Padova, June 2024

COMETA – Multiboson EFT workshop

COMETA

EFT in triboson analyses

Cristiano Tarricone

INFN – Sezione di Torino

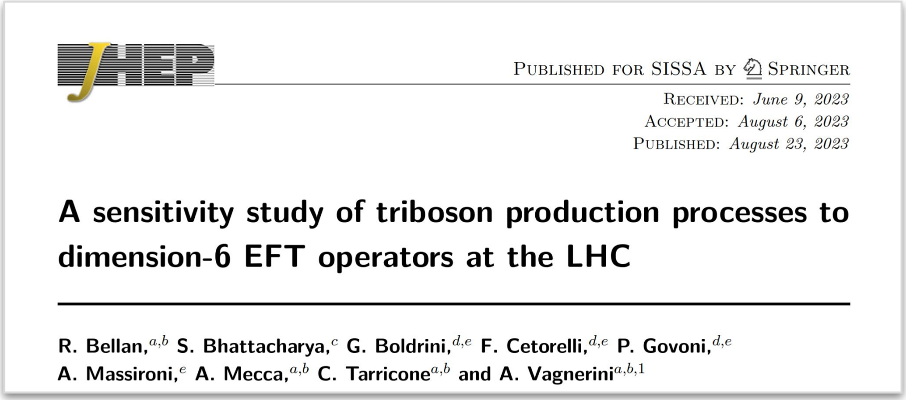
Università degli Studi di Torino

Outline

- Theoretical framework: **SMEFT**
- **Motivation** for **triboson measurements**
- Experimental results at **LHC**
- **Sensitivity study** to constrain **dimension-6** SMEFT operators
    - Triboson processes
    - Analysis Strategy
    - One and Two-dimensional operator constraints
    - Profiled constraints
- Summary and Outlook

Reference

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


JHEP

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

R. Bellan,[a,b] S. Bhattacharya,[c] G. Boldrini,[d,e] F. Cetorelli,[d,e] P. Govoni,[d,e] A. Massironi,[e] A. Mecca,[a,b] C. Tarricone[a,b] and A. Vagnerini[a,b,1]

Theory introduction: SMEFT approach

- **Triboson processes** predicted by the SM to be very rare → **test** of the **EWSB**
- **EW sector still unexplored** since **several rare processes** not yet **observed**!
  - **Any deviation** in **kinematic observables** could point to **New Physics**

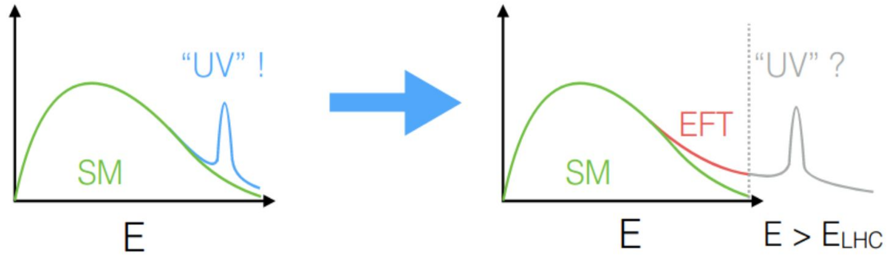
$SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant

Dim. *n* operator

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

Λ unknown NP energy scale

Wilson coefficient



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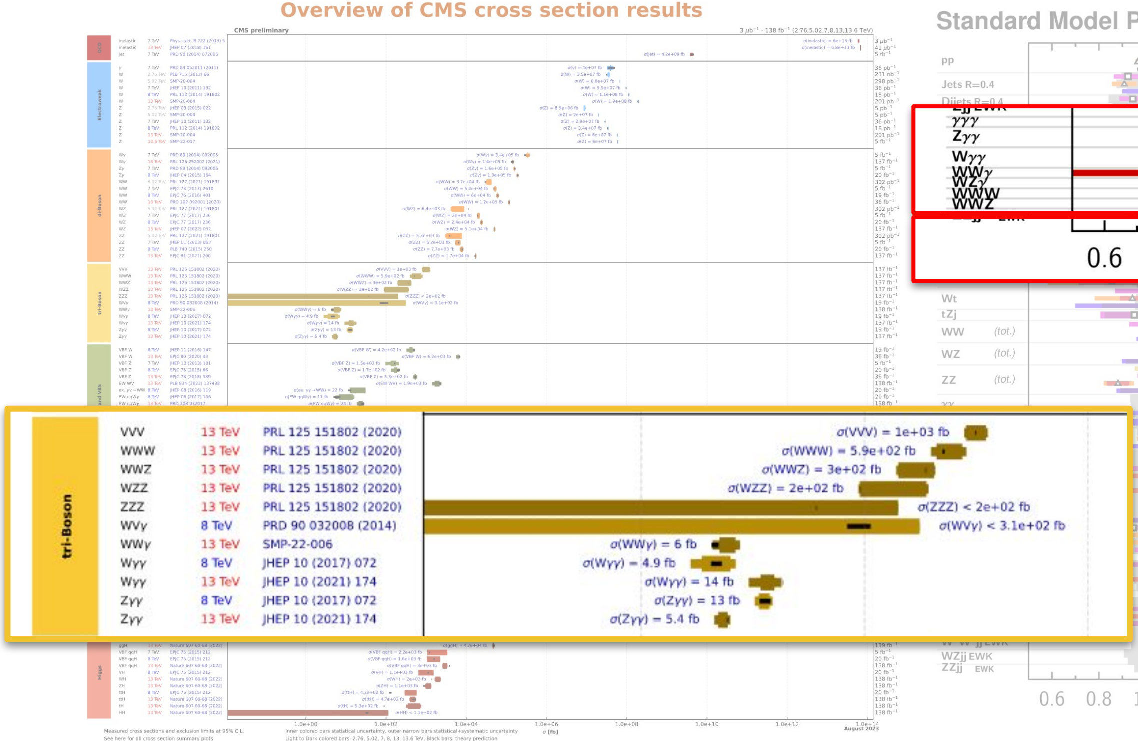
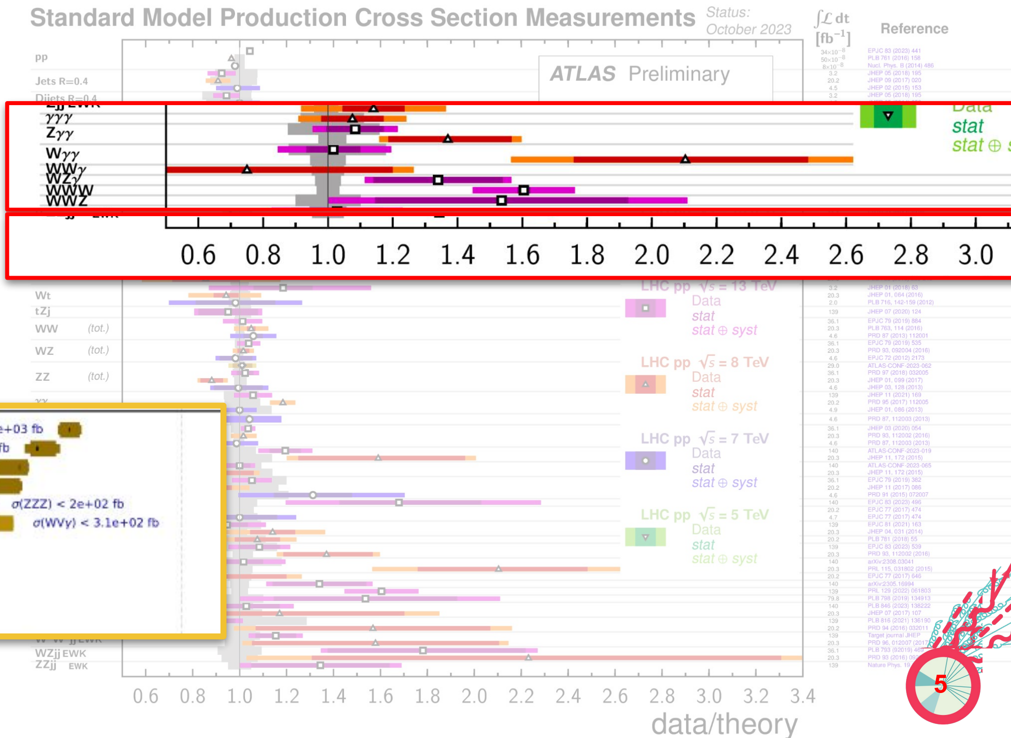
- **SMEFT bottom-up approach:**
  - **Effective Lagrangian** with only light **SM** particles
  - **BSM effects** incorporated as a **momentum expansion**

Triboson measurements at LHC

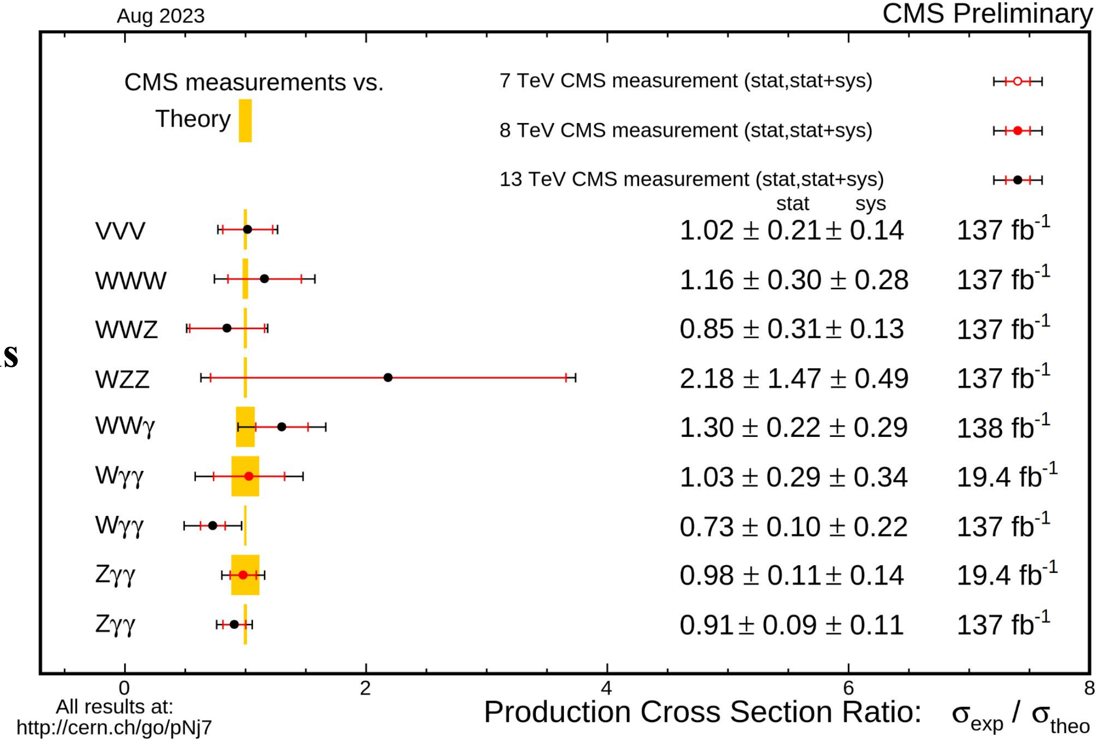
- The **ATLAS** and **CMS collaborations** have a **rich program** of **multi-boson** analyses
- Many **triboson** processes **have been studied** with at least a **photon** in final state





Triboson measurements at LHC

- **Extremely rare processes:**
  σ × BR(to leptons) ~O(1fb)
- **Observed three massive gauge** boson production and in **channels** with **a photon VVγ** and **two photons Vγγ**
- **BSM effects** as both **aTGC/aQGCs** and as anomalous **Higgs-gauge coupling**



Constraints on SMEFT operators

- Triboson 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 of a **triboson** combination?
  - What is the **interplay** with **other multiboson** constraints? (see Roberto's talk)

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

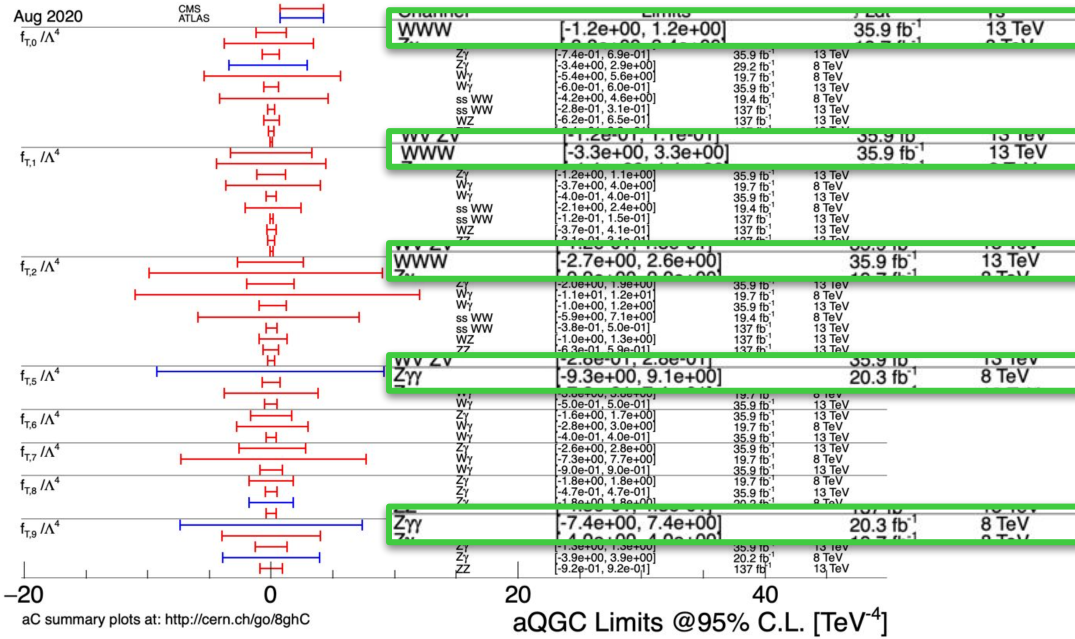
- **Assess sensitivity interplay** between **multi-boson analyses at LHC**
  - in the future **global EFT fit** will be necessary to provide the most stringent constraints to **SMEFT operators** (top, Higgs, EW, etc)

Motivation for dim.-6 EFT sensitivity study

- **Interpretation** of **triboson results** *traditionally* in terms of **dim-8 SMEFT operators (aQGCs)** at the LHC

- However, **dim-6 EFT operators** can have an impact on triboson production processes too!

- **First LHE sensitivity** study **of VBS +WW** [JHEP05(2022)039] including **O(Λ^{-4}) dim-6** EFT terms
  → **extended to triboson processes**



- Recently: [JHEP10(2021)174] → new stringent EFT constraints from CMS $V\gamma\gamma$ analysis (more details in backup)

SMEFT Montecarlo generation

- The **triboson** study focuses on a subset of **bosonic** ops
  - 6 bosonic operators affecting a subset of triboson channels
    (for Yukawa sector see JHEP04(2021)023)

- **Generated** at the **LO**: **SMEFTsim** [JHEP04(2021)073] **interfaced** with **MadGraph5_aMC@NLO (2.6.5)**
  - **U(3)⁵ flavour symmetry**
  - **$\{m_W, m_Z, G_F\}$ input scheme**
  - **CP-even**
  - **Λ = 1 TeV**

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

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

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

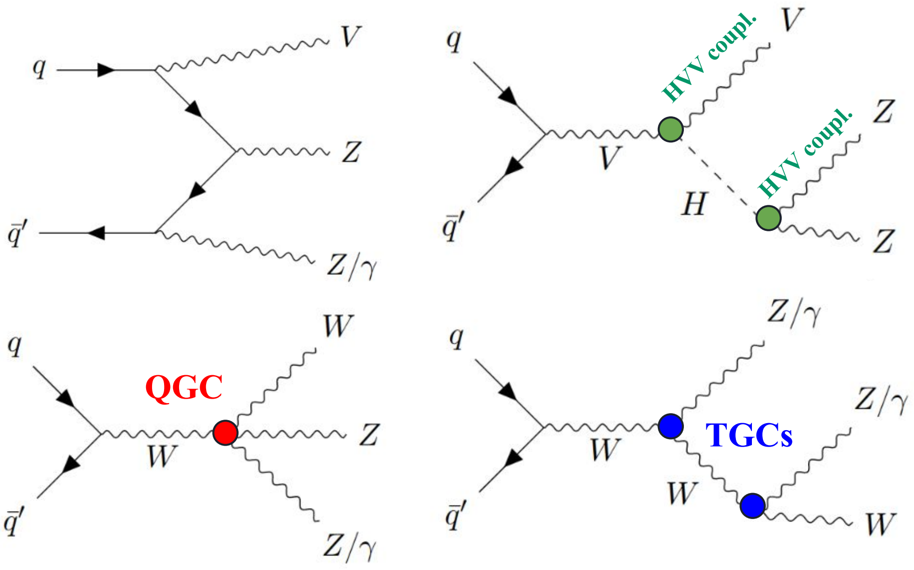
- **Insertion** of **one operator** per **diagram** to generate directly **single components**

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

Processes of interest

- **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



Processes of interest – EFT sensitivity

- **Summary** of the sensitivity of **each process** to the subset of operators
  - empty cells → no impact from the EFT

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		ψ^2	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi l}$	$(\varphi^\dagger i$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger$

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

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

Fit Procedure

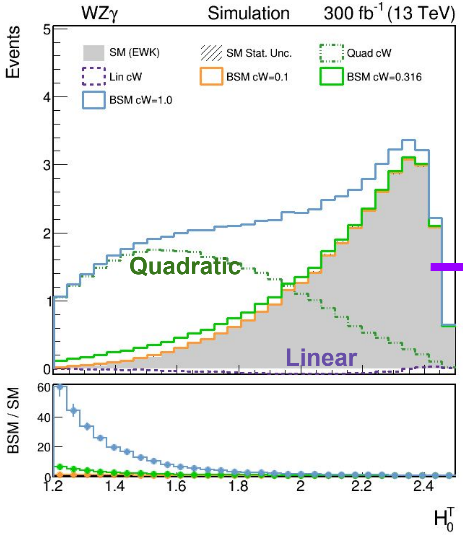
- **Likelihood scan** for each **variable** varying the **Wilson coefficient** in a fixed range

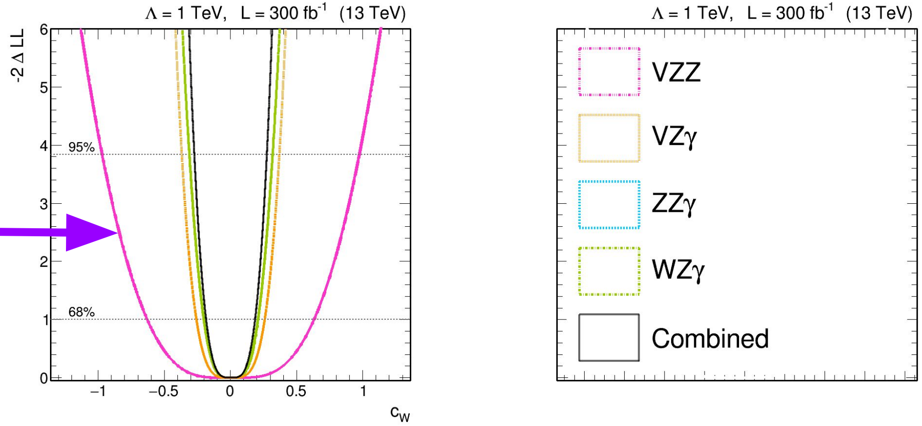
$$\mathcal{L}(\mathbf{c}) = \underbrace{\prod_{bin=k} \frac{(N_k(\mathbf{c}))^{n_k}}{n_k!} e^{-N_k(\mathbf{c})}}_{Poisson} \times \overbrace{\prod_{syst=j} \pi(\tilde{\theta}|\theta)}^{Nuisances}$$

- **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%** and **95% CL** estimated as **-2ΔLL <1(2.30)** and **-2ΔLL <3.84(5.99)** for single (pair) Wilson coefficient

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)

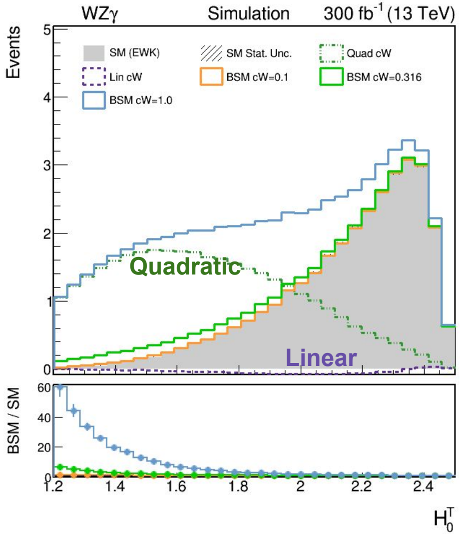




- **Optimal variable** extracted per **operator** used in **combination**

Triboson: fully leptonic WZγ

- **WZγ** production **extremely rare** process **~O(fb)** studied in **fully leptonic** channel
- In the SM, **WZγ** depends on **QGCs** → very sensitive to Q_W effects

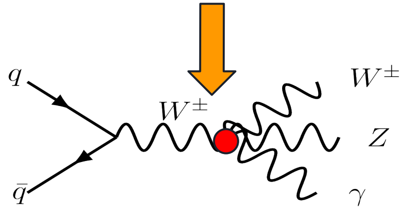


Fox-Wolfram variable

[PRD.87.073014]

→ good **discrimination** between **O(Λ^{-4}) dim-6** contribution and **SM**

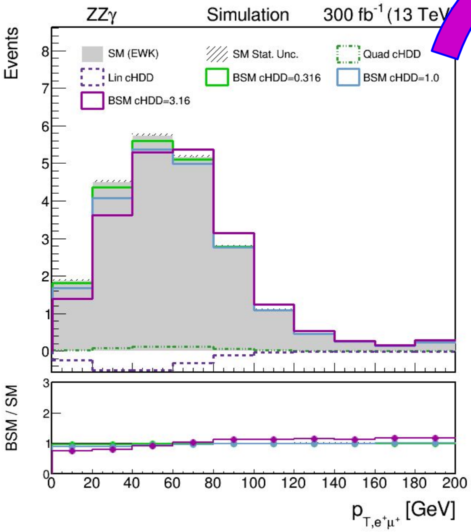
$$Q_W = \epsilon^{IJK} W_\mu^{I\,\nu} W_\nu^{J\,\rho} W_\rho^{K\,\mu}$$

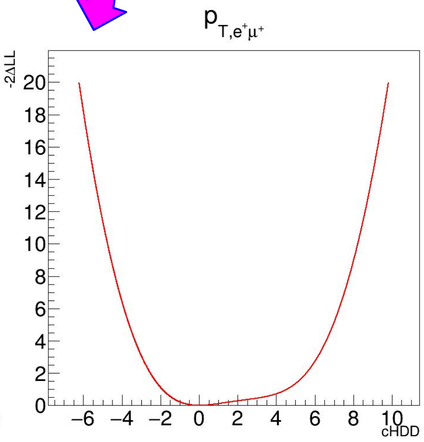


$$H_\ell^T = \sum_{i,j=\text{particle}} \frac{p_{T,i}\,p_{T,j}}{\left(\sum_{k=i,j} p_{T,k}\right)^2} P_\ell\left(\cos\,\Omega_{i,j}\right)$$

Triboson: fully leptonic ZZγ

- **Higgs-gauge boson** couplings affect the **electroweak** vertices in **ZZγ**
- **Best variable:** total $\mathbf{p_T}$ of same-sign leptons → **non-negligible linear term**



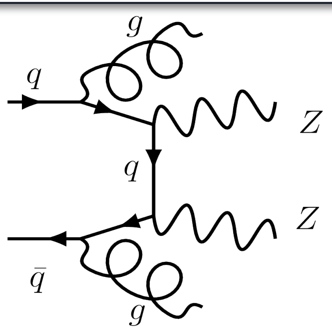


Consequence:
evident **asymmetry** in the likelihood scan

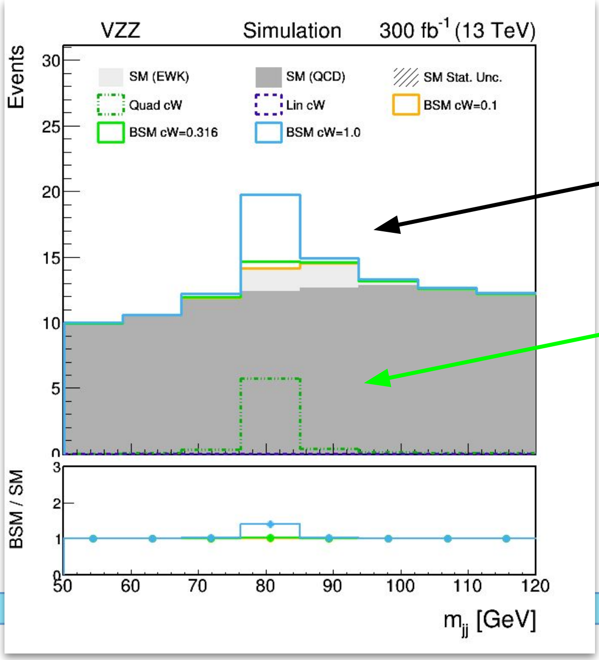
Triboson: semi-leptonic VZZ

- **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.



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

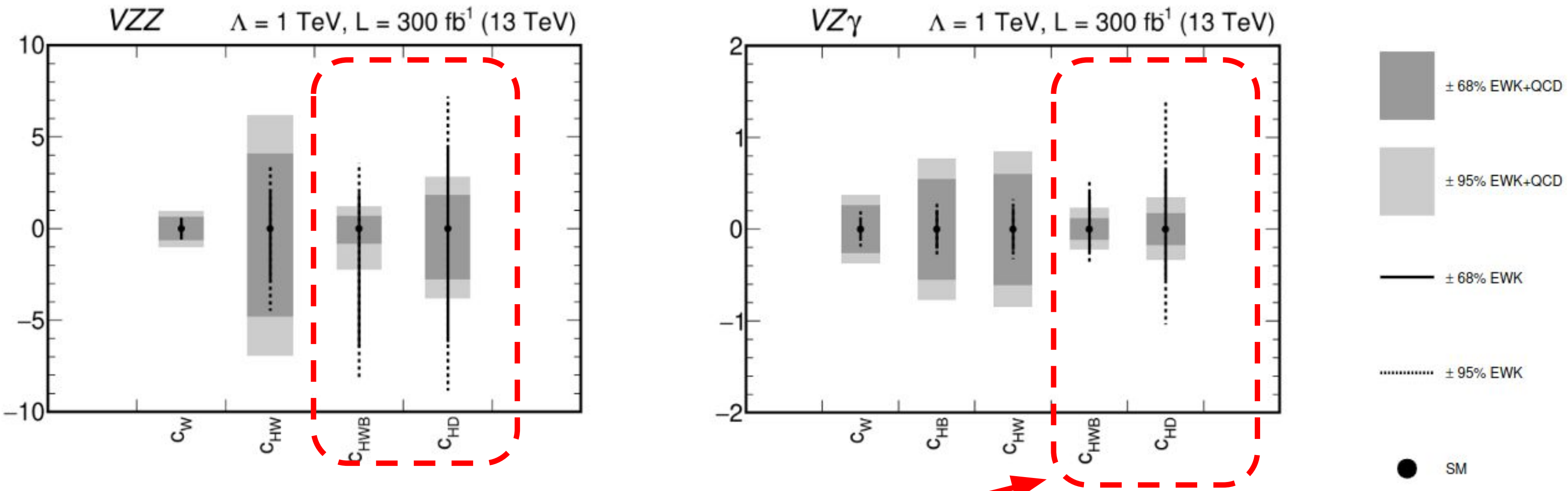


EWK SM term broad peak around $(m_W+m_Z)/2$

Quadratic term resonates at m_W

Triboson: semi-leptonic VZZ/VZγ

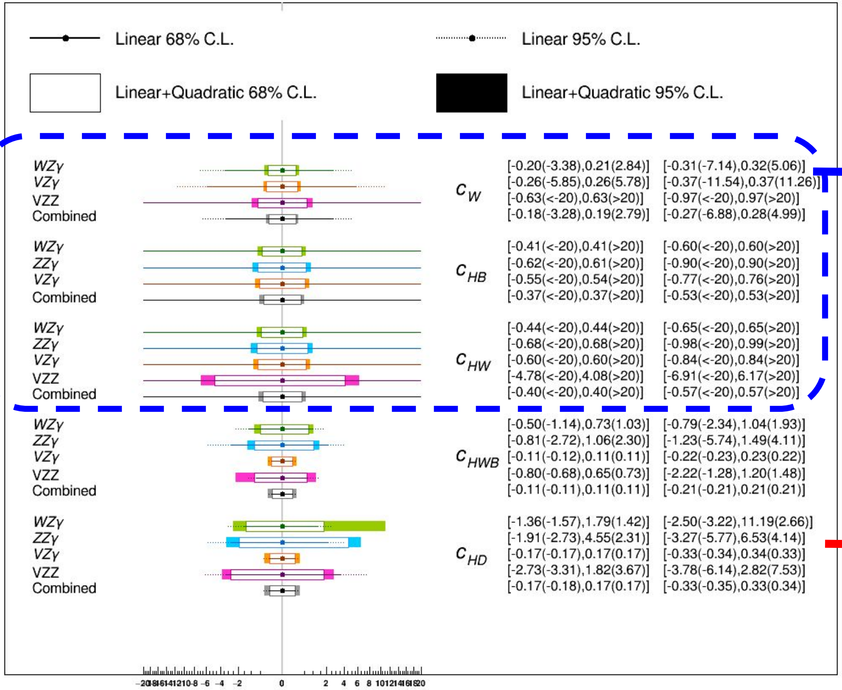
- **Impact of QCD** background on **semi-leptonic** channels **VZZ/VZγ sensitivity**
- **Q_{HWB}** and **Q_{HD} induce EWK anomalies** in **QCD** diagrams unlike other operators

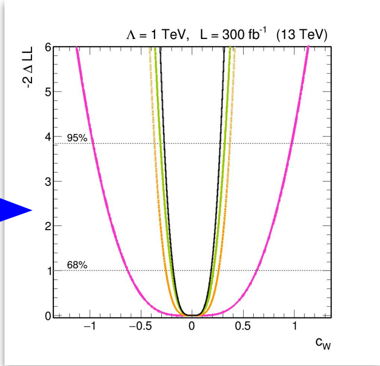


- **EFT operators impact on QCD diagrams** enhances the overall sensitivity despite larger bkg.

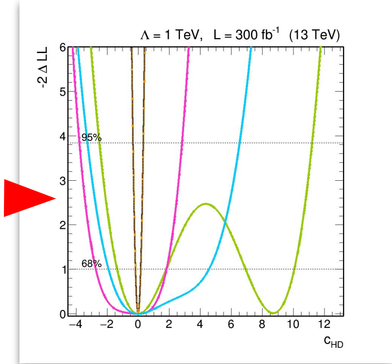
Individual constraints

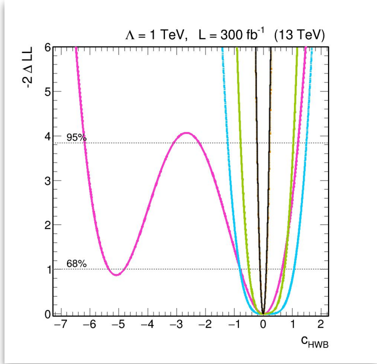
Individual operator constraints with(without) **O(Λ^{-4})** quadratic **terms**





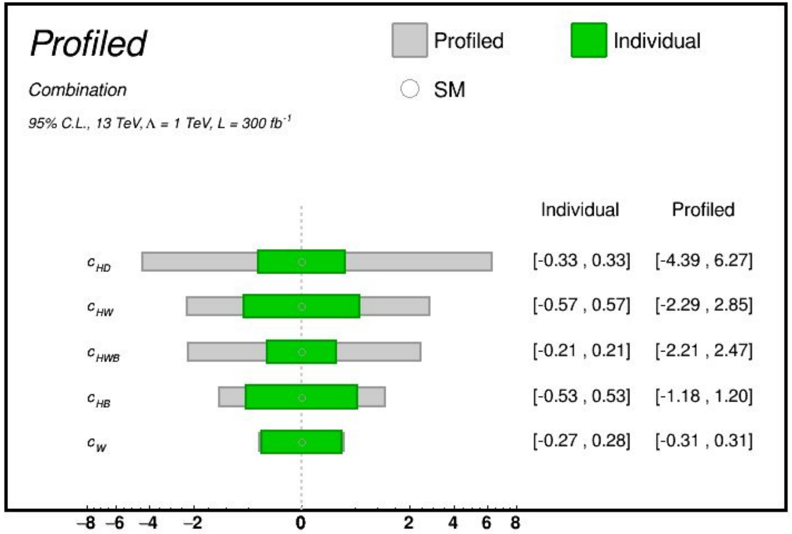
Large impact of **quadratic terms** on Q_W , Q_{HW} , Q_{HB} **ops**





- For other **operators**, linear interference term dominates

Profiled constraints



Comparison between profiled and individual expected constraints on the Wilson coefficients from the combination of the leptonic VZZ/VZγ channels

Profiled fit:

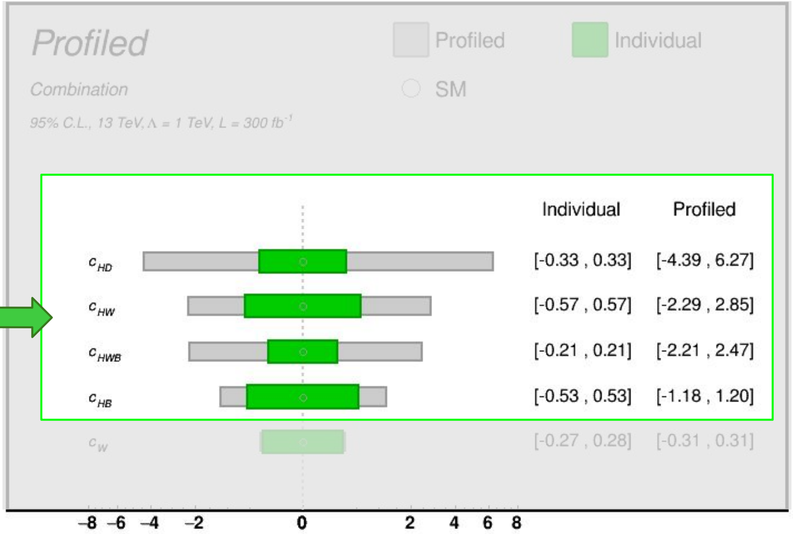
All the coefficients
(except for the one of interest)

floating parameters

Unconstrained nuisances
with a **flat prior**
in the maximum range (-20, 20).

Profiled constraints

Profiled constraints up to 10x less stringent than individual



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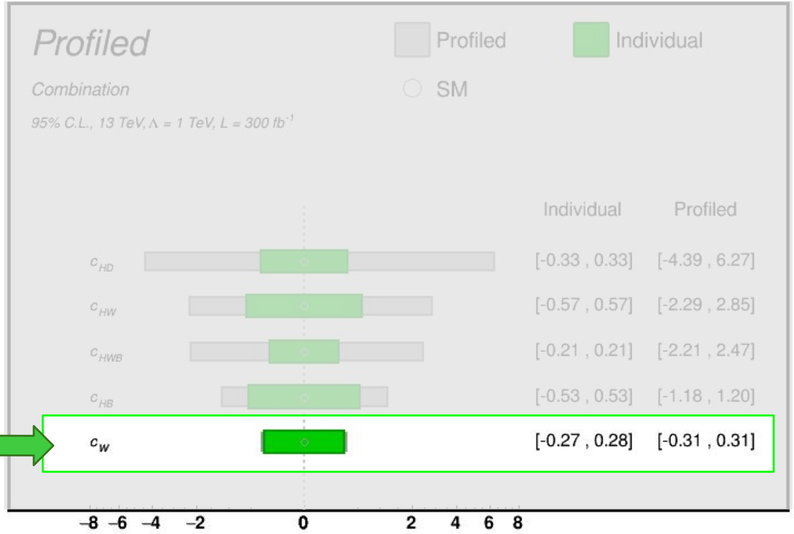


Q_W effects **uncorrelated** with the other operators

Comparison between profiled and individual expected constraints on the Wilson coefficients from the combination of the leptonic VZZ/VZγ channels

Profiled fit:

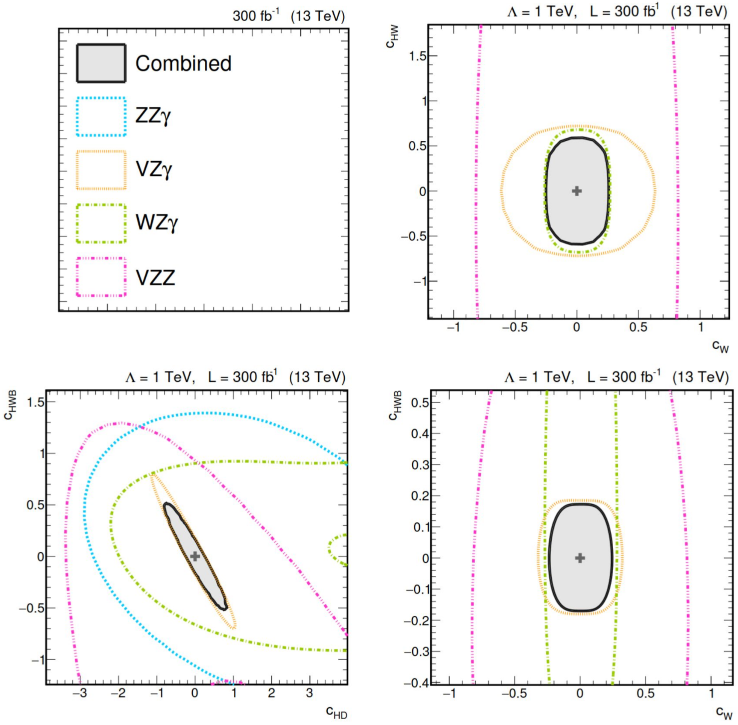
All the coefficients
(except for the one of interest)

floating parameters

Unconstrained nuisances
with a **flat prior**
in the maximum range (-20, 20).

2D constraints

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



Summary and outlook

- **Triboson** measurements **powerful tool** to explore BSM physics with the **EFT model-independent approach** → **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**

↓ Processes	Operators →	Q_W	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HD}
Triboson	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]

- **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

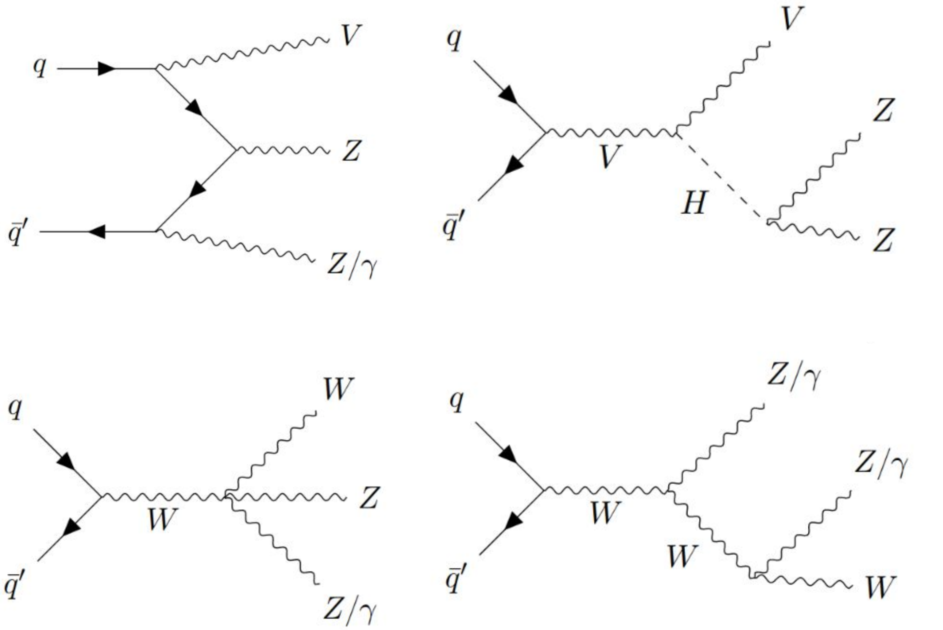
Thanks for your attention!

OTHER CONTENTS

Motivations

- Triboson production from p-p scatterings at 13 TeV
  - processes predicted by the **Standard Model** (SM) to be extremely rare

- Fundamental test for the **electroweak sector** of the SM
  - Triple and Quartic Gauge Couplings (TGCs, QGCs), and Higgs-gauge bosons couplings
  - Potentially anomalies in TGCs and QGCs (aTGC, aQGC) may hint to **new physics**
    - **SM-EFT** studies



– Main Feynman diagrams involved in the **VZγ/VZZ** channel

VZZ/VZγ studies

Approach and models

- Sensitivity study [10.1007/JHEP08(2023)158] at the parton level to the **dimension-six EFT** effects on **VZZ/VZγ** production processes (focused on Warsaw basis bosonic operators)

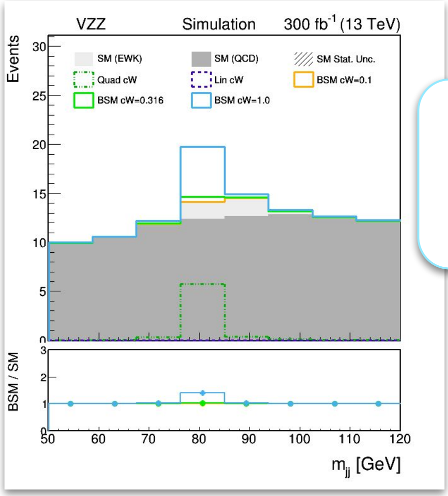
WZγ	ZZγ
pp → WZγ → $\mu^\pm$ ν_μ $e^+e^-\gamma$	pp → ZZγ → $\mu^+\mu^-$ $e^+e^-\gamma$
VZγ	**VZZ**
pp → VZγ → jj' l^+l^- γ	pp → VZZ → jj' $\mu^+\mu^-$ e^+e^-

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$	$\psi^2\varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$		
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$		
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$		
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$		
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$		
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$		
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$		
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$		

Operators → ↓ Processes	Q_W	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HD}
WZγ	✓	✓	✓	✓	✓
ZZγ		✓	✓	✓	✓
VZγ	✓	✓	✓	✓	✓
VZZ	✓		✓	✓	✓

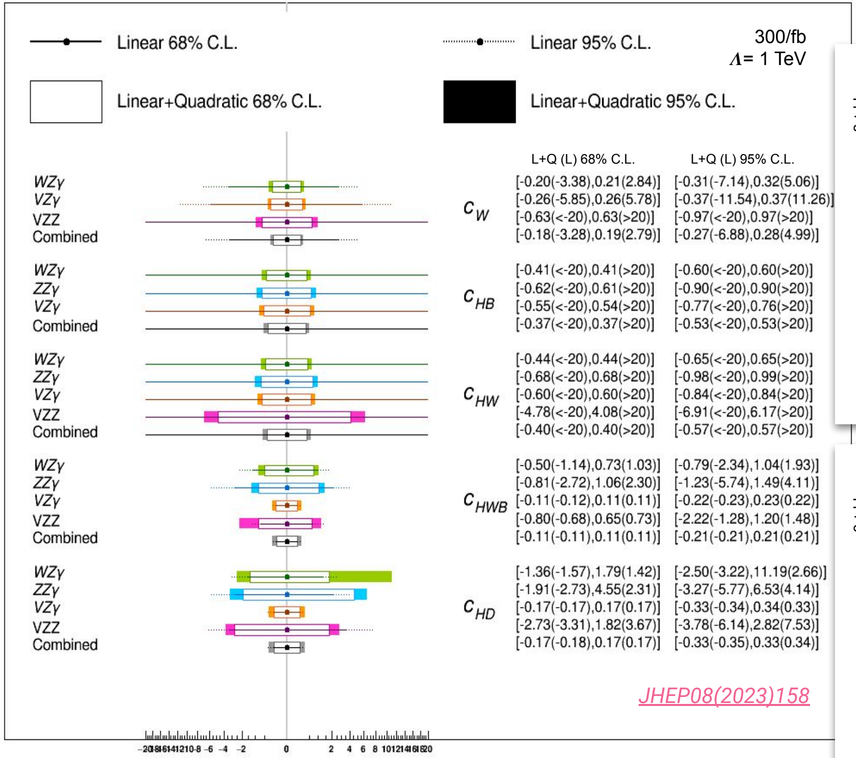
- MC generation (LO)
  - MadGraph5_aMC@NLO 2.6.5 interfaced with SMEFTsim 3.0
  - U(3)^5 flavor symmetry, $\{m_W, m_Z, G_F\}$ as an input scheme
  - No triboson intermediate states forced
    - →**EWK irreducible bkg.** automatically included (+ **interference** w/ signal processes)
    - →**QCD bkg.** generated for the semi-leptonic channels (but **suppressed** by the kinematic selection)

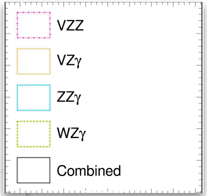


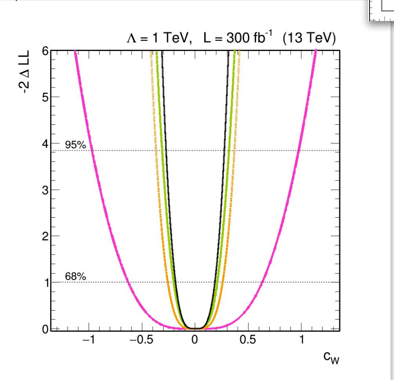
studies based on the EFT framework developed by the **Milano-Bicocca** group (G. Boldrini *et al.*)

VZZ/VZγ studies

Results

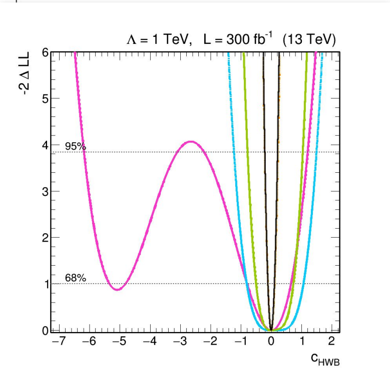


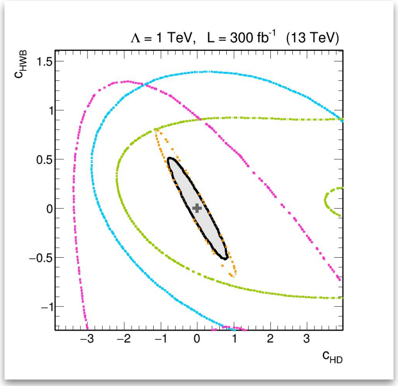




Interpretation of triboson results *traditionally* in terms of **dim-8 SMEFT** operators (aQGCs)

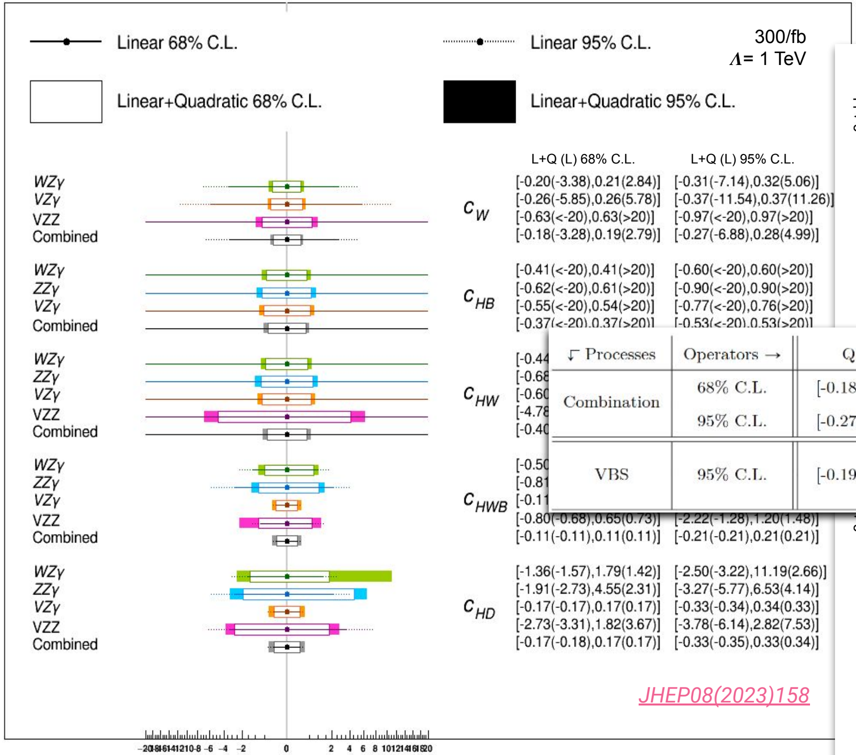
- **Dim-6 EFT operators have an impact too**!
- proof of **quadratic** terms importance!
- very **competitive** constraints!
- identification of the **most sensitive variables**
- fundamental role of **combination** of the analyses



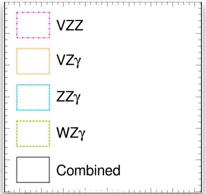


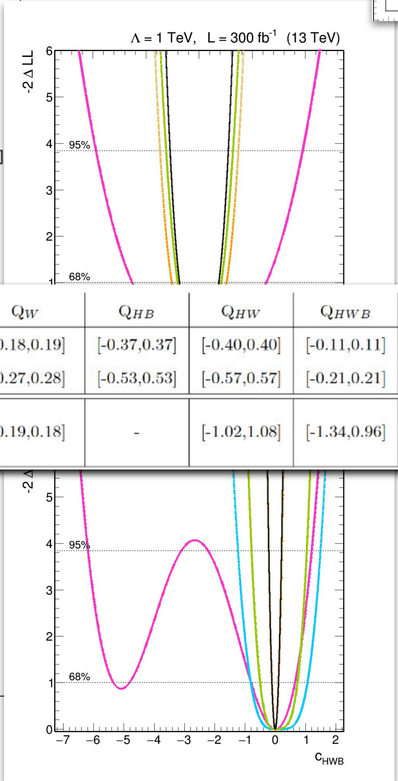
VZZ/VZγ studies

Results



JHEP08(2023)158





↓ Processes	Operators →	Q_W	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HD}
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]

Interpretation of triboson results *traditionally* in terms of **dim-8 SMEFT** operators (aQGCs)

- **Dim-6 EFT operators have an impact too**!
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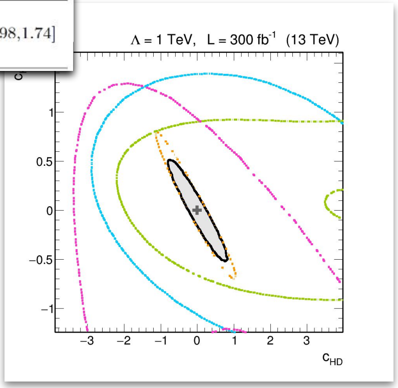

WZγ, ZZγ, VZγ , and VZZ channels

Kinematic selection and variables under study

Process	Variables of interest	Selections
VZγ ($pp \to 2j\ 2l\ \gamma$)	m_{ll}, m_{jj}, p_T^Z, p_T^V, p_T^γ, $p_T^{l_1}$, $p_T^{l_2}$, $p_T^{j_1}$, $p_T^{j_2}$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, η_{j_1}, η_{j_2}, η_{l_1}, η_{l_2}, ϕ_{j_1}, ϕ_{j_2}, η^γ, ϕ^γ, $p^{l_1}_{T(Z\gamma)}$, $p^{l_2}_{T(Z\gamma)}$, $p^{l_1}_{T(Z)}$, $p^{l_2}_{T(Z)}$, $p^{l_1}_{T(VZ)}$, $p^{l_2}_{T(VZ)}$, $p^{l_1}_{T(V)}$, $p^{l_2}_{T(V)}$, $p^{l_1}_{T(\gamma)}$, $p^{l_2}_{T(\gamma)}$, $p^{j_1}_{T(\gamma)}$, $p^{j_2}_{T(\gamma)}$, $p^{\gamma}_{T(Z)}$, $p^{V}_{T(Z)}$, $p^{V}_{T(\gamma)}$, $p^{V}_{T(Z\gamma)}$, $p^{\gamma}_{T(VZ)}$, $H^x_\ell(jj)$, $H^x_\ell(ll)$, $H^x_\ell(2l\ 2j\gamma)$	$50<m_{jj}<120$ GeV $60<m_{ll}<120$ GeV $p_{T,l^1} > 20$ GeV $p_{T,l^2} > 10$ GeV $p_{T,l^i} > 5$ 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 ($pp \to 2j\ 4l$)	m_{ll}, m_{jj}, m_{4l}, m_{4ljj}, p_T^Z, p_T^{ll}, $p_T^{j_1}$, $p_T^{j_2}$, $p_T^{l_1}$, $p_T^{l_2}$, p_T^V, $p_T^{e^\pm\mu^\pm}$, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, η_{j_1}, η_{j_2}, η_{l_1}, η_{l_2}, ϕ_{j_1}, ϕ_{j_2}, $p^{l_1}_{T(ZZ)}$, $p^{l_2}_{T(ZZ)}$, $p^{j_1}_{T(ZZ)}$, $p^{j_2}_{T(ZZ)}$, $p^{l_1}_{T(Z_i)}$, $p^{l_2}_{T(Z_i)}$, $p^{j_1}_{T(Z_i)}$, $p^{j_2}_{T(Z_i)}$, $p^{Z_1}_{T(Z_2)}$, $p^{V}_{T(Z_i)}$, $p^{V}_{T(ZZ)}$, $H^x_\ell(jj)$, $H^x_\ell(ll)$, $H^x_\ell(4ljj)$	$50<m_{jj}<120$ GeV $60<m_{ll}<120$ 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 $\lvert\eta_{j^i}\rvert < 2.5$ $\lvert\eta_{l^i}\rvert < 2.5$ $\Delta R(l^i, j^k) > 0.4$

Process	Variables of interest	Selections
WZγ ($pp \to 3l\ \nu\ \gamma$)	MET, m_{ll}, $m_{T,W}$, p_T^Z, p_T^W, p_T^γ, p_T^{ll}, $p_T^{l_1}$, $p_T^{l_2}$, p_T^γ, $p_T^{e^+\mu^+}$, η_{l_1}, η_{l_2}, η^γ, ϕ^γ, $p^{l_1}_{T(Z\gamma)}$, $p^{l_2}_{T(Z\gamma)}$, $p^{l_1}_{T(Z)}$, $p^{l_2}_{T(Z)}$, $p^{l_1}_{T(WZ)}$, $p^{l_2}_{T(WZ)}$, $p^{l_1}_{T(W)}$, $p^{l_2}_{T(W)}$, $p^{\gamma}_{T(Z)}$, $p^{W}_{T(Z)}$, $p^{W}_{T(\gamma)}$, $p^{\gamma}_{T(WZ)}$, $H^x_\ell(ll)$, $H^x_\ell(3l\nu\gamma)$	$50<m_{l\nu}<110$ GeV $60<m_{ll}<120$ GeV MET > 30 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 $\lvert\eta_\gamma\rvert < 2.5$ $\Delta R(l^i,\gamma) > 0.4$
ZZγ ($pp \to 4l\ \gamma$)	m_{ll}, m_{4l}, $p_T^{Z_1}$, $p_T^{Z_2}$, $p_T^{l_1}$, $p_T^{l_2}$, p_T^{ll}, p_T^γ, $p_T^{e^\pm\mu^\pm}$, η_{l_1}, η_{l_2}, η^γ, ϕ^γ, $p^{l_1}_{T(Z\gamma)}$, $p^{l_2}_{T(Z\gamma)}$, $p^{l_1}_{T(Z_1)}$, $p^{l_2}_{T(Z_1)}$, $p^{l_1}_{T(Z_2)}$, $p^{l_2}_{T(Z_2)}$, $p^{l_1}_{T(ZZ)}$, $p^{l_2}_{T(ZZ)}$, $p^{l_1}_{T(\gamma)}$, $p^{l_2}_{T(\gamma)}$, $p^{\gamma}_{T(Z_1)}$, $p^{\gamma}_{T(Z_2)}$, $p^{\gamma}_{T(ZZ)}$, $H^x_\ell(ll)$, $H^x_\ell(4l\gamma)$	$60<m_{ll}<120$ 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 $\lvert\eta_\gamma\rvert < 2.5$ $\Delta R(l^i,\gamma) > 0.4$

<table>
<tr><th>WZγ</th><th>ZZγ</th><th>VZγ</th><th>VZZ</th></tr>
<tr><td>pp -> WZγ -> $\mu^+\nu_\mu e^+e^-\gamma$</td><td>pp -> ZZγ -> $\mu^+\mu^- e^+e^-\gamma$</td><td>pp -> VZγ -> jj’ $l^+l^-\gamma$</td><td>pp -> VZZ -> jj’ $\mu^+\mu^- e^+e^-$</td></tr>
<tr><td colspan="4">$60 < m_{ll} < 120$ GeV
$p_T^{l1} > 20$ GeV $p_T^{l2} > 10$ GeV $p_T^{l} > 5$ GeV
$|\eta_l| < 2.5$</td></tr>
<tr><td>$50 < m_{\mu\nu} < 110$ GeV
MET > 30 GeV</td><td>TGCs and QGCs not involved
⇩
Q_W has no effect on this channel</td><td colspan="2">$50 < m_{jj} < 120$ GeV
$p_T^{j} > 30$ GeV
$|\eta_j| < 2.5$
$\Delta R_{lj} > 0.4$</td></tr>
<tr><td colspan="3">$p_T^{\gamma} > 20$ GeV
$|\eta_\gamma| < 2.5$
$\Delta R_{l\gamma} > 0.4$</td><td rowspan="2">No Photons
⇩
Q_{HB} has no effect on this channel</td></tr>
<tr><td colspan="2">No hadron jets ⟹ No QCD-induced bkg</td><td>$\Delta R_{j\gamma} > 0.4$</td></tr>
</table>

Standard Model-Effective Field Theories
Dimension-6 operators

Model-independent approach: **SM-EFT** framework

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

Dim. $n > 4$ op.

New Physics scale
(Λ set to 1 TeV)

Wilson coefficient

Effect of an individual dimension-6 operator, e.g. Q_W :

$$|\mathcal{A}|^2 = \underbrace{|\mathcal{A}_{\mathrm{SM}}|^2}_{\mathrm{SM}} + \underbrace{2\,\frac{c_W}{\Lambda^2} Re(\mathcal{A}^*_{Q_W} \mathcal{A}_{\mathrm{SM}})}_{\mathrm{Linear}} + \underbrace{\frac{c_W^2}{\Lambda^4} |\mathcal{A}_{Q_W}|^2}_{\mathrm{Quadratic}}$$

Further extension to the effects of couple of operators combined

$$|\mathcal{A}|^2 = \underbrace{|\mathcal{A}_{\mathrm{SM}}|^2}_{\mathrm{SM}} + \underbrace{2\sum_i \frac{c_i}{\Lambda^2} Re(\mathcal{A}^*_{Q_i} \mathcal{A}_{\mathrm{SM}})}_{\mathrm{Linear}} +$$

$$+ \underbrace{\sum_{i \neq j} \frac{c_i c_j}{\Lambda^4} Re(\mathcal{A}^*_{Q_i} \mathcal{A}_{Q_j})}_{\mathrm{Mixed\ interference}} + \underbrace{\sum_i \frac{c_i^2}{\Lambda^4} |\mathcal{A}_{Q_i}|^2}_{\mathrm{Quadratic}}$$

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Dim. 6 operators from the Warsaw basis [2]

[2] B. Grzadkowski et al. Dimension-six terms in the standard model lagrangian. Journal of High Energy Physics, 2010(10):1–18, 2010

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$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$	$\psi^2\varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$		
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$		
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$		
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$		
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$		
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$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$		
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$		

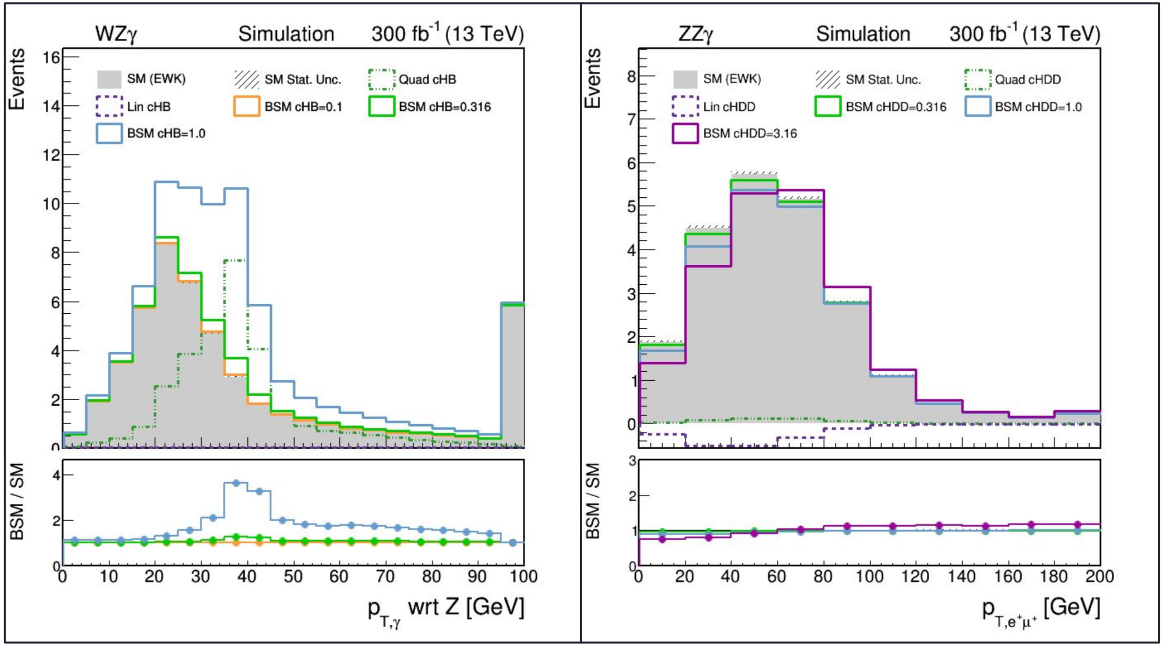
Operators → ↓ Processes	Q_W	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HD}
WZγ	✓	✓	✓	✓	✓
ZZγ		✓	✓	✓	✓
VZγ	✓	✓	✓	✓	✓
VZZ	✓		✓	✓	✓

Dim. 6 operators under study from the Warsaw basis [2]

2 B. Grzadkowski et al. Dimension-six terms in the standard model lagrangian. Journal of High Energy Physics, 2010(10):1–18, 2010

Shape analysis

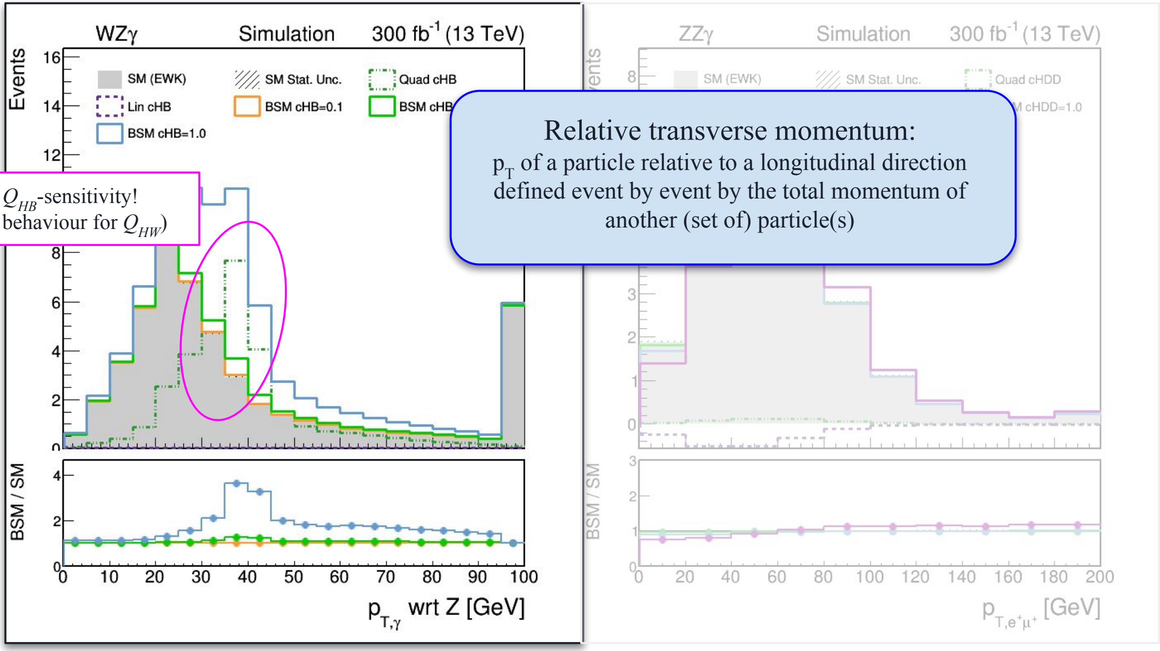
Effects of a single operator



Examples of remarkable variables of interest and the corresponding SM and SM+EFT event distributions for the fully leptonic channels WZγ and ZZγ

Shape analysis

Effects of a single operator



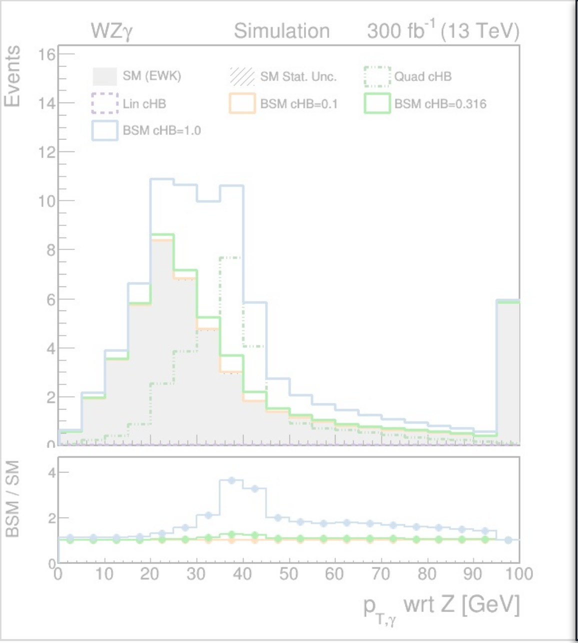
high Q_{HB}-sensitivity!
(similar behaviour for Q_{HW})

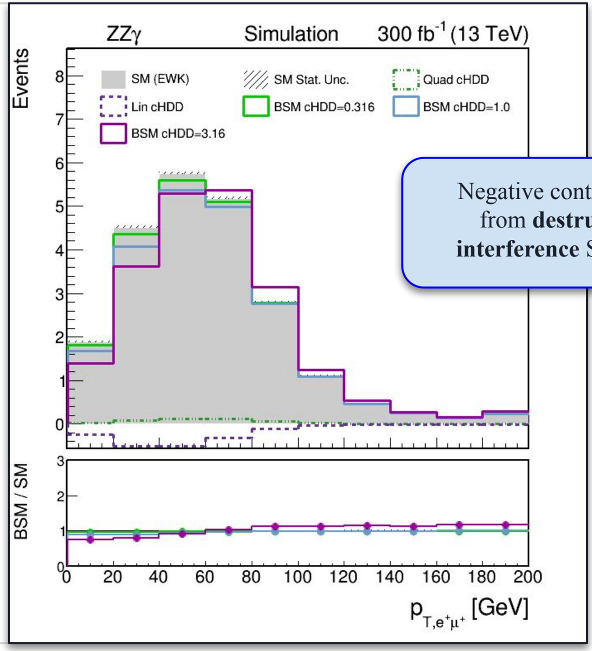
Relative transverse momentum:
p_T of a particle relative to a longitudinal direction defined event by event by the total momentum of another (set of) particle(s)

Examples of remarkable variables of interest and the corresponding SM and SM+EFT event distributions for the fully leptonic channels WZγ and ZZγ

Shape analysis

Effects of a single operator





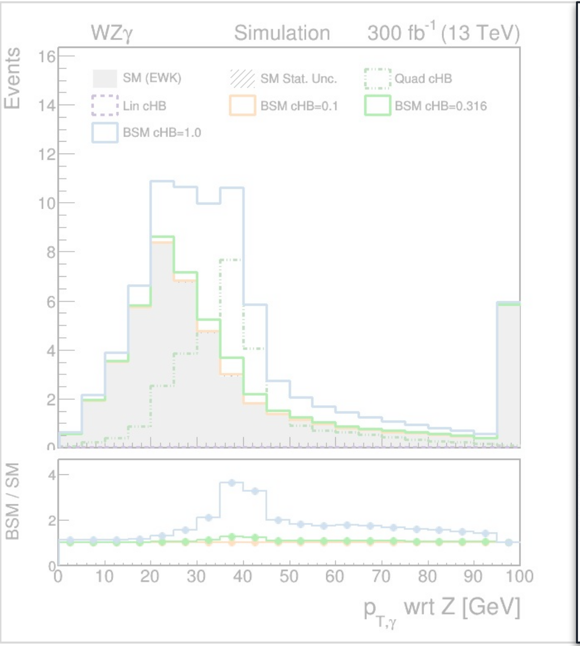
Negative contribution from **destructive interference** SM-Q_{HD}

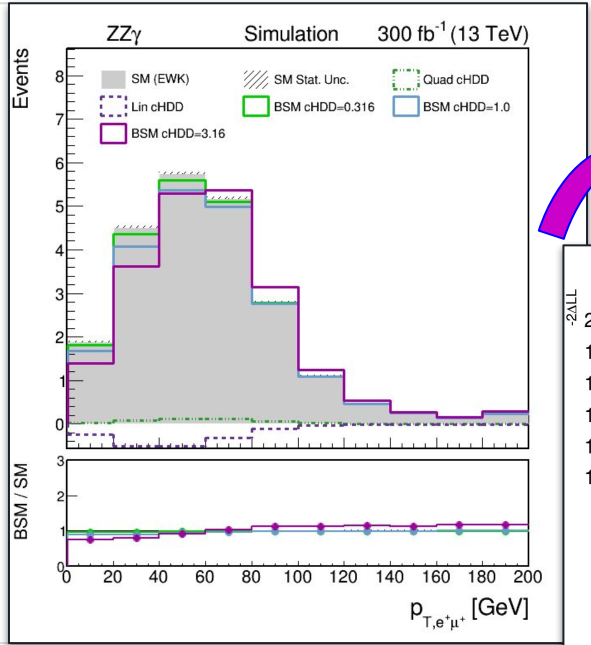
Positive contribution from pure BSM quadratic Q_{HD} term

Examples of remarkable variables of interest and the corresponding SM and SM+EFT event distributions for the fully leptonic channels WZγ and ZZγ

Shape analysis

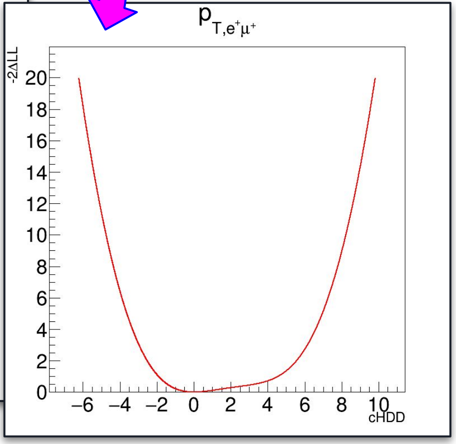
Effects of a single operator





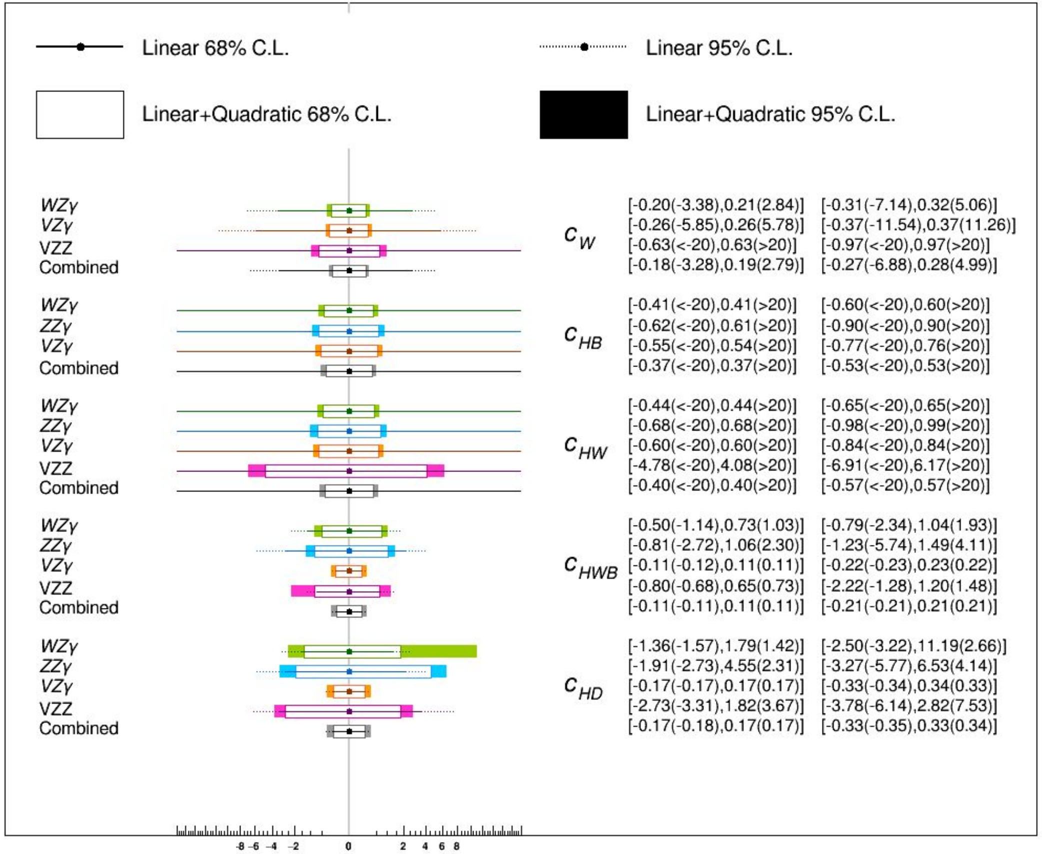
Examples of remarkable variables of interest and the corresponding SM and SM+EFT event distributions for the fully leptonic channels WZγ and ZZγ

<u>Consequence</u>: evident **asymmetry** in the likelihood scan

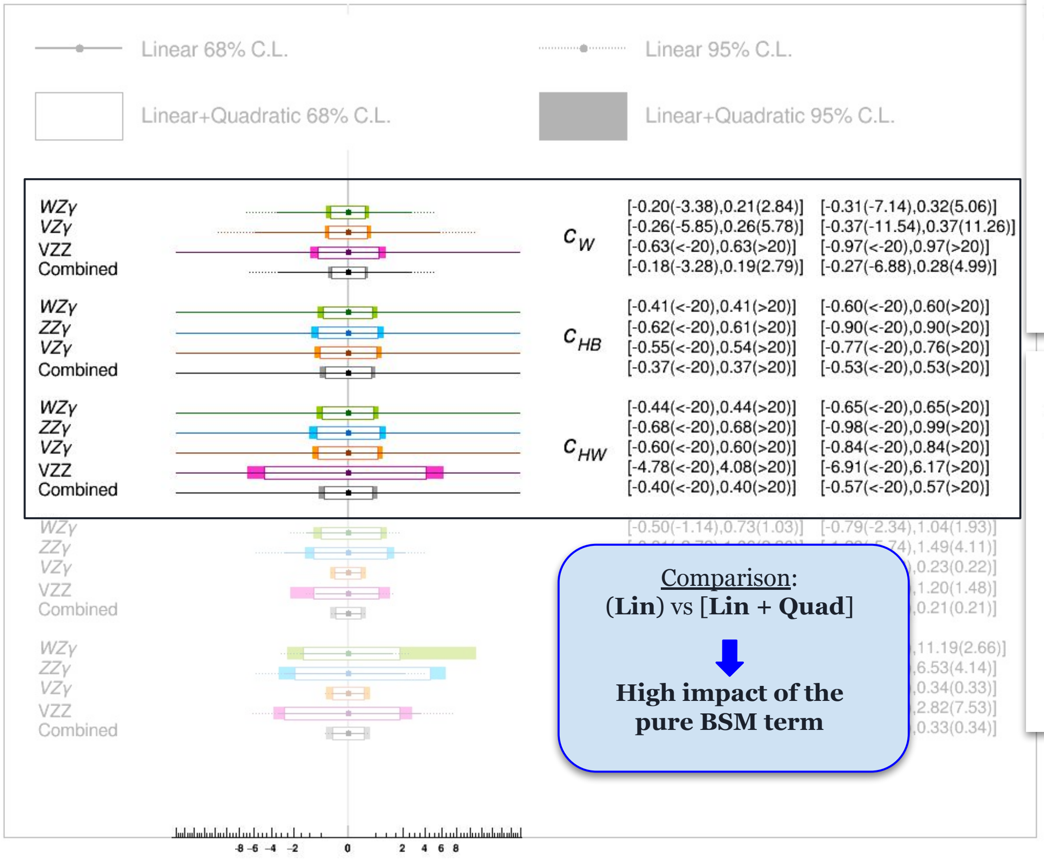


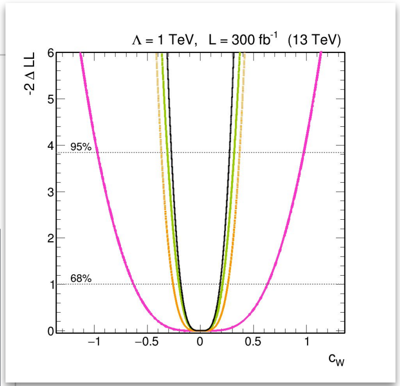
Likelihood scan relative to c_{HD} for the channel ZZγ

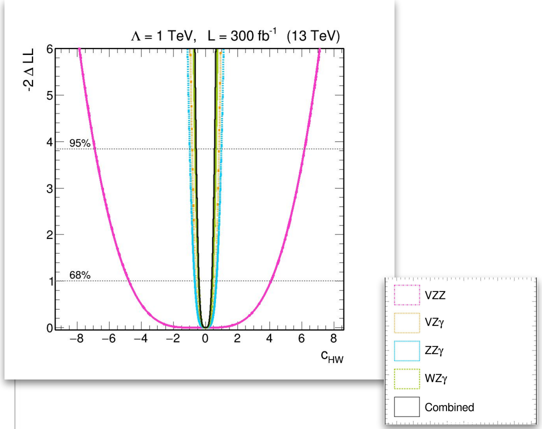
1D constraints



1D constraints





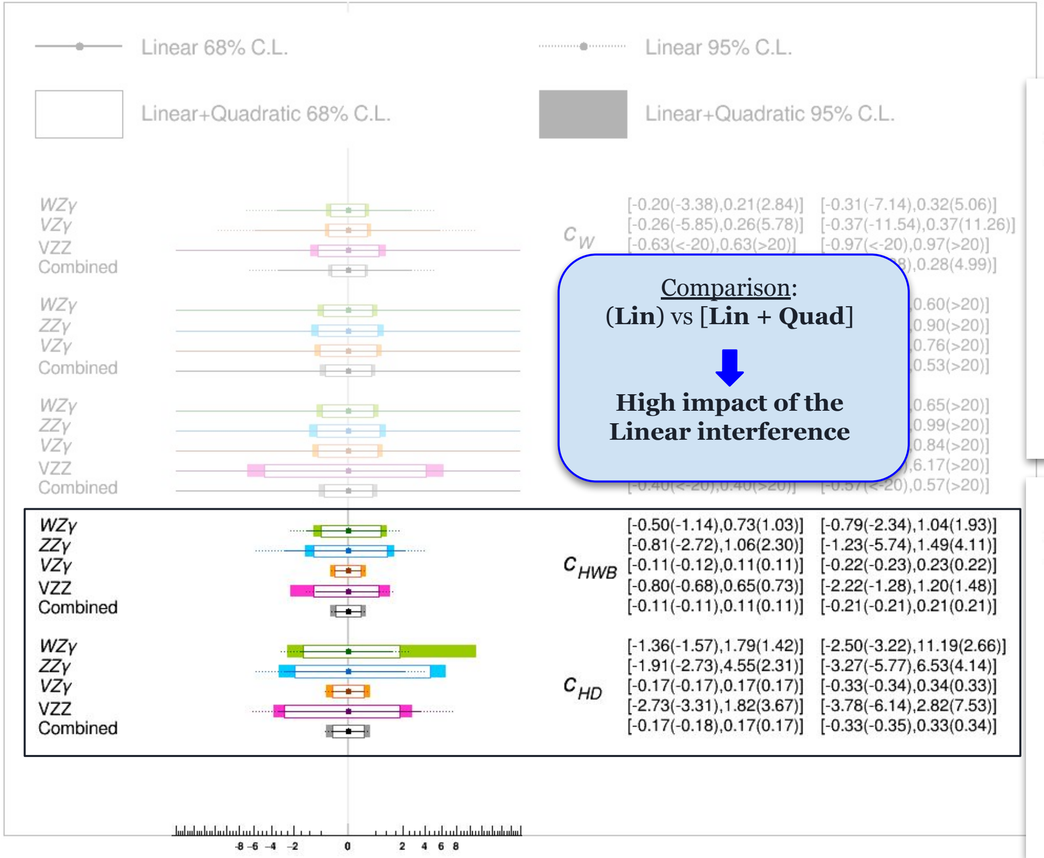


Comparison:
(Lin) vs [Lin + Quad]

⬇

High impact of the pure BSM term

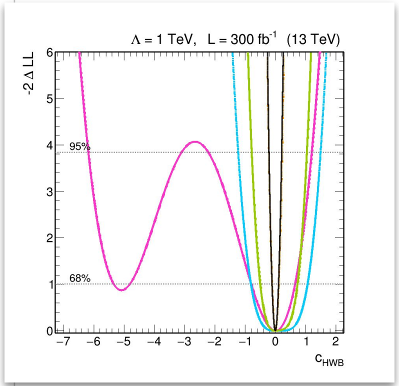
1D constraints

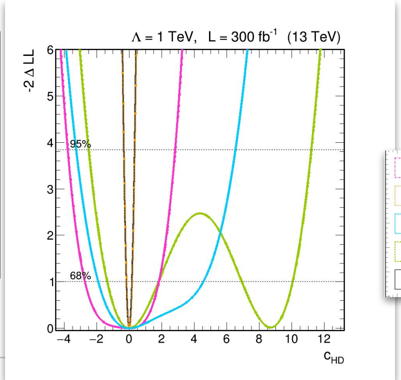


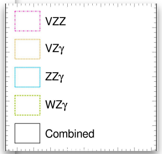
<u>Comparison</u>:
(Lin) vs [Lin + Quad]

⬇

High impact of the Linear interference



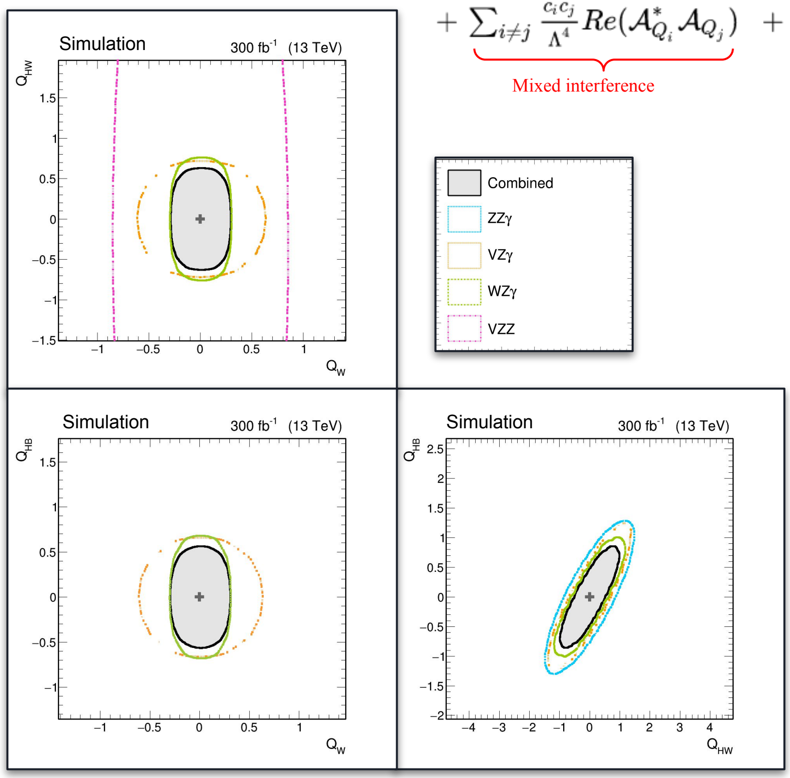




2D confidence areas

$$|\mathcal{A}|^2 = \underbrace{|\mathcal{A}_{SM}|^2}_{\text{SM}} + \underbrace{2\sum_i \frac{c_i}{\Lambda^2} Re(\mathcal{A}^*_{Q_i}\mathcal{A}_{SM})}_{\text{Linear}} + \underbrace{\sum_{i\neq j} \frac{c_i c_j}{\Lambda^4} Re(\mathcal{A}^*_{Q_i}\mathcal{A}_{Q_j})}_{\text{Mixed interference}} + \underbrace{\sum_i \frac{c_i^2}{\Lambda^4}|\mathcal{A}_{Q_i}|^2}_{\text{Quadratic}}$$

Examples of **contours** of the 68 % C.L. **exclusion areas** for pairs of operators affecting the channels of interest



$Q_{\phi W} = \phi^\dagger\phi\, W^I_{\mu\nu} W^{I\mu\nu}$

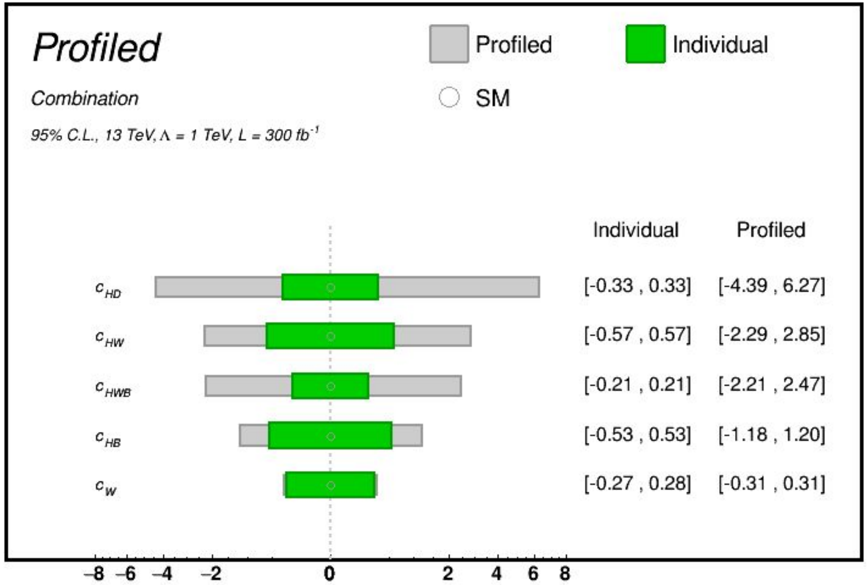
$Q_{\phi B} = \phi^\dagger\phi\, B_{\mu\nu} B^{\mu\nu}$

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

$Q_{\phi W} = \phi^\dagger\phi\, W^I_{\mu\nu} W^{I\mu\nu}$

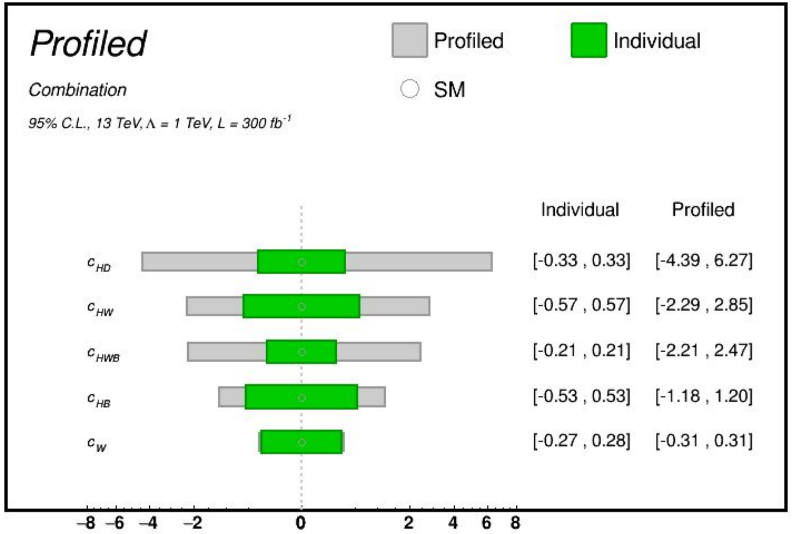
Profiled constraints

- Performed **global fit** ensuring SMEFT model independence including all $\mathbf{O(\Lambda^{-4})}$ terms
  - **single operator** fit with all other **coefficients profiled** (free-floating in fit)
- **Profiled** constraints are up to **10x less stringent** wrt **individual** ones
- $\mathbf{Q_W}$ **-induced anomalies** uncorrelated with other operators



Global fit

Profiled constraints



Comparison between profiled and individual expected constraints on the Wilson coefficients from the combination of the leptonic VZZ/VZγ channels

Profiled fit:

All the coefficients
(except for the one of interest)

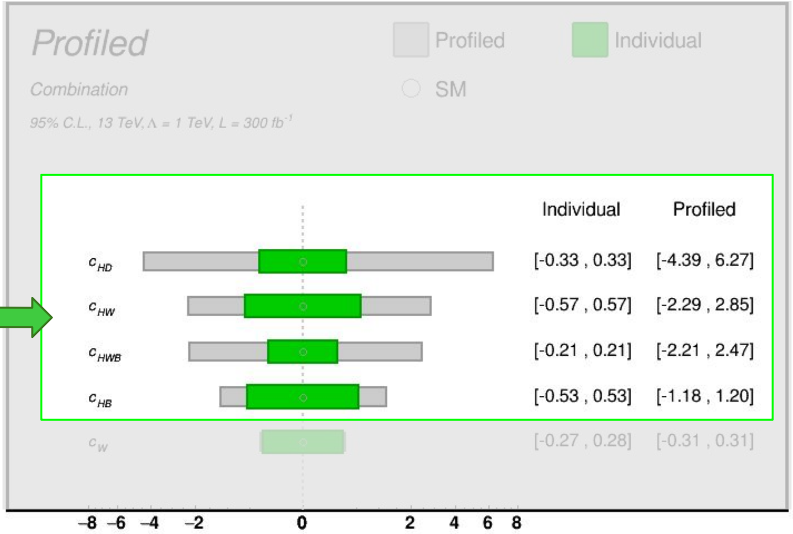
floating parameters

Unconstrained nuisances
with a **flat prior**
in the maximum range (-20, 20).

Global fit

Profiled constraints

decrease in the sensitivity of the profiled fit with respect to the individual constraints



	Individual	Profiled
c_{HD}	[-0.33 , 0.33]	[-4.39 , 6.27]
c_{HW}	[-0.57 , 0.57]	[-2.29 , 2.85]
c_{HWB}	[-0.21 , 0.21]	[-2.21 , 2.47]
c_{HB}	[-0.53 , 0.53]	[-1.18 , 1.20]
c_W	[-0.27 , 0.28]	[-0.31 , 0.31]

Comparison between profiled and individual expected constraints on the Wilson coefficients from the combination of the leptonic VZZ/VZγ channels

<u>Profiled fit</u>:

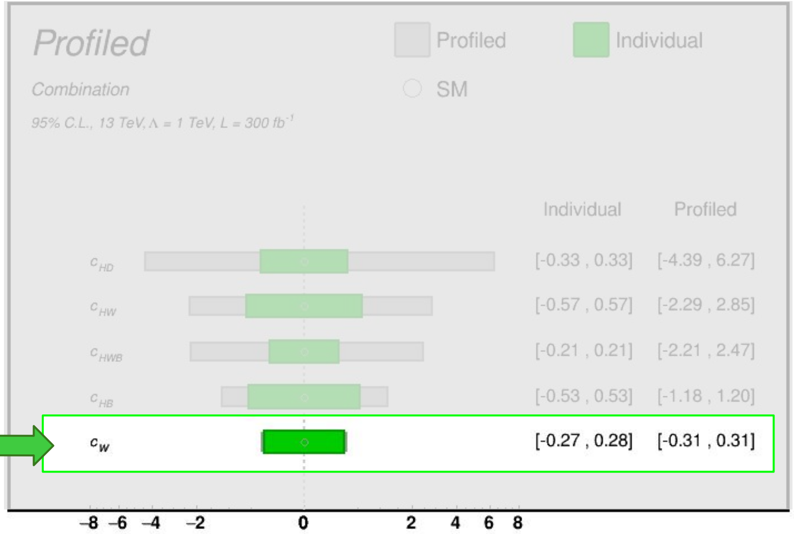
All the coefficients (except for the one of interest)

floating parameters

Unconstrained nuisances with a **flat prior** in the maximum range (-20, 20).

Global fit

Profiled constraints



Q_W effects **uncorrelated** with the other operators

Comparison between profiled and individual expected constraints on the Wilson coefficients from the combination of the leptonic VZZ/VZγ channels

Profiled fit:

All the coefficients (except for the one of interest)

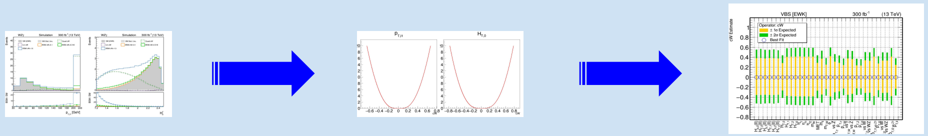
floating parameters

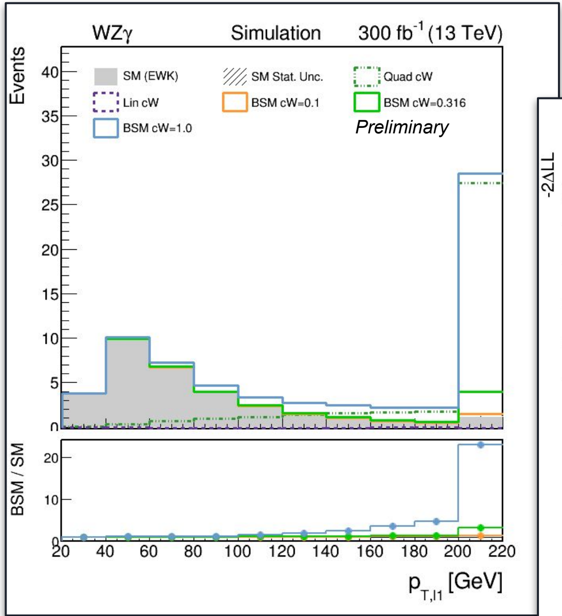
Unconstrained nuisances with a **flat prior** in the maximum range (-20, 20).

Shape analysis

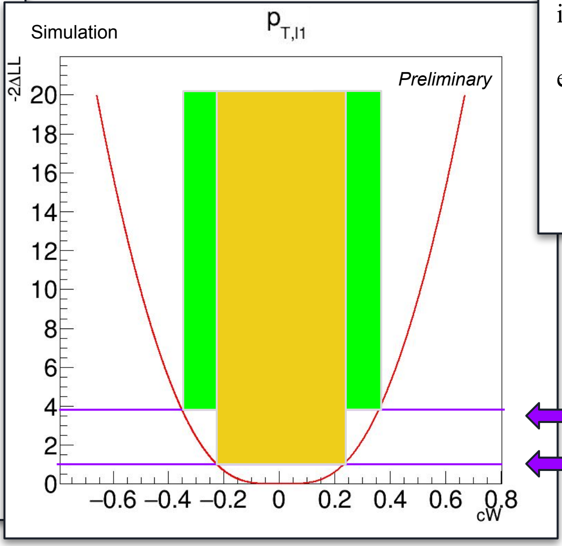
Likelihood scan

Q_W





SM and SM+EFT event distributions as a function of the leading lepton transverse momentum (fully leptonic WZγ channel)



Likelihood scan with respect to $p_{T,l1}$

$-2\Delta LL = -2[log\mathcal{L}(c_i) - log\mathcal{L}_{\mathrm{MAX}}]$

Likelihood scan: for each variable evaluation of the likelihood varying a single Wilson coefficient in a fixed range

e.g.: $\mathcal{L}(c_W) = \prod_k \frac{(N_k(c_W))^{n_k}}{n_k!} \cdot e^{-N_k(c_W)}$

where $n_k = N_k(0)$

with $\frac{c_W}{(1\ \mathrm{TeV})^2} \epsilon [-1.5, 1.5]$

$95\%\ C.L. \rightarrow -2\Delta log\mathcal{L} < 3.84$

$68\%\ C.L. \rightarrow -2\Delta log\mathcal{L} < 1$

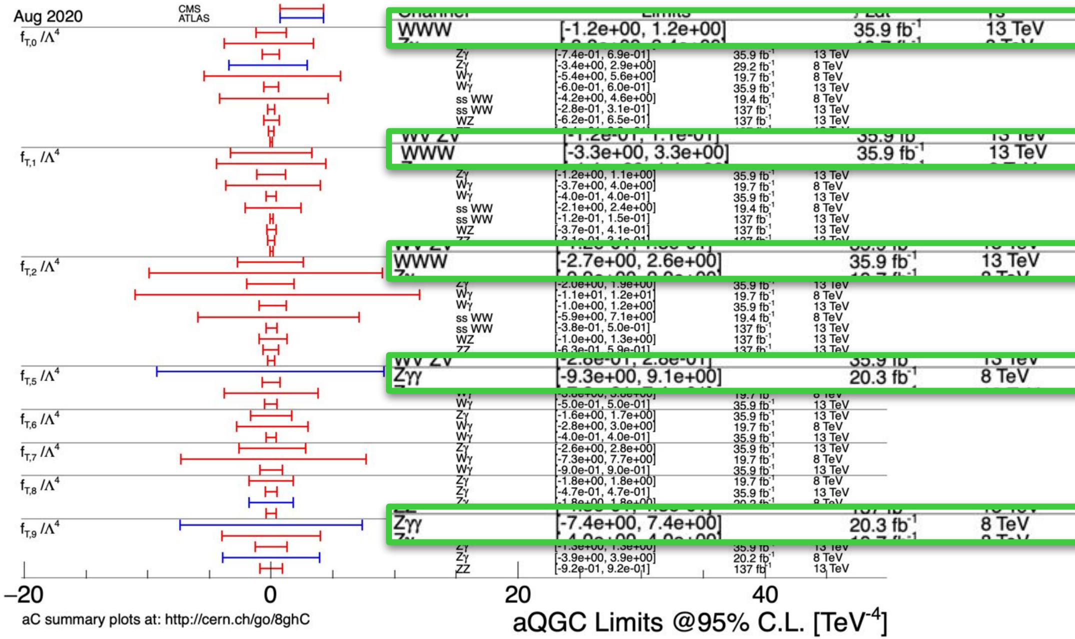
Exclusion confidence intervals on the Wilson coefficient

Motivation for dim.-6 EFT sensitivity study

- **Interpretation** of **triboson results** *traditionally* in terms of **dim-8 SMEFT operators (aQGCs)** at the LHC

- However, **dim-6 EFT operators** can have an impact on triboson production processes too!

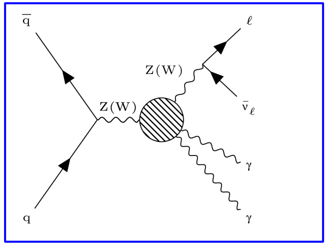
- **First LHE sensitivity** study **of VBS +WW** [JHEP05(2022)039] including **O(Λ^{-4}) dim-6** EFT terms
  → **extended to triboson processes**



- Recently: [JHEP10(2021)174] → new stringent EFT constraints from CMS $V\gamma\gamma$ analysis (more details in backup)

$V\gamma\gamma$

Results: SM & aQGCs

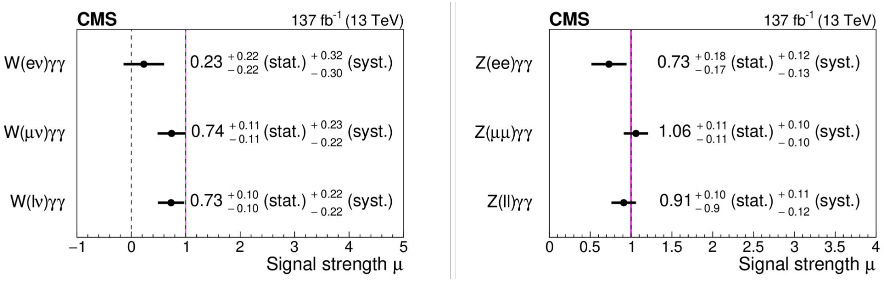


Example of BSM diagram affected by aQGC

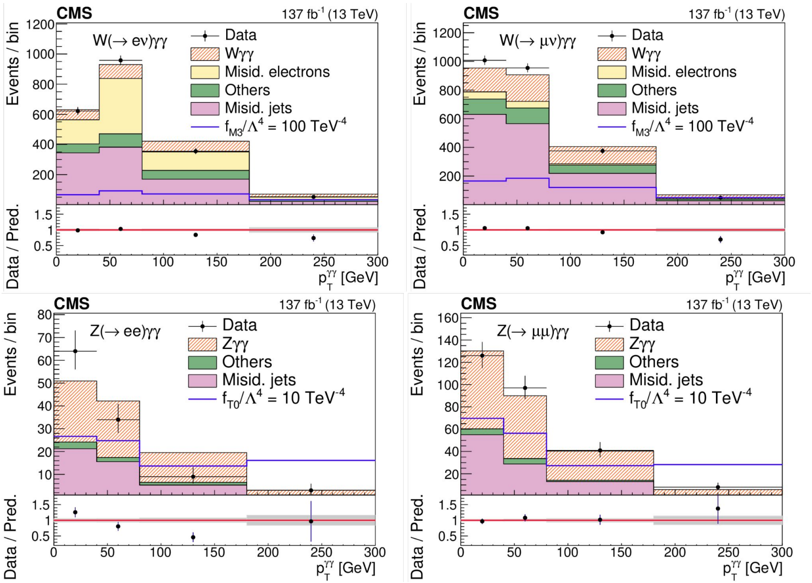
Measured cross section:

$\sigma_{W\gamma\gamma} = 13.63^{+1.93}_{-1.89}(\text{stat.})^{+4.04}_{-4.02}(\text{syst.}) \pm 0.08(\text{PDF+scale})$ — 3.1 S.D

$\sigma_{Z\gamma\gamma} = 5.41^{+0.58}_{-0.55}(\text{stat.})^{+0.64}_{-0.70}(\text{syst.}) \pm 0.06\ (\text{PDF+scale})$ — 4.8 S.D



[JHEP 10 (2021) 174]



Parameter	$W\gamma\gamma$ (TeV^{-4}) Expected	$W\gamma\gamma$ (TeV^{-4}) Observed	$Z\gamma\gamma$ (TeV^{-4}) Expected	$Z\gamma\gamma$ (TeV^{-4}) Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	—	—	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	—	—	[−1.54, 1.54]	[−1.82, 1.82]

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