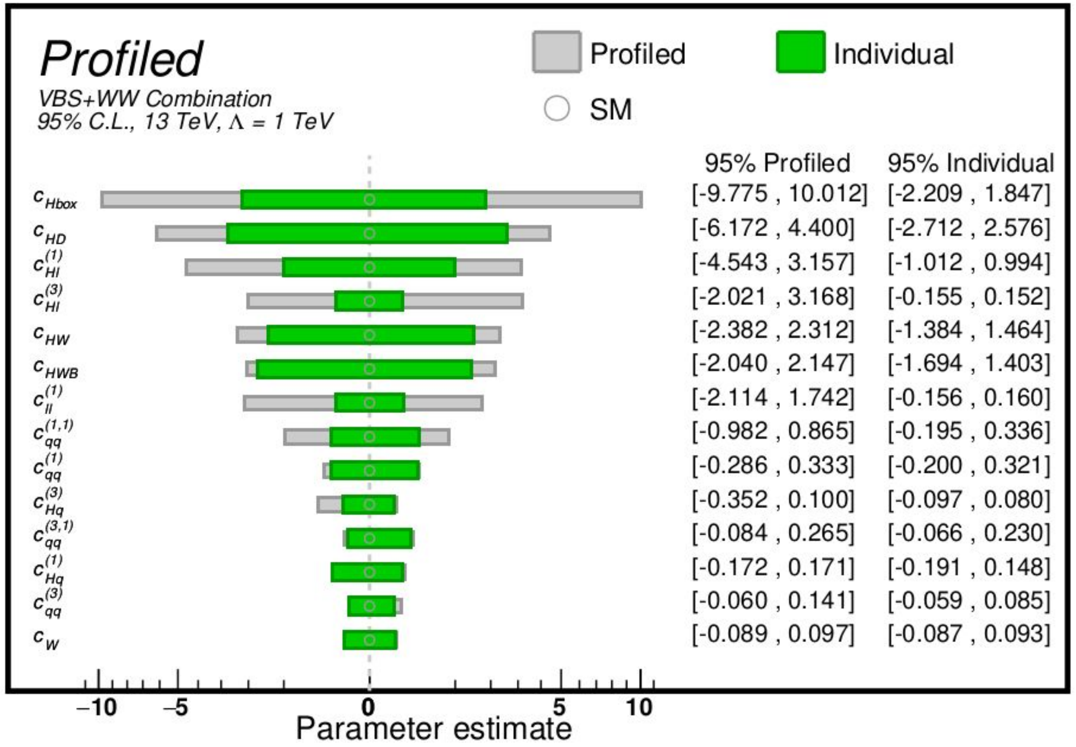


- **Large impact** of **quadratic terms** on **Q_W , Q_{HW} ,Q_{HB} ops**
- For other **operators**, linear interference term dominates

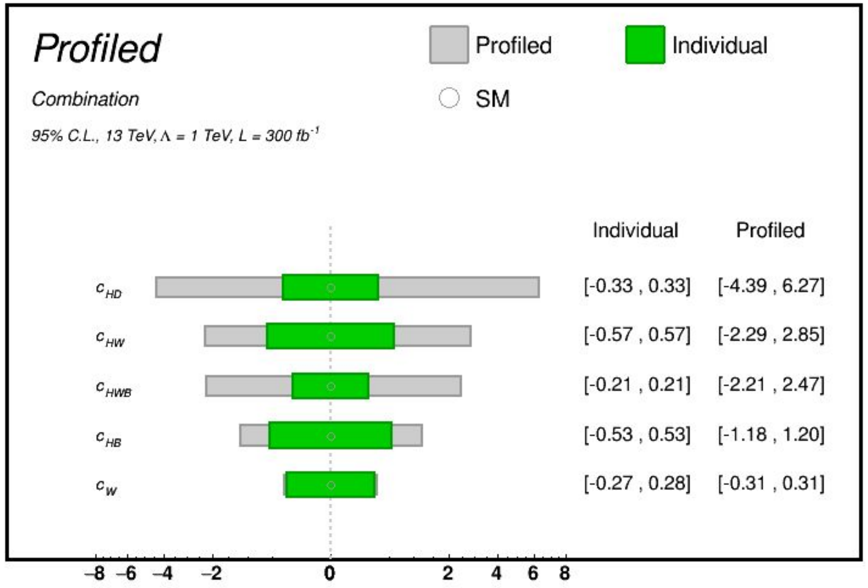
Profiled constraints

- Performed **global fit** ensuring SMEFT model independence including all **O(Λ^{-4})** terms
  - **single operator** fit with all other **coefficients profiled** (free-floating in fit)

VBS+ WW diboson



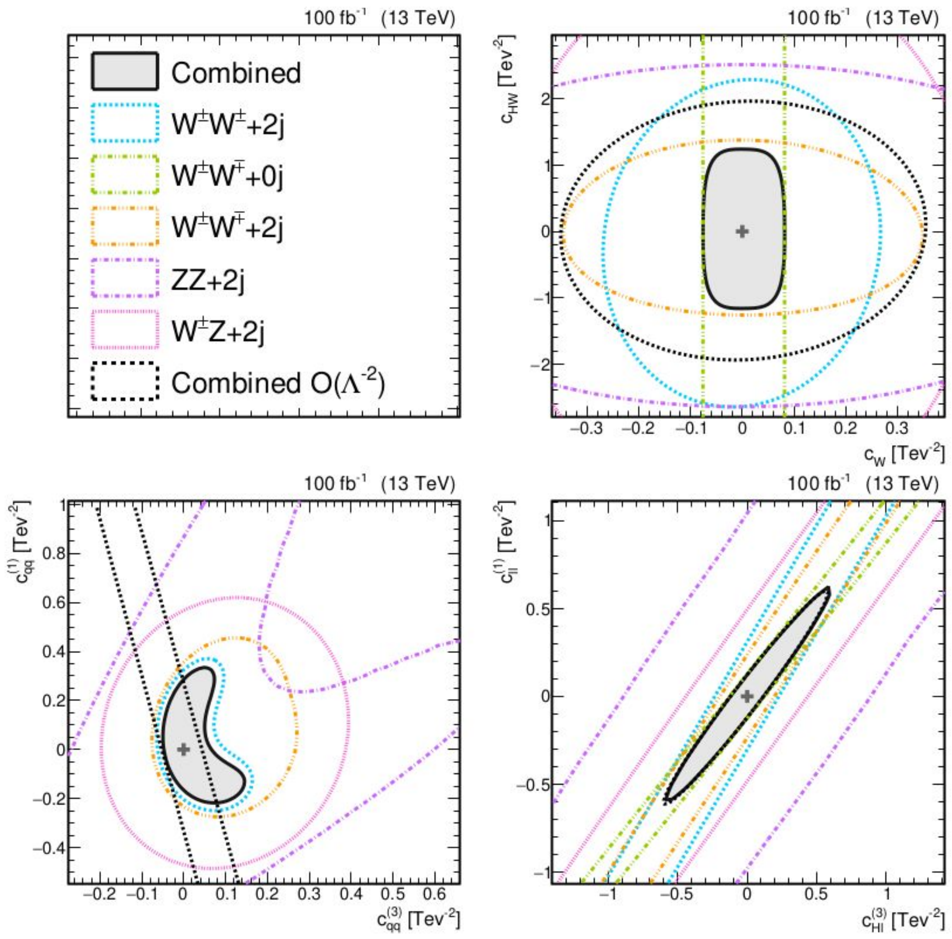
triboson



- **Profiled** constraints are up to **10x less stringent** wrt **individual** ones
- **Q_W -induced anomalies** uncorrelated with other operators

2D constraints - VBS + WW combination

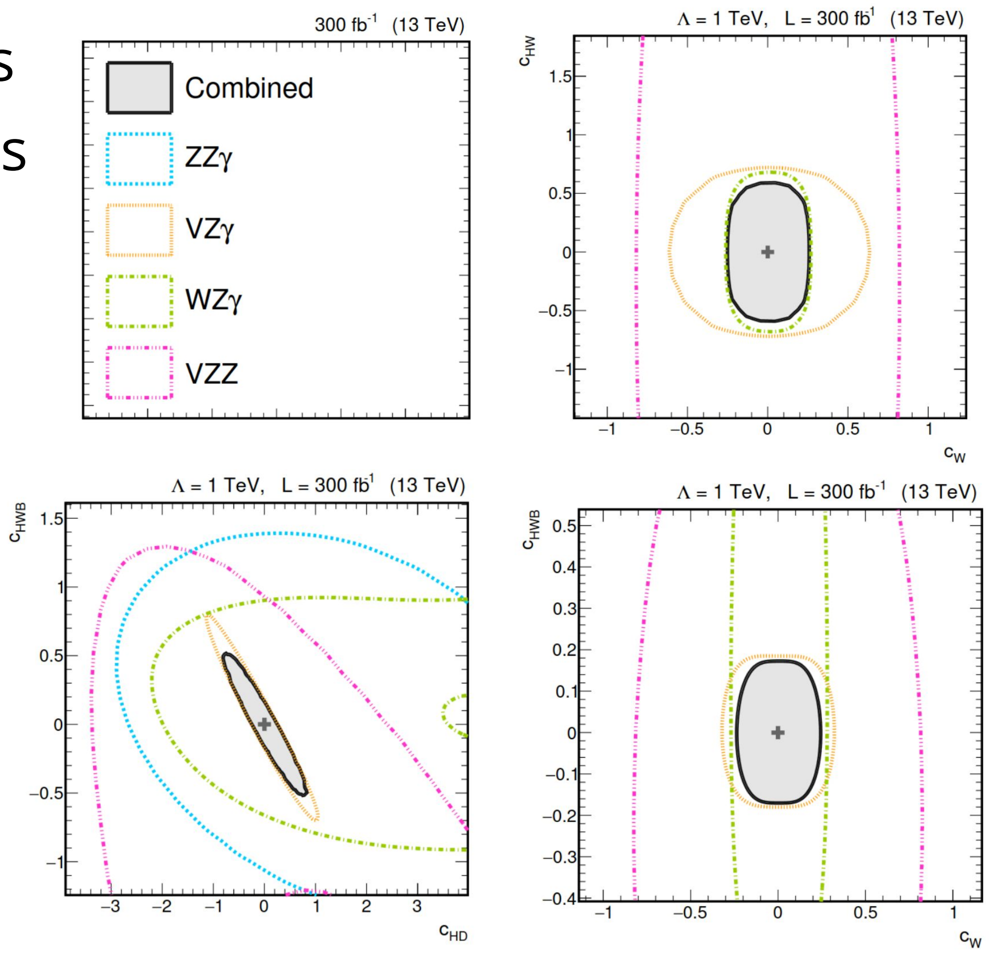
- Impact of **sensitivity** to **operator pairs** using **2D template fit**
  - **contours** allow assessing **interplay** of **VBS** and **di-boson** measurements



1. **Orthogonal** constraints between **WW** and and **VBS** for **(Q_W,Q_{HWB})**
2. **4-quark ops** constrained only by VBS
3. **flat directions $Q_{Hl}^{(3)}$~ $Q_{ll}^{(1)}$ resolved** thanks to **channel combination**

2D constraints - Triboson combination

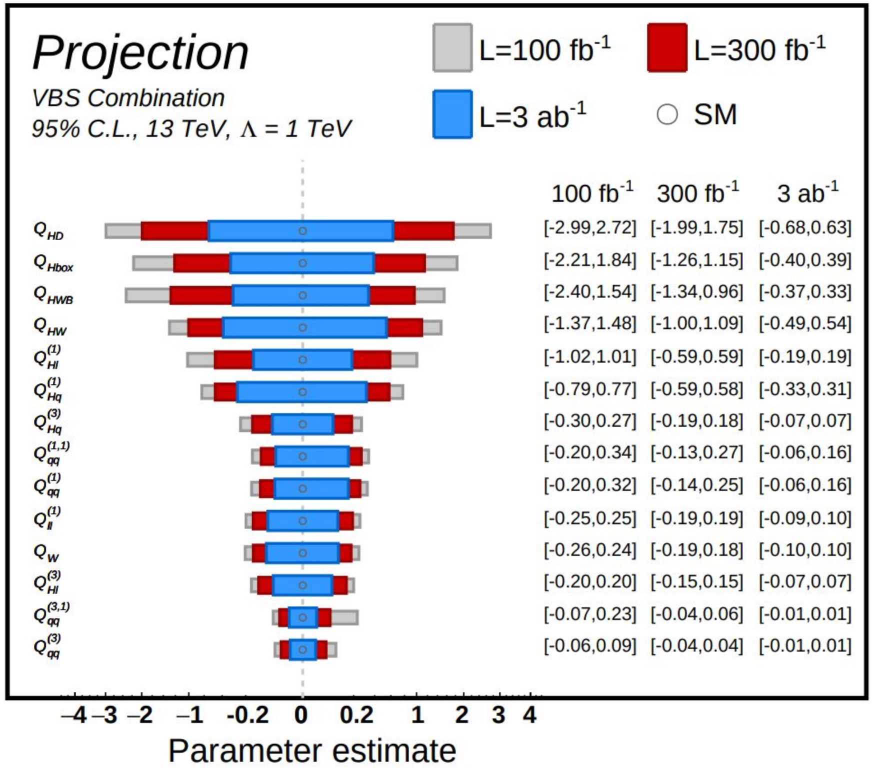
- In **triboson** studies, most **sensitive** process **WZγ** fully-leptonic to $\mathbf{Q_W}$**-induced** anomalies
- Semi-leptonic **VZγ** leads to **strongest** constraints for $\mathbf{Q_{HWB}}$ and $\mathbf{Q_{HD}}$ operators
- **Small mutual interference** term for operator pairs $\mathbf{Q_W}$-$\mathbf{Q_{HWB}}$



Summary & Outlook

- **Multi-boson** measurements **powerful tool** to explore BSM physics in "**UV-agnostic**" way : **consistency test** of EWK sector

- First **phenomenological dim-6 study** on tri-boson **VZZ/VZγ** processes at **O(Λ^{-4})**
  - **competitive** & **complementary** constraints w.r.t. combination **VBS**+**di-boson WW**



- **Expand scope of EFT analysis**
  - combination of **multi-boson analyses** (**VBS**, **di-boson**, **tri-boson**) with **Higgs** measurements at **reco level** to constrain both **dimension 6** and **8 EFT** operators

Comparison VBS vs tri-boson combination

↓ Processes	Operators →	Q_W	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HD}
$WZ\gamma$	Best var.	p_T^{l1}	$p^{\gamma}_{T(Z)}$	$p^{\gamma}_{T(Z)}$	$p^{\gamma}_{T(Z)}$	$p^{l1}_{T(WZ)}$
	68% C.L.	[-0.20,0.21]	[-0.41,0.41]	[-0.44,0.44]	[-0.50,0.73]	[-1.36,1.79]
	95% C.L.	[-0.31,0.32]	[-0.60,0.60]	[-0.65,0.65]	[-0.79,1.04]	[-2.50,11.2]
$ZZ\gamma$	Best var.	No diagrams	$p^{\gamma}_{T(Z_1)}$	$m_{\mu\mu}$	$m_{\mu\mu}$	$p_T^{e^+\mu^+}$
	68% C.L.		[-0.62,0.61]	[-0.68,0.68]	[-0.81,1.06]	[-1.91,4.55]
	95% C.L.		[-0.90,0.90]	[-0.98,0.99]	[-1.23,1.49]	[-3.27,6.53]
$VZ\gamma$	Best var.	p_T^{l1}	m_{jj}	m_{jj}	$p^{l1}_{T(\gamma)}$	$p^{l2}_{T(\gamma)}$
	68% C.L.	[-0.26,0.26]	[-0.55,0.54]	[-0.60,0.60]	[-0.11,0.11]	[-0.17,0.17]
	95% C.L.	[-0.37,0.37]	[-0.77,0.76]	[-0.84,0.84]	[-0.22,0.23]	[-0.33,0.34]
VZZ	Best var.	p_T^{l1}	Negligible	p_T^V	$m_{\mu\mu}$	$p_T^{e^+\mu^+}$
	68% C.L.	[-0.63,0.63]		[-4.78,4.08]	[-0.80,0.65]	[-2.73,1.82]
	95% C.L.	[-0.97,0.97]		[-6.91,6.17]	[-2.22,1.20]	[-3.78,2.82]
Combination	68% C.L.	[-0.18,0.19]	[-0.37,0.37]	[-0.40,0.40]	[-0.11,0.11]	[-0.17,0.17]
	95% C.L.	[-0.27,0.28]	[-0.53,0.53]	[-0.57,0.57]	[-0.21,0.21]	[-0.33,0.33]
VBS	95% C.L.	[-0.19,0.18]	-	[-1.02,1.08]	[-1.34,0.96]	[-1.98,1.74]

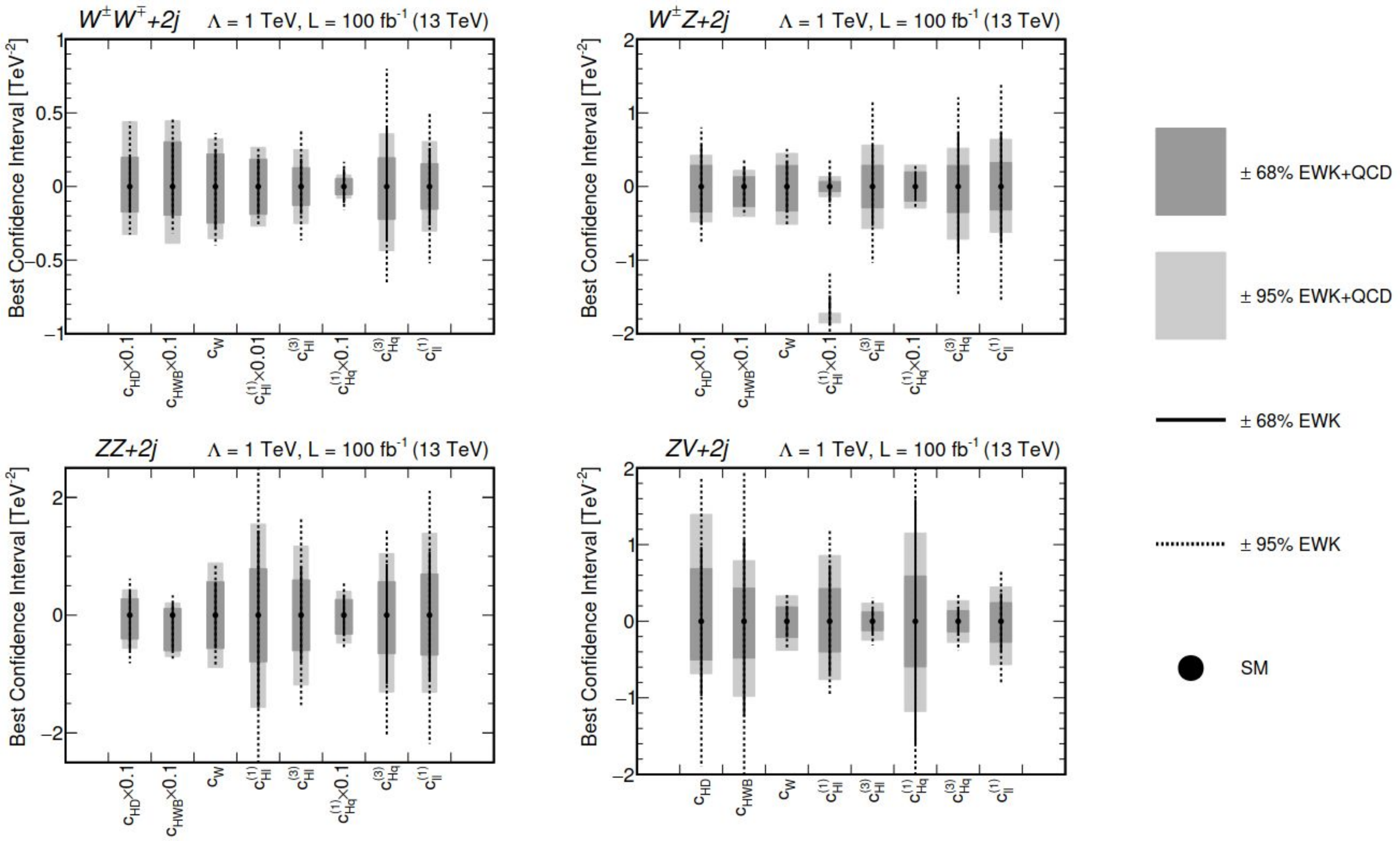
WWW fully-leptonic 95% CL bound
c_W is [-0.13(-0.22), 0.13(0.22)]

VBS, WW inclusive, triboson selection

Process	Variables of interest	Selections	Expected events
WW $(pp \to 2l2\nu)$	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 $\lvert\eta_{l^i}\rvert < 2.5$	(EW) 30600
SSWW+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 $\Delta\eta_{jj} > 2.5$ $\lvert\eta_{j^i}\rvert < 5$ $\lvert\eta_{l^i}\rvert < 2.5$	(EW) 197
OSWW+2j $(pp \to 2l2\nu jj)$			(EW) 493 (QCD) 1967
WZ+2j $(pp \to 2e\mu\nu jj)$	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^*		(EW) 35 (QCD) 90
ZZ+2j $(pp \to 2e2\mu 2j)$	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}, $p_{T,l^\pm l^\pm}$, $p_{T,l^\pm l^\mp}$, $p_{T,Z}$, $\Delta\phi_{jj}$, $\Delta\eta_{jj}$, 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 $\Delta\eta_{jj} > 2.4$ $\lvert\eta_{j^i}\rvert < 4.7$ $\lvert\eta_{l^i}\rvert < 2.5$ $\Delta R(l^i, j^k) > 0.4$	(EW) 11 (QCD) 176
ZV+2j $(pp \to 2ljjjj)$	m_{jj}^{max}, m_{jj}^{nomax}, m_{ll}, ϕ_{j^i}, p_{T,j^i}, p_{T,l^i} $p_{T,ll}$, $\Delta\eta_{jj}$, $\Delta\eta_{jj}^{nomax}$, $\Delta\phi_{jj}^{max}$ $\Delta\phi_{jj}^{nomax}$, $\eta_{j^i}\eta_{l^i}$	$m_{jj} > 1500$ 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 $\Delta\eta_{jj} > 3.5$ $\lvert\eta_{j^i}\rvert < 5$ $\lvert\eta_{l^i}\rvert < 2.5$	(EW) 142 (QCD) 50

Process	Variables of interest	Selections
WZγ $(pp \to \mu^\pm \overset{(-)}{\nu}_\mu\ 2e\ \gamma)$ Expected events: (EW) 50	$\not{E}_T$, m_{ee}, $m_{T,W}$, p_T^Z, p_T^W, p_T^γ, $p_T^{SFOS-ll}$, $p_T^{l_i}$, p_T^γ, $p_T^{e^+\mu^+}$, η_{l_i}, η^γ, ϕ^γ, $p_{T(Z\gamma)}^{l_i}$, $p_{T(Z)}^{l_i}$, $p_{T(WZ)}^{l_i}$, $p_{T(W)}^{l_i}$, $p_{T(Z)}^\gamma$, $p_{T(Z)}^W$, $p_{T(\gamma)}^W$, $p_{T(WZ)}^\gamma$, $H_\ell^T(ee)$, $H_\ell^T(3l\nu\gamma)$	$50 < m_{\mu\nu} < 110$ GeV $60 < m_{ee} < 120$ GeV $p_{T,l^1} > 20$ GeV $p_{T,l^2} > 10$ GeV $p_{T,l^i} > 5$ GeV $\lvert\eta_{l^i}\rvert < 2.5$ $p_{T,\gamma} > 20$ GeV $\lvert\eta_\gamma\rvert < 2.5$ $\not{E}_T > 30$ GeV $\Delta R(l^i, \gamma) > 0.4$
ZZγ $(pp \to 2e\ 2\mu\ \gamma)$ Expected events: (EW) 22	$m_{SFOS-ll}$, m_{4l}, $p_T^{Z_i}$, $p_T^{l_i}$, $p_T^{SFOS-ll}$, p_T^γ, $p_T^{e^\pm\mu^\pm}$, η_{l_i}, η^γ, ϕ^γ, $p_{T(Z\gamma)}^{l_i}$, $p_{T(Z_i)}^{l_k}$, $p_{T(ZZ)}^{l_i}$, $p_{T(\gamma)}^{l_i}$, $p_{T(Z_i)}^\gamma$, $p_{T(ZZ)}^\gamma$, $H_\ell^T(SFOS-ll)$, $H_\ell^T(4l\gamma)$	$60 < m_{SFOS-ll} < 120$ GeV $p_{T,l^1} > 20$ GeV $p_{T,l^2} > 10$ GeV $p_{T,l^i} > 5$ GeV $\lvert\eta_{l^i}\rvert < 2.5$ $p_{T,\gamma} > 20$ GeV $\lvert\eta_\gamma\rvert < 2.5$ $\Delta R(l^i, \gamma) > 0.4$
VZγ **QCD – Zγjj** $(pp \to 2j\ 2l\ \gamma)$ Expected events: (EW) 620 (QCD) 31385	m_{ll}, m_{jj}, p_T^Z, p_T^V, p_T^γ, $p_T^{l_i}$, $p_T^{j_i}$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, η_{j_i}, η_{l_i}, ϕ_{j_i}, η^γ, ϕ^γ, $p_{T(Z\gamma)}^{l_i}$, $p_{T(Z)}^{l_i}$, $p_{T(VZ)}^{l_i}$, $p_{T(V)}^{l_i}$, $p_{T(\gamma)}^{l_i}$, $p_{T(\gamma)}^{j_i}$, $p_{T(Z)}^\gamma$, $p_{T(Z)}^V$, $p_{T(\gamma)}^V$, $p_{T(Z\gamma)}^V$, $p_{T(VZ)}^\gamma$, $H_\ell^T(jj)$, $H_\ell^T(ll)$, $H_\ell^T(2l\ 2j\gamma)$	$50 < m_{jj} < 120$ GeV $60 < m_{ll} < 120$ GeV $p_{T,l^1} > 20$ GeV $p_{T,l^2} > 10$ GeV $\lvert\eta_{l^i}\rvert < 2.5$ $p_{T,\gamma} > 20$ GeV $\lvert\eta_\gamma\rvert < 2.5$ $p_{T,j^{1,2}} > 30$ GeV $\lvert\eta_{j^i}\rvert < 2.5$ $\Delta R(l^i, \gamma) > 0.4$ $\Delta R(l^i, j^k) > 0.4$ $\Delta R(\gamma, j^k) > 0.4$
VZZ **QCD – ZZjj** $(pp \to 2j\ 2e\ 2\mu)$ Expected events: (EW) 4 (QCD) 95	$m_{SFOS-ll}$, m_{jj}, m_{4l}, m_{4ljj}, p_T^Z, $p_T^{SFOS-ll}$, $p_T^{j_i}$, $p_T^{l_i}$, p_T^V, $p_T^{e^\pm\mu^\pm}$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, η_{j_i}, η_{l_i}, ϕ_{j_i}, $p_{T(ZZ)}^{l_i}$, $p_{T(ZZ)}^{j_i}$, $p_{T(Z_i)}^{l_i}$, $p_{T(Z_i)}^{j_i}$, $p_{T(Z_2)}^{Z_1}$, $p_{T(Z_i)}^V$, $p_{T(ZZ)}^V$, $H_\ell^T(jj)$, H_ℓ^T(SFOS-ll), $H_\ell^T(4ljj)$	$50 < m_{jj} < 120$ GeV $60 < m_{SFOS-ll} < 120$ 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 $\lvert\eta_{j^i}\rvert < 2.5$ $\lvert\eta_{l^i}\rvert < 2.5$ $\Delta R(l^i, j^k) > 0.4$

Impact of QCD bkg on sensitivity -VBS



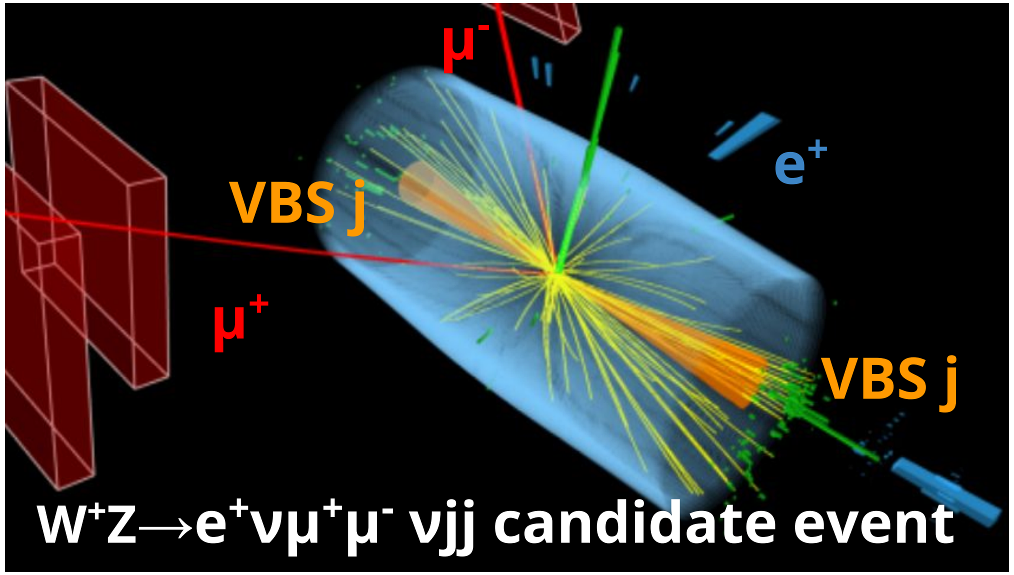
Best variables

- Study **best variables** to constrain **pairs** of coefficients in 1D and 2D fit
  - $p_T l^1$ for **cHW, cW** , $p_T j^{1,2}$ for fermionic operators

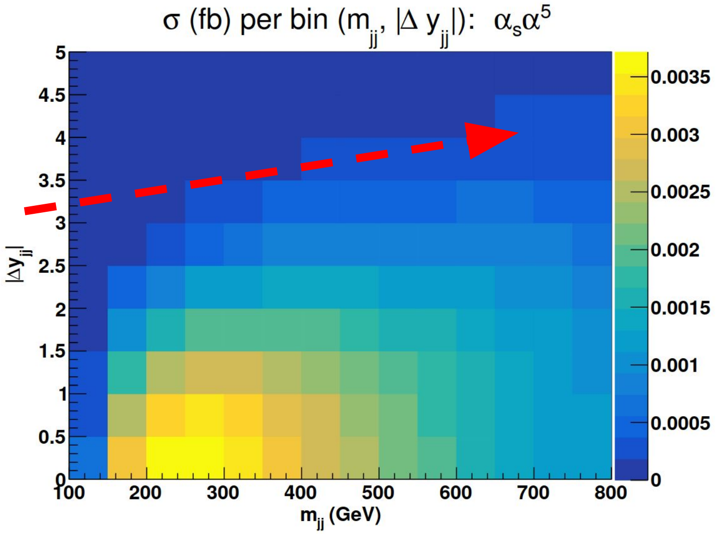
	$c_{qq}^{(3,1)}$	$c_{qq}^{(1,1)}$	$c_{qq}^{(1)}$	c_W	$c_{Hl}^{(3)}$	$c_{Hq}^{(3)}$	$c_{ll}^{(1)}$	$c_{Hl}^{(1)}$	c_{HW}	$c_{Hq}^{(1)}$	c_{HD}	c_{HWB}	$c_{H\Box}$
$c_{qq}^{(3)}$	p_{T,j^1}	p_{T,j^1}	p_{T,j^2}	p_{T,l^1}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,l^1}	p_{T,j^1}	p_{T,j^1}	p_{T,j^1}	p_{T,j^1}
$c_{qq}^{(3,1)}$	—	p_{T,j^1}	p_{T,j^2}	p_{T,l^1}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,l^1}	p_{T,j^1}	p_{T,j^2}	p_{T,j^1}	p_{T,j^1}
$c_{qq}^{(1,1)}$	—	—	p_{T,j^2}	p_{T,l^1}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,l^1}	p_{T,j^1}	p_{T,j^2}	p_{T,j^1}	p_{T,j^1}
$c_{qq}^{(1)}$	—	—	—	p_{T,l^1}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,l^1}	p_{T,j^1}	p_{T,j^2}	p_{T,j^1}	p_{T,j^1}
c_W	—	—	—	—	p_{T,l^1}	p_{T,l^1}	p_{T,l^1}	p_{T,l^1}	p_{T,l^1}	p_{T,l^1}	p_{T,l^1}	p_{T,l^1}	m_{4l}
$c_{Hl}^{(3)}$	—	—	—	—	—	p_{T,j^1}	m_{jj}	m_{jj}	$p_{T,ee}$	p_{T,j^1}	m_{jj}	m_{jj}	m_{4l}
$c_{Hq}^{(3)}$	—	—	—	—	—	—	p_{T,j^1}	p_{T,j^1}	p_{T,l^1}	p_{T,j^1}	p_{T,l^1}	p_{T,l^1}	p_{T,l^2}
$c_{ll}^{(1)}$	—	—	—	—	—	—	—	m_{jj}	$p_{T,Z}$	p_{T,j^1}	$p_{T,e^-\mu^-}$	$p_{T,Z}$	p_{T,j^2}
$c_{Hl}^{(1)}$	—	—	—	—	—	—	—	—	m_{4l}	p_{T,j^1}	$p_{T,e^+\mu^+}$	$p_{T,ee}$	$\Delta\eta_{jj}$
c_{HW}	—	—	—	—	—	—	—	—	—	p_{T,l^1}	m_{4l}	$p_{T,Z}$	m_{4l}
$c_{Hq}^{(1)}$	—	—	—	—	—	—	—	—	—	—	$p_{T,e^-\mu^-}$	$p_{T,e^-\mu^-}$	p_{T,l^2}
c_{HD}	—	—	—	—	—	—	—	—	—	—	—	m_{4l}	$\Delta\eta_{jj}$
c_{HWB}	—	—	—	—	—	—	—	—	—	—	—	—	m_{4l}

ZZ scattering at the LHC

- **Event topology**:
  - **2 Z-bosons** produced **centrally**
  - **2 energetic tagging jets** emitted back-to-back



- **Signature** based on **diboson** final states:
  - **fully leptonic: 4 e/μ** ; 2 jets



- Irreducible **tree-level contributions** to the final state:
  - **EW = $O(\alpha^6_{EW})$ signal** component
  - **QCD= $O(\alpha^4_{EW}\alpha^2_S)$ bkg** suppressed in **high m_{jj}-$|\Delta\eta_{jj}|$** region
  - **INT = $O(\alpha^5_{EW}\alpha_S)$ term: ~O(%) of** the **signal**

Summary of aQGCs limits

L = 35.9 fb^{-1}

		$W^{\pm}W^{\pm} + WZ$ (TeV^{-4}) Observed	$W^{\pm}W^{\pm} + WZ$ (TeV^{-4}) Expected	ZZ (TeV^{-4}) Observed	ZZ (TeV^{-4}) Expected	$W\gamma$ (TeV^{-4}) Observed	$W\gamma$ (TeV^{-4}) Expected	$Z\gamma$ (TeV^{-4}) Observed	$Z\gamma$ (TeV^{-4}) Expected
Transverse (4 gauge tensors)	f_{T0}/Λ^4	[-0.25, 0.28]	[-0.35, 0.37]	[-0.24, 0.22]	[-0.37, 0.35]	[-0.6, 0.6]	[-0.6, 0.6]	[-0.52,0.44]	[-0.64,0.57]
	f_{T1}/Λ^4	[-0.12, 0.14]	[-0.16, 0.19]	[-0.31, 0.31]	[-0.49, 0.49]	[-0.4, 0.4]	[-0.3, 0.4]	[-0.65,0.63]	[-0.81,0.90]
	f_{T2}/Λ^4	[-0.35, 0.48]	[-0.49, 0.63]	[-0.63, 0.59]	[-0.98, 0.95]	[-1.0, 1.2]	[-1.0, 1.2]	[-1.36,1.21]	[-1.68,1.54]
	f_{T5}/Λ^4	—	—	—	—	[-0.5, 0.5]	[-0.4, 0.4]	[-0.45,0.52]	[-0.58,0.64]
	f_{T6}/Λ^4	—	—	—	—	[-0.4, 0.4]	[-0.3, 0.4]	[-1.02,1.07]	[-1.30,1.33]
	f_{T7}/Λ^4	—	—	—	—	[-0.9, 0.9]	[-0.8, 0.9]	[-1.67,1.97]	[-2.15,2.43]
	f_{T8}/Λ^4	—	—	[-0.43, 0.43]	[-0.68, 0.68]	—	—	[-0.36,0.36]	[-0.47,0.47]
	f_{T9}/Λ^4	—	—	[-0.92, 0.92]	[-1.50, 1.50]	—	—	[-0.72,0.72]	[-0.91,0.91]
Mixed (2 Higgs-fields 2 gauge tensors)	f_{M0}/Λ^4	[-2.7, 2.9]	[-3.6, 3.7]	—	—	[-8.1, 8.0]	[-7.7, 7.6]	[-12.5,12.8]	[-15.8,16.0]
	f_{M1}/Λ^4	[-4.1, 4.2]	[-5.2, 5.5]	—	—	[-12, 12]	[-11, 11]	[-28.1,27.0]	[-35.0,34.7]
	f_{M2}/Λ^4	—	—	—	—	[-2.8, 2.8]	[-2.7, 2.7]	[-5.21,5.12]	[-6.55,6.49]
	f_{M3}/Λ^4	—	—	—	—	[-4.4, 4.4]	[-4.0, 4.1]	[-10.2,10.3]	[-13.0,13.0]
	f_{M4}/Λ^4	—	—	—	—	[-5.0, 5.0]	[-4.7, 4.7]	[-10.2,10.2]	[-13.0,12.7]
	f_{M5}/Λ^4	—	—	—	—	[-8.3, 8.3]	[-7.9, 7.7]	[-17.6,16.8]	[-22.2,21.3]
	f_{M6}/Λ^4	[-5.4, 5.8]	[-7.2, 7.3]	—	—	[-16, 16]	[-15, 15]	—	—
	f_{M7}/Λ^4	[-5.7, 6.0]	[-7.8, 7.6]	—	—	[-21, 20]	[-19, 19]	[-44.7,45.0]	[-56.6,55.9]
Scalar	f_{S0}/Λ^4	[-5.7, 6.1]	[-5.9, 6.2]	—	—	—	—	—	—
	f_{S1}/Λ^4	[-16, 17]	[-18, 18]	—	—	—	—	—	—

- **Competitive** limits for different final states **(no clipping)**
- Expected/observed limits are in good agreement

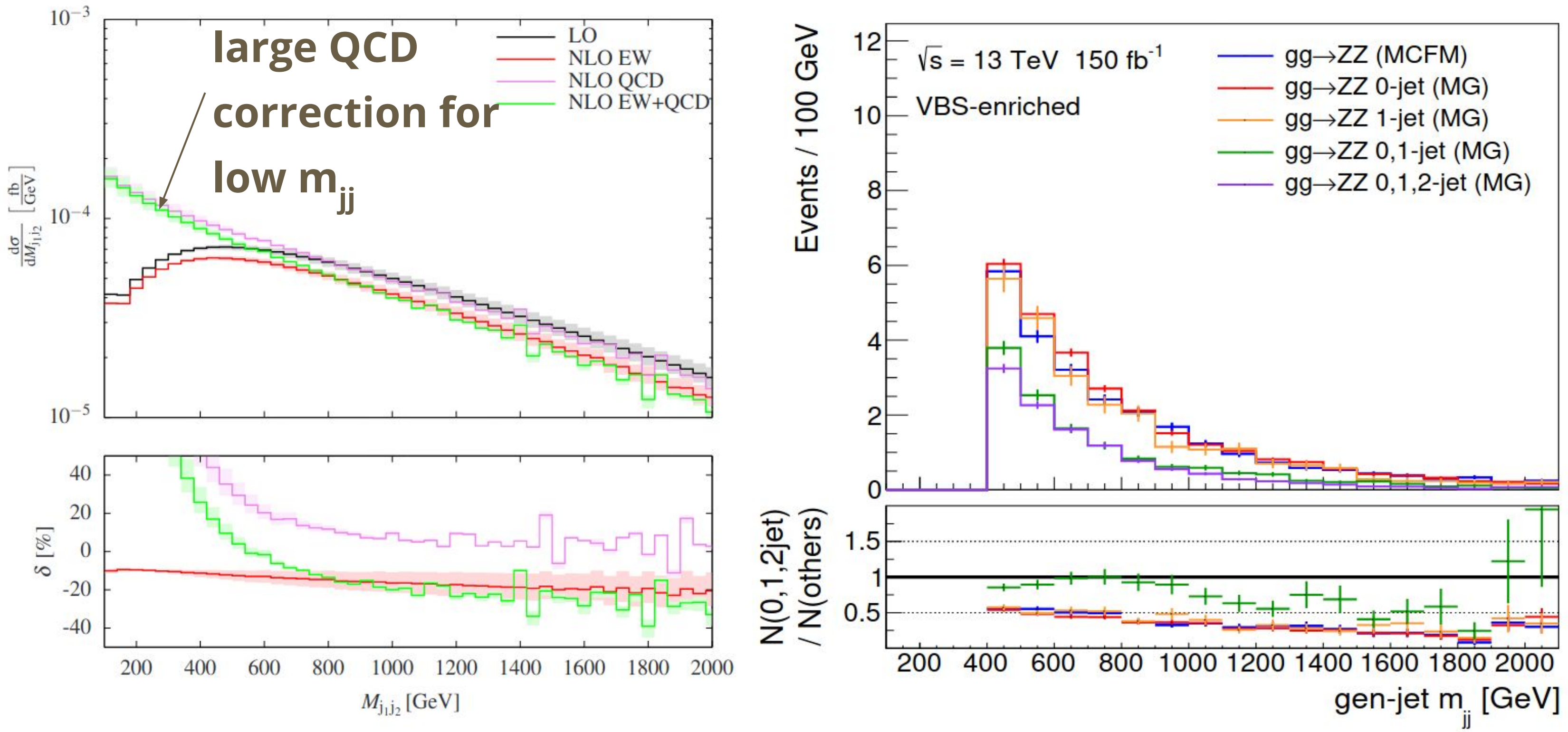
Processes of interest

- **Modelling** of **VBS ZZ 2→6(4) processes** including non-resonant diagrams
  - both **EWK** and **QCD-induced** contributions for **SM** and **EFT processes**

Process	Variables of interest	Selections	Expected events
ZZ+2j ($pp \to 2e2\mu 2j$)	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}, $p_{T,l^\pm l^\pm}$, $p_{T,l^\pm l^\mp}$, $p_{T,Z}$, $\Delta\phi_{jj}$, $\Delta\eta_{jj}$, η_{j^i}, η_{l^i}	$m_{jj} > 400\,\mathrm{GeV}$ $60 < m_{ll} < 120\,\mathrm{GeV}$ $m_{4l} > 180\,\mathrm{GeV}$ $p_{T,l^1} > 20\,\mathrm{GeV}$ $p_{T,l^2} > 10\,\mathrm{GeV}$ $p_{T,l^i} > 5\,\mathrm{GeV}$ $p_{T,j^{1,2}} > 30\,\mathrm{GeV}$ $\Delta\eta_{jj} > 2.4$ $\lvert\eta_{j^i}\rvert < 4.7$ $\lvert\eta_{l^i}\rvert < 2.5$ $\Delta R(l^i, j^k) > 0.4$	(EW) 11 (QCD) 176

- **Fully-leptonic final state 2e2μ+2j** studied with **VBS-enriched topology**
  - study **observables most sensitive** to EFT-induced anomalies

VBS ZZ NLO correction



- **VBS** approximation less accurate at **LO** than **NLO**
  - in full computation **tri-boson processes** contribute where one **V->qq** decays hadronically
  - for **real QCD radiation**, one of the **two tagging jets may** arise from V boson