IFAE 2023
Incontri di Fisica delle Alte Energie

Catania, Aprile 2023

[English version below]

Studio di sensibilità di processi di produzione tribosonica ad operatori EFT di dimensione 6

Tratto da
arXiv:2303.18215v1
[hep-ph] 31 Mar 2023

INFN SEZIONE DI TORINO

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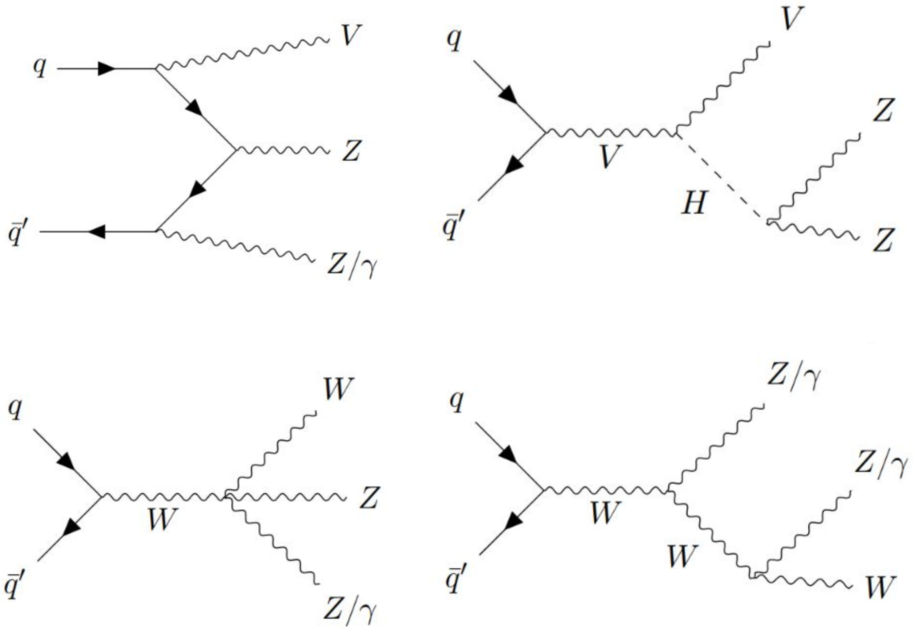
UNIVERSITÀ DI TORINO

Introduzione

Processi di produzione tribosonica

- ❖ Produzione tribosonica da urti protone-protone a 13 TeV
  - ➢ processi rari predetti dal **Modello Standard**



– Diagrammi di Feynman inclusi nei canali **VZγ/VZZ**

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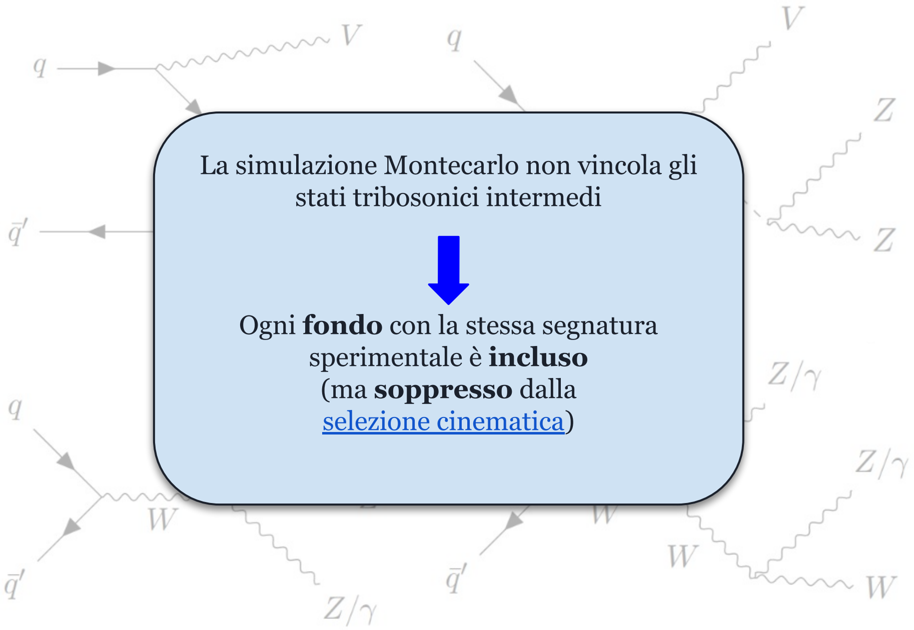
WZγ	ZZγ
pp(→ WZγ)→ $\mu^{\pm}\overset{(-)}{\nu}_{\mu}e^{+}e^{-}\gamma$	pp(→ ZZγ)→ $\mu^{+}\mu^{-}e^{+}e^{-}\gamma$
VZγ	**VZZ**
pp(→ VZγ)→ jj’ $l^{+}l^{-}\gamma$	pp(→ VZZ)→ jj’ $\mu^{+}\mu^{-}e^{+}e^{-}$



La simulazione Montecarlo non vincola gli stati tribosonici intermedi

⬇

Ogni **fondo** con la stessa segnatura sperimentale è **incluso** (ma **soppresso** dalla selezione cinematica)

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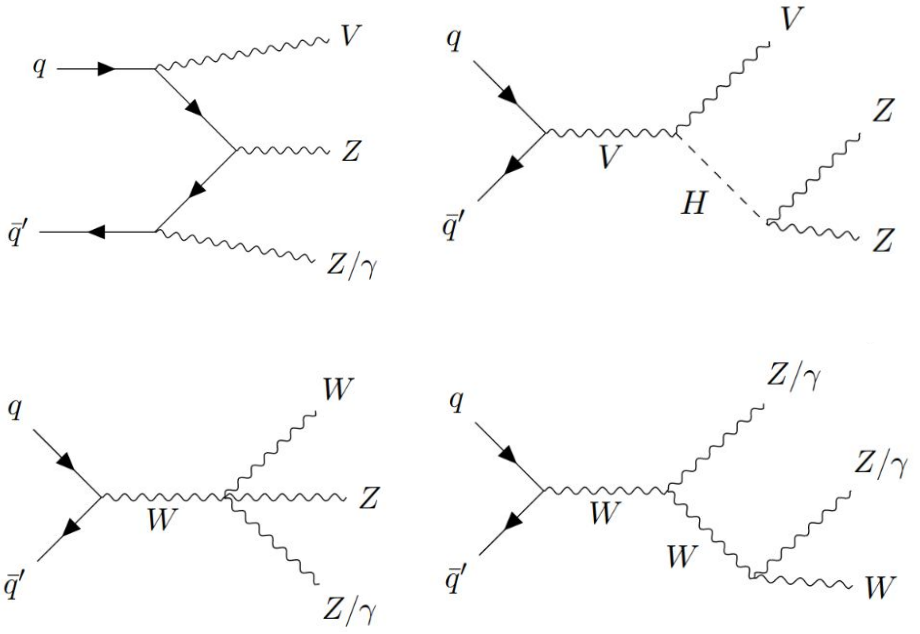

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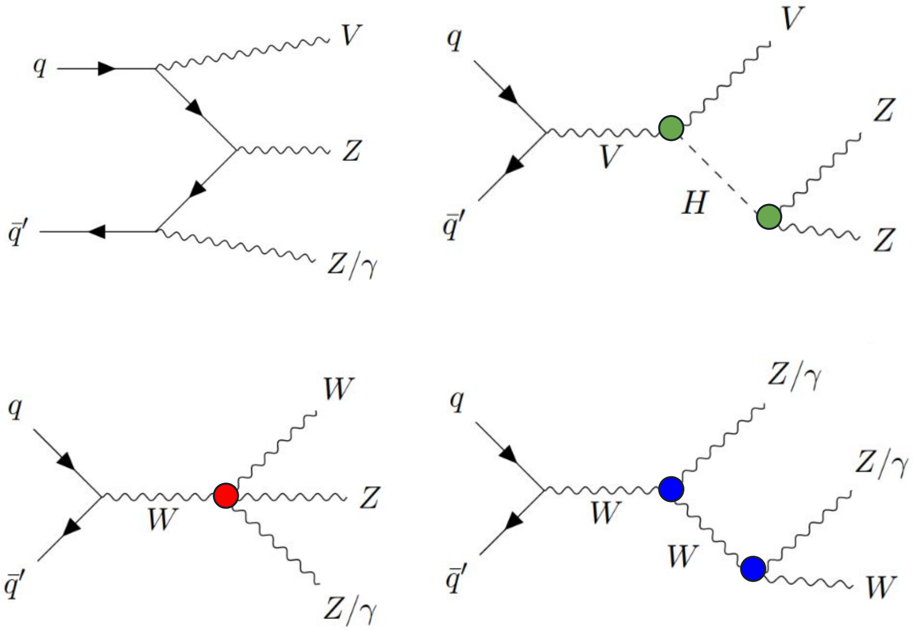
- Test fondamentale del **settore elettrodebole** del Modello Standard
  - Accoppiamenti di gauge tripli, quartici e con il bosone di Higgs



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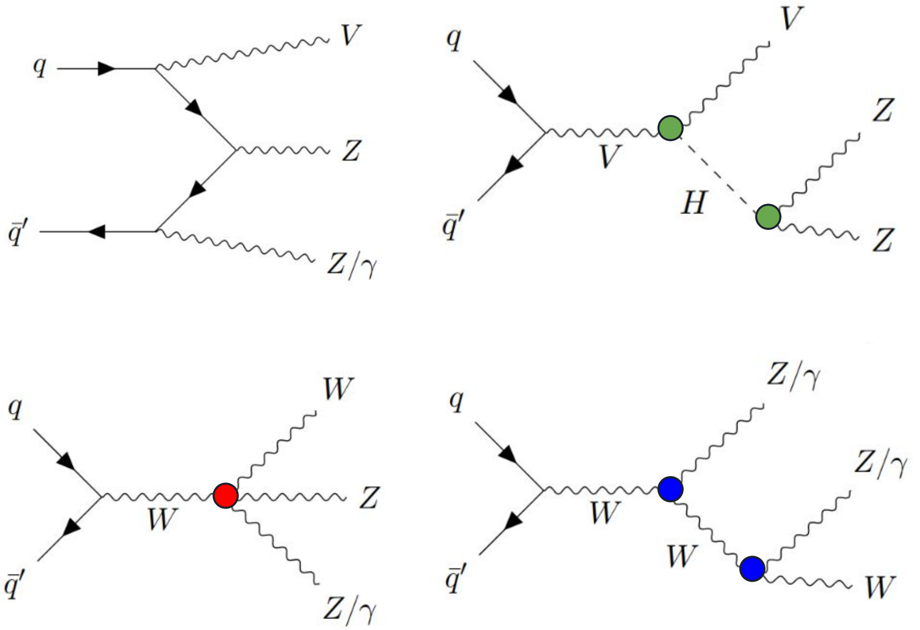
  - Accoppiamenti di gauge tripli, quartici e con il bosone di Higgs
- Potenziali anomalie che aprirebbero a **nuova fisica**
  - studi **SM-EFT**



– Diagrammi di Feynman inclusi nei canali **VZγ/VZZ**

Teorie Efficaci di Campo (EFT)

Operatori di dimensione 6

Approccio modello-independente: framework **SM-EFT**

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

← Dim. $n > 4$

Scala di nuova fisica (Λ = 1 TeV)

coefficienti di Wilson

Effetto di un singolo operatore di dimensione 6, es. Q_W :

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

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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_{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}	$(\bar{l}_p\sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
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$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p \gamma^\mu d_r)$

Operatori di dim. 6 dalla base di Varsavia [2]

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

Operatori di dim. 6 studiati dalla base di Varsavia [2]

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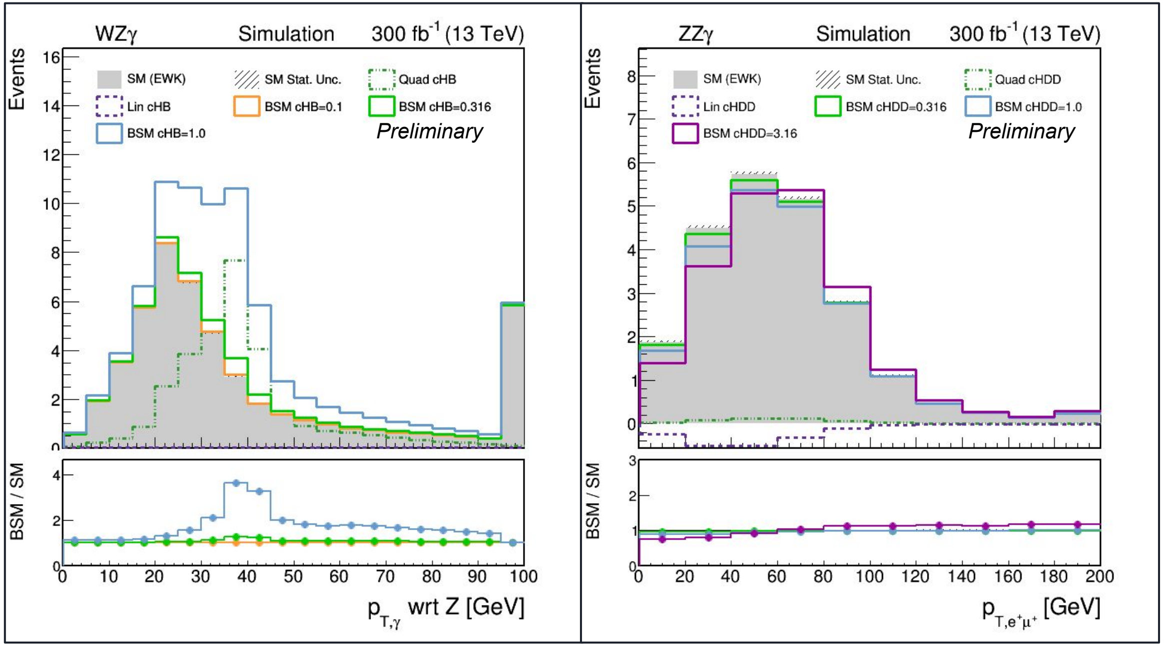
Analisi delle distribuzioni

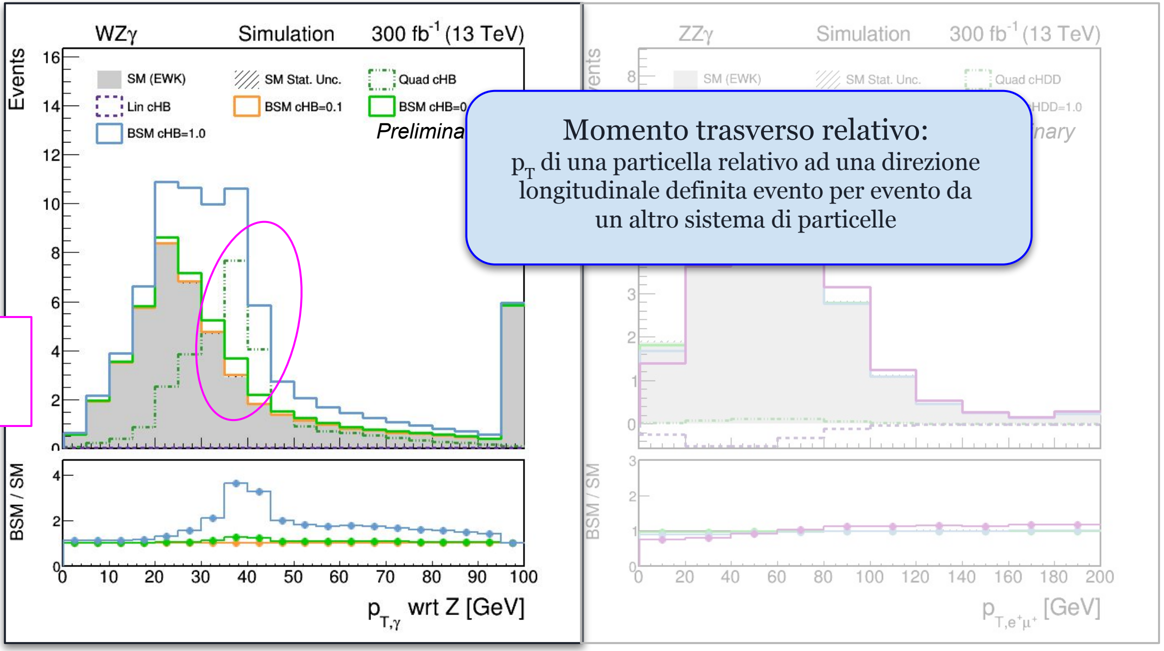
Effetto di un singolo operatore



Esempi di variabili di interesse particolarmente sensibili e delle corrispondenti distribuzioni di eventi attese a partire dal Modello Standard e aggiungendo le componenti EFT, per i canali totalmente leptonici WZγ e ZZγ

Analisi delle distribuzioni

Effetto di un singolo operatore



Momento trasverso relativo:
p_T di una particella relativo ad una direzione longitudinale definita evento per evento da un altro sistema di particelle

Alta sensibilità agli effetti indotti da Q_{HB}

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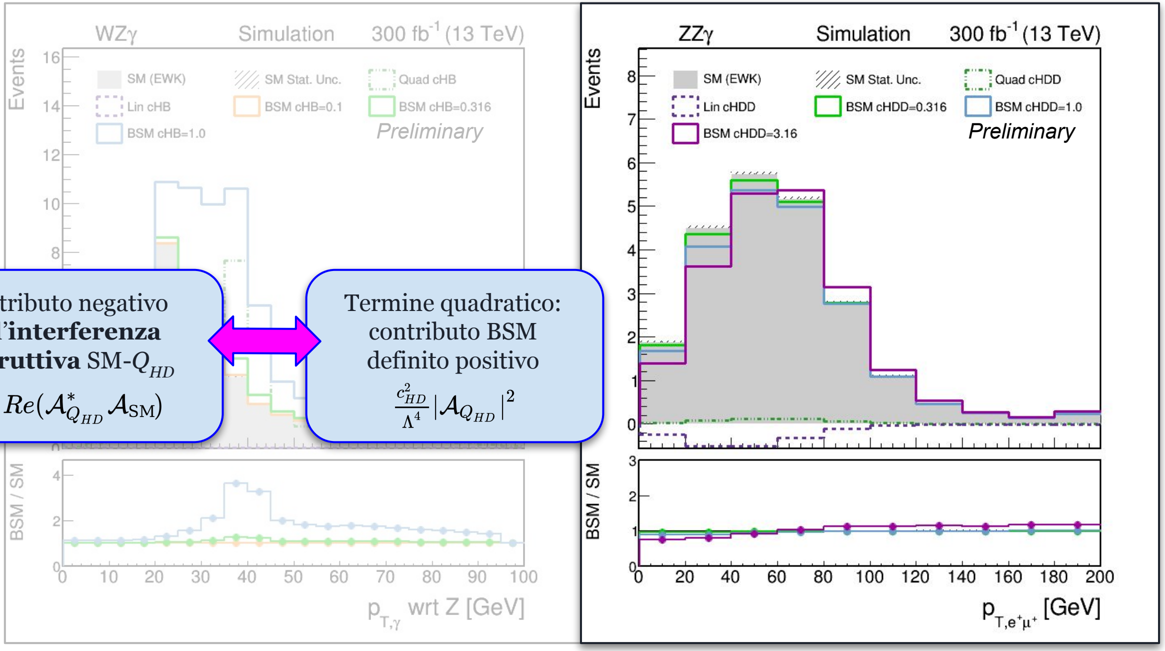

Contributo negativo dell'**interferenza distruttiva** SM-Q_{HD}

$$\frac{c_{HD}}{\Lambda^2} Re(\mathcal{A}^*_{Q_{HD}} \mathcal{A}_{SM})$$

Termine quadratico: contributo BSM definito positivo

$$\frac{c^2_{HD}}{\Lambda^4} |\mathcal{A}_{Q_{HD}}|^2$$

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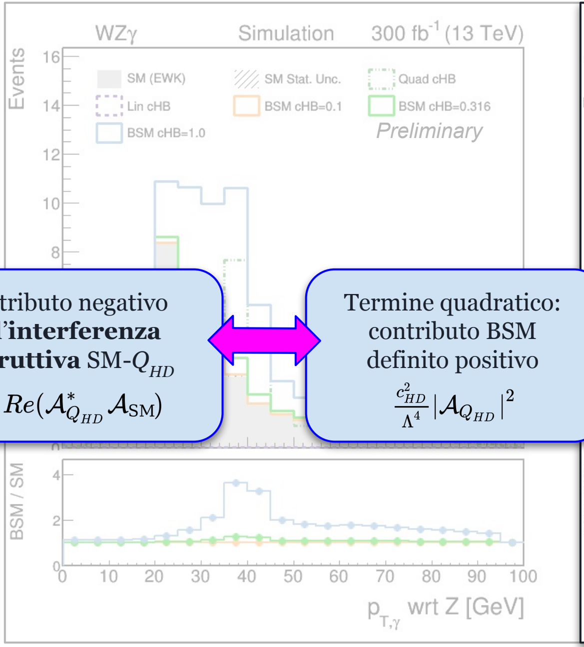

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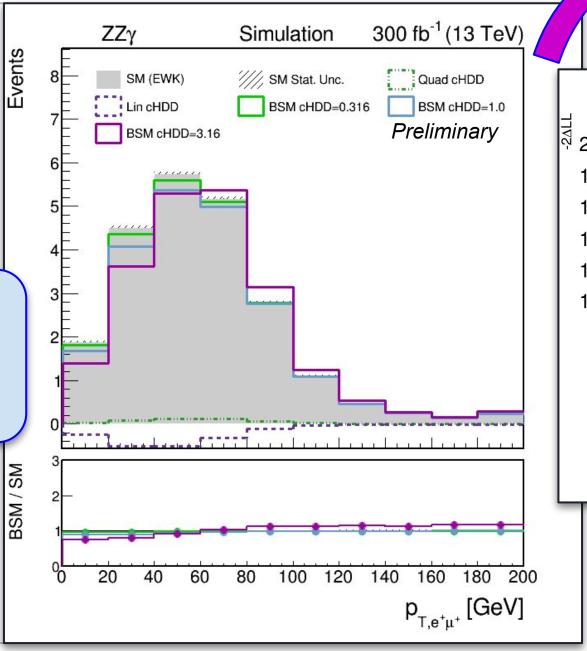
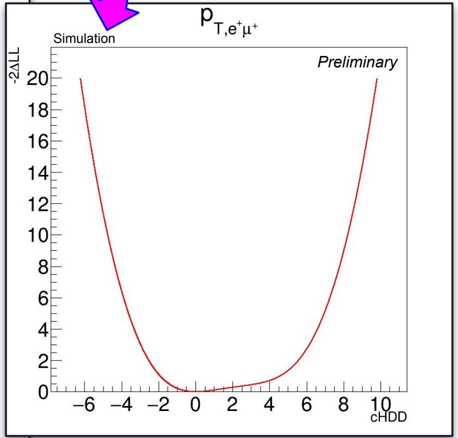


Conseguenza: **asimmetria** evidente nel likelihood scan



Likelihood scan relativo a c_{HD} per il canale ZZγ

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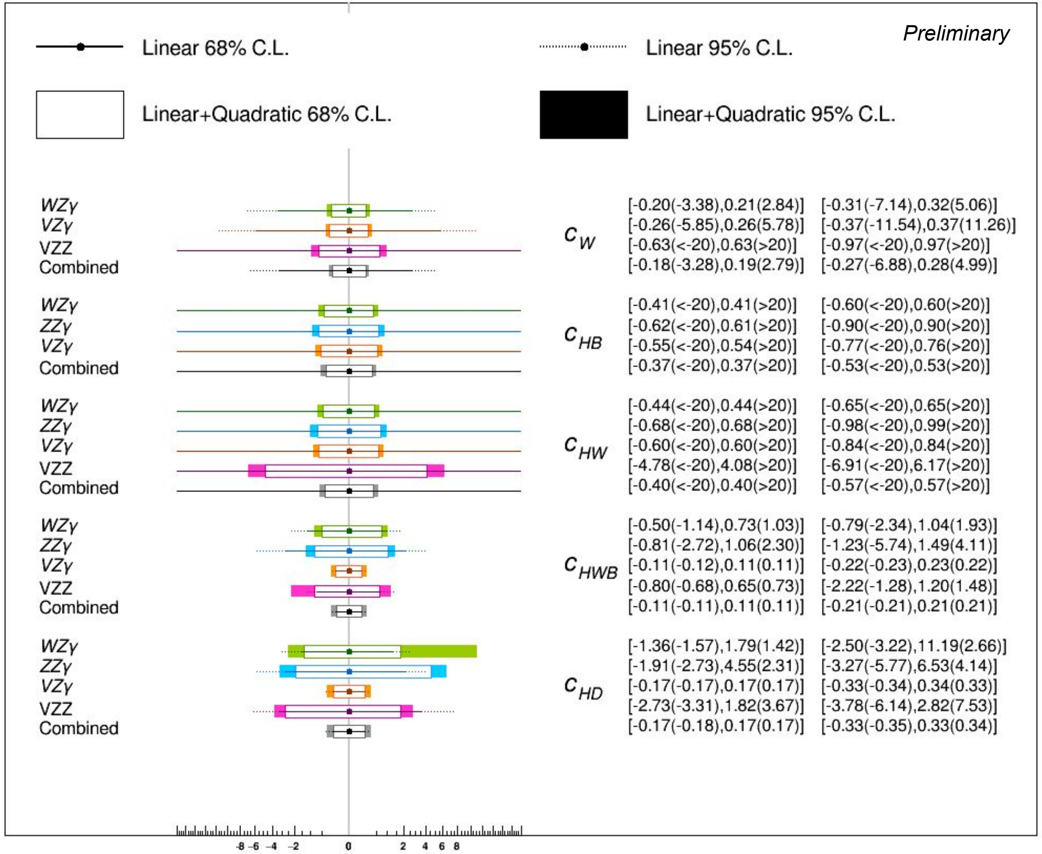
Limiti sui singoli coefficienti



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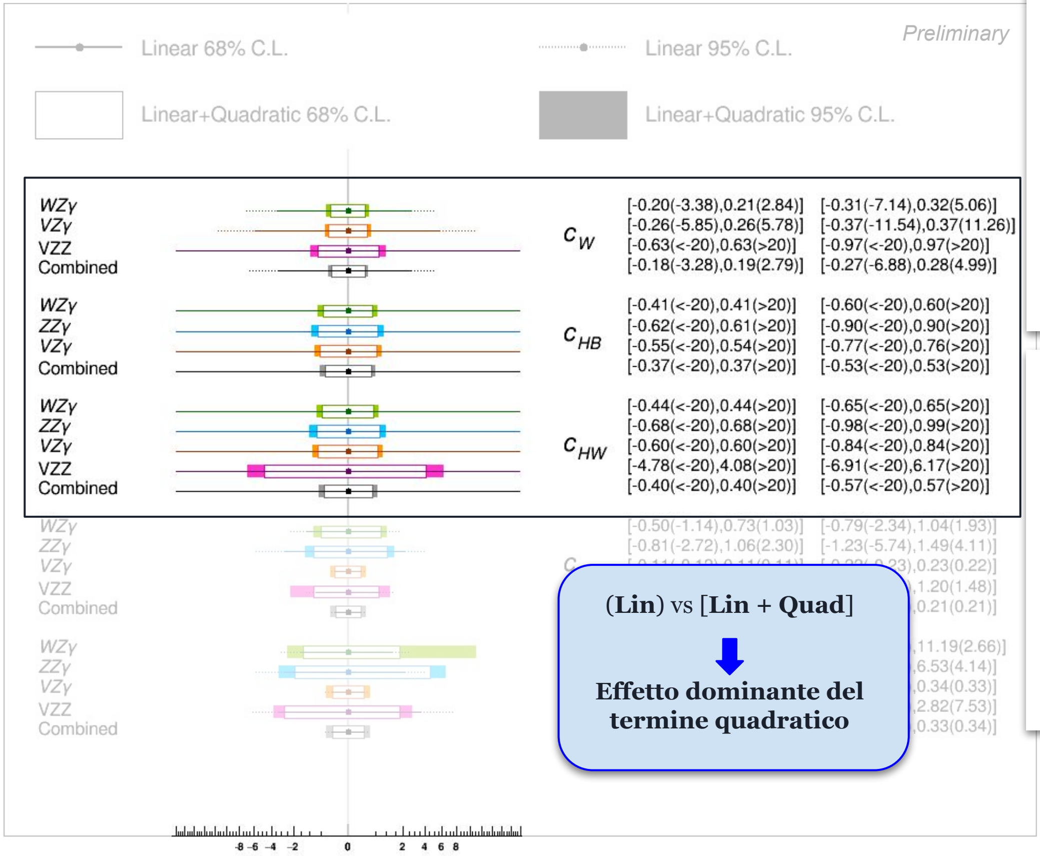

(Lin) vs [Lin + Quad]

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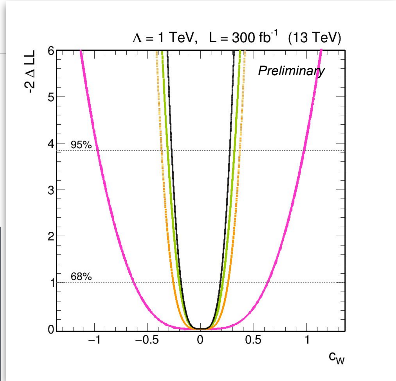
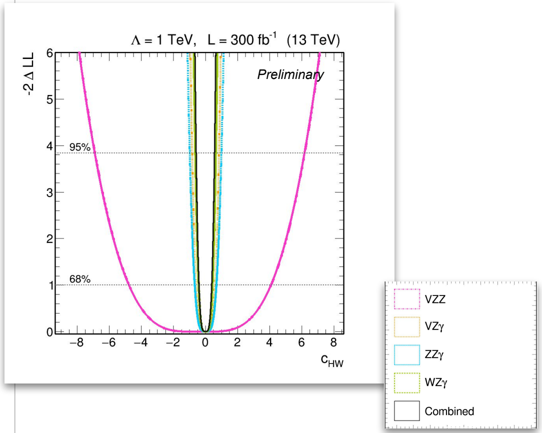
Effetto dominante del termine quadratico





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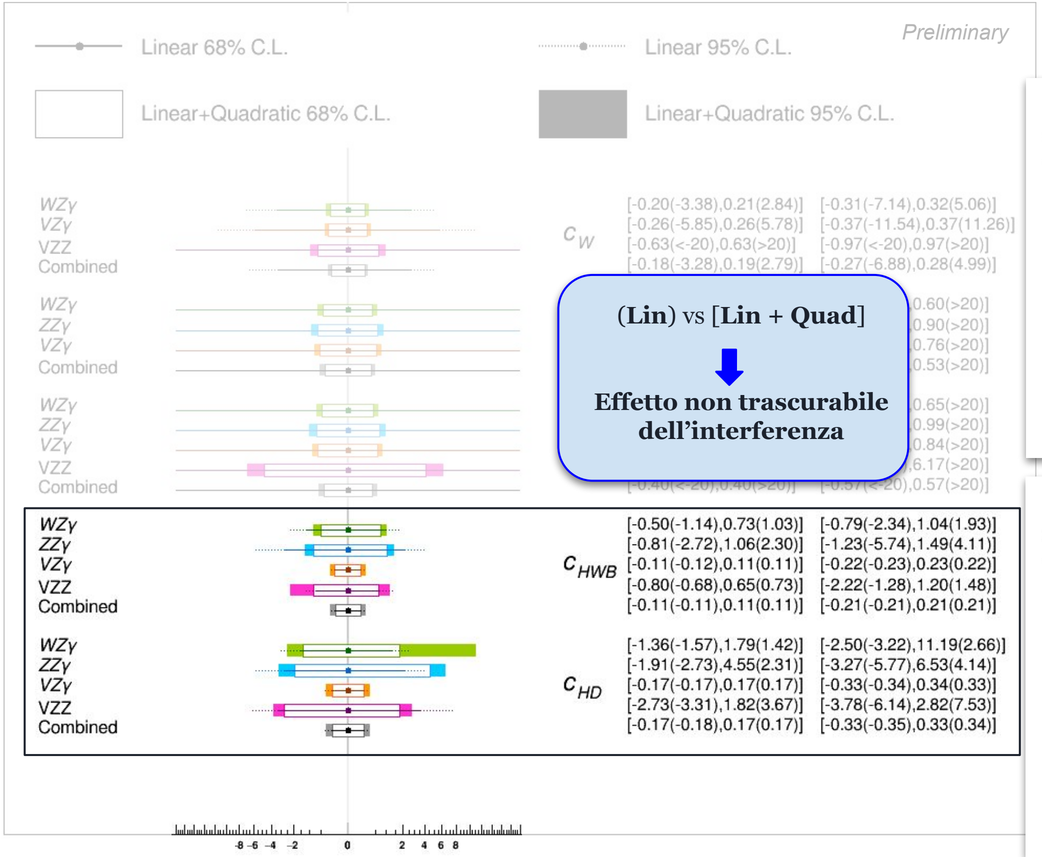

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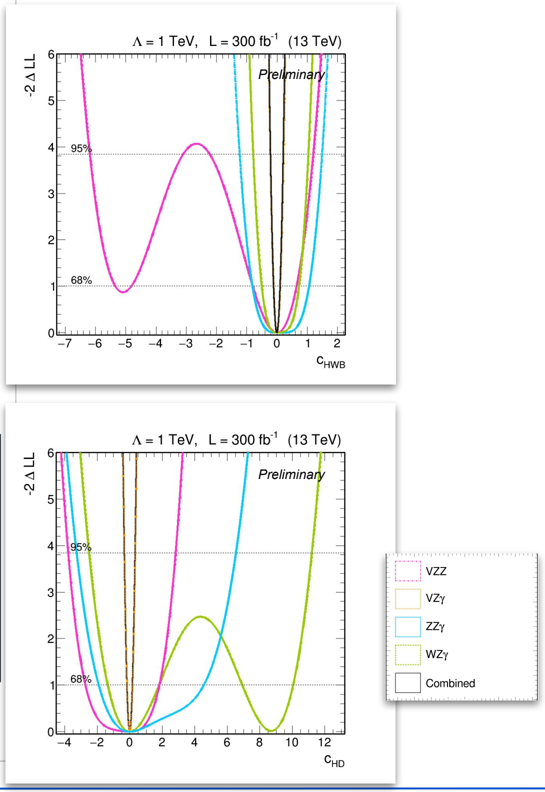
Effetto non trascurabile dell'interferenza



Aree di confidenza 2D

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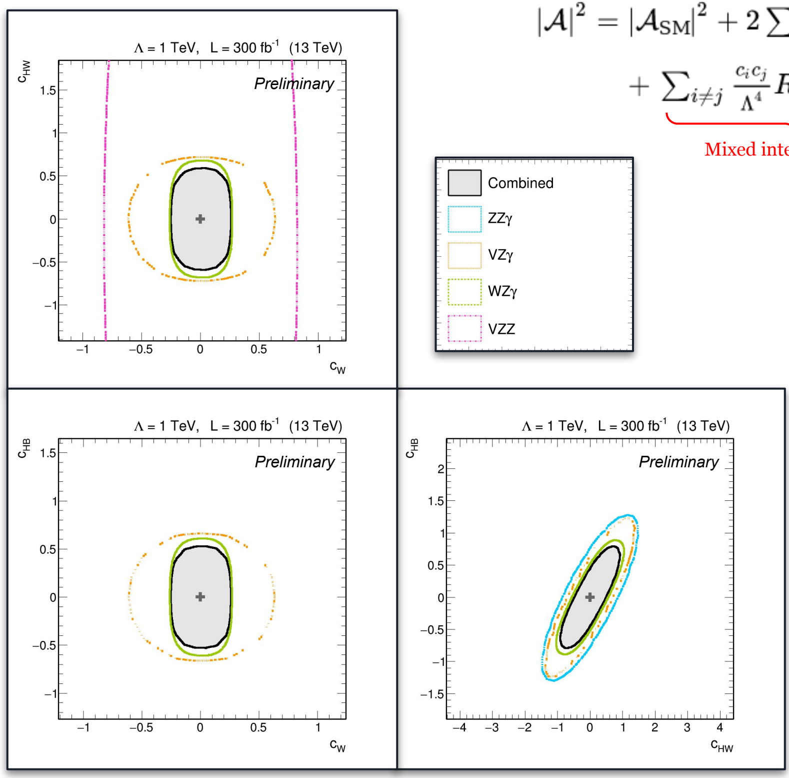
Esempi di **contorni** delle **aree di esclusione** al 68 % C.L. per coppie di coefficienti di Wilson

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

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



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[matrice completa {Qi,Qj}]

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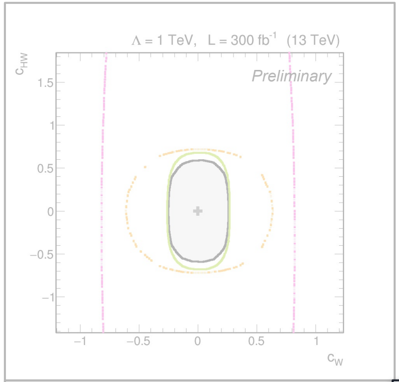

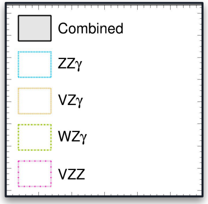

Termine di mutua interferenza: Responsabile della correlazione fra le stime dei coefficienti

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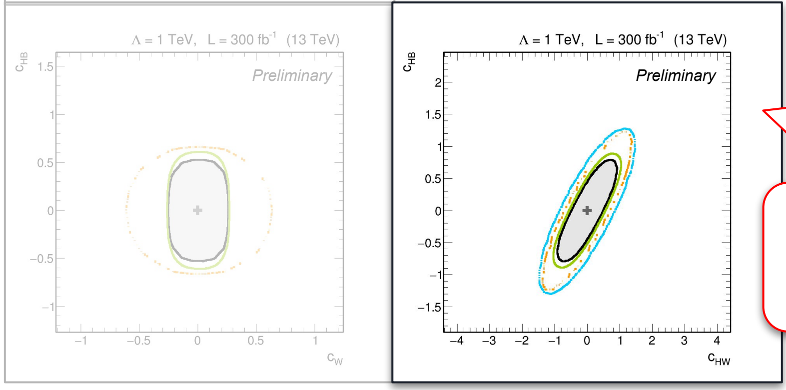

$Q_W = \epsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$ $\quad Q_{\phi W} = \phi^\dagger \phi\, W^I_{\mu\nu} W^{I\mu\nu}$

Q_{HB}-Q_{HW}

Ruolo rilevante dell'interferenza

[matrice completa {Qi,Qj}]

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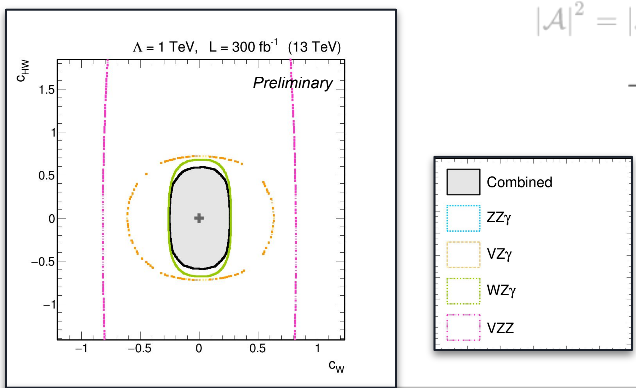

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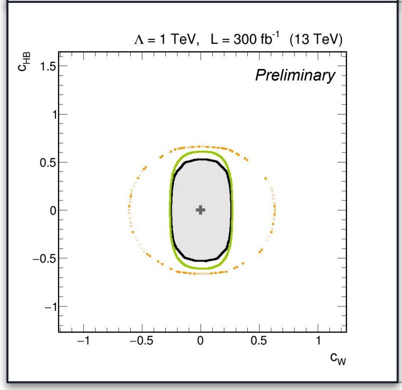
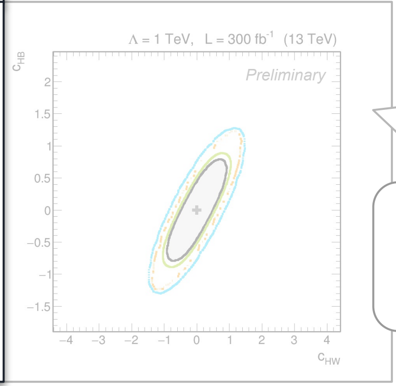




$Q_W = \epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$ $\qquad Q_{\phi W} = \phi^\dagger \phi\, W^I_{\mu\nu} W^{I\mu\nu}$

Q_W-$Q_{HB(W)}$

Mutua interferenza **trascurabile**

↓

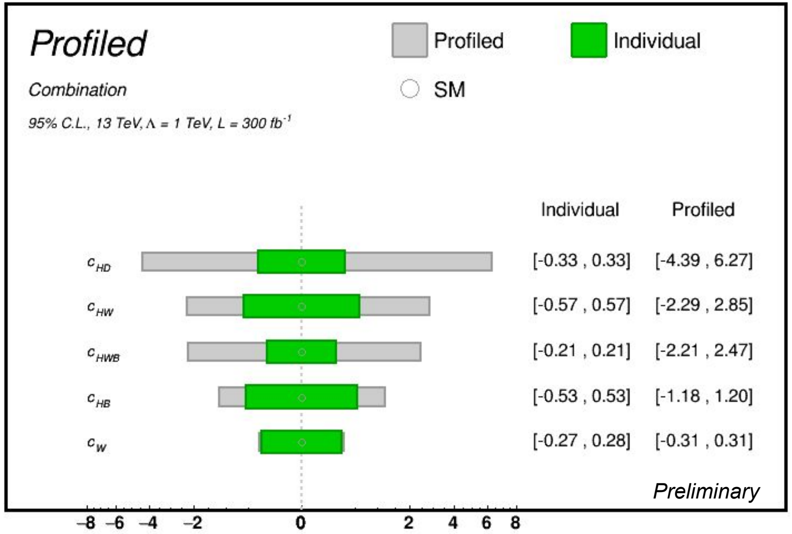
Contorno:
Forma ellittica centrata e simmetrica

Q_{HB}-Q_{HW}

Ruolo rilevante dell'interferenza

[matrice completa {Qi,Qj}]

Fit globale
Limiti profilati



Confronto tra i limiti attesi profilati e individuali sui coefficienti di Wilson dalla combinazione dei canali VZZ/VZγ

<u>Likelihood scan profilato:</u>

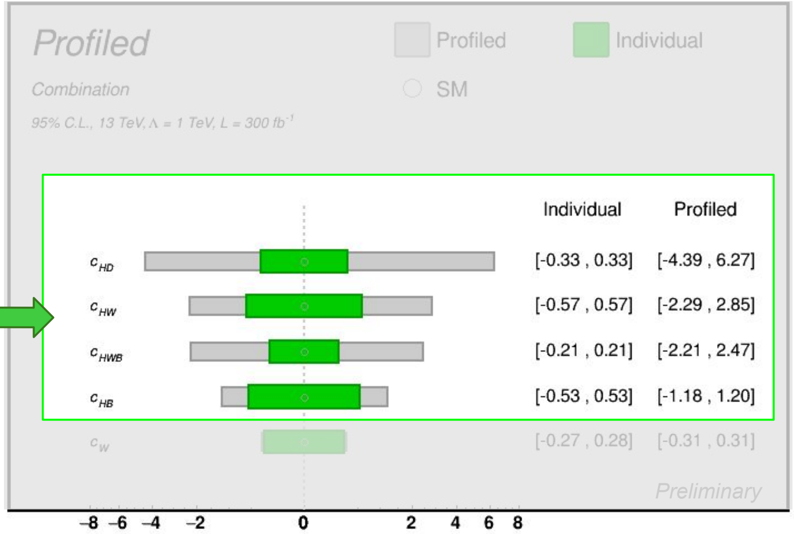
Tutti i coefficienti
(escluso il parametro di interesse)

↓

parametri non vincolati
rispetto ad una **prior uniforme**

Fit globale
Limiti profilati

Minore sensibilità del fit globale rispetto ai limiti individuali



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<u>Likelihood scan profilato:</u>

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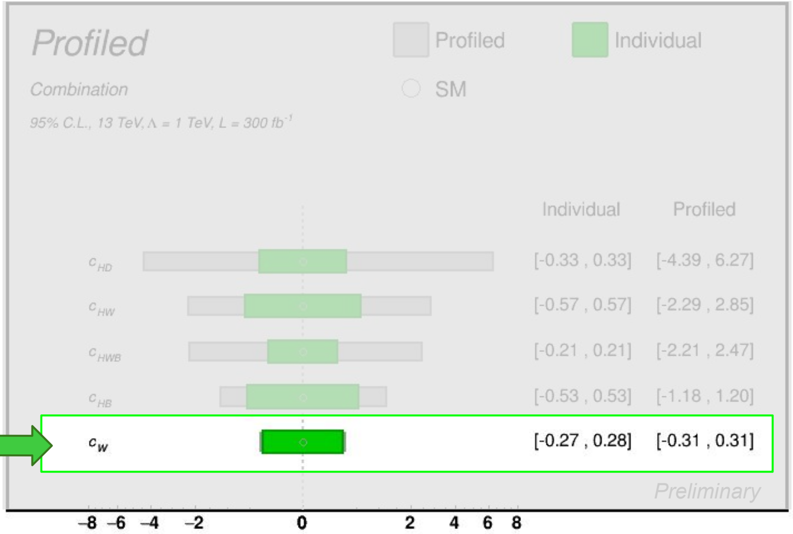
Fit globale

Limiti profilati



Effetti di Q_W **scorrelati** da quelli degli altri operatori

Confronto tra i limiti attesi profilati e individuali sui coefficienti di Wilson dalla combinazione dei canali VZZ/VZγ

Likelihood scan profilato:

Tutti i coefficienti
(escluso il parametro di interesse)

↓

parametri non vincolati
rispetto ad una **prior uniforme**

Conclusioni

- Primo studio fenomenologico degli effetti di operatori EFT di dim. 6 su processi VZZ/VZγ
  - limiti molto competitivi!
  - ruolo fondamentale della combinazione delle diverse analisi

- Prospettive future nel contesto delle EFT:
  - combinazione di analisi dibosoniche e tribosoniche
  - combinazione effetti di operatori di dim. 6 e dim. 8
  - studi a livello ricostruito

Grazie!

Bibliografia

1. R. Bellan et al., A sensitivity study of triboson production processes to dimension-6 EFT operators at the LHC, arXiv preprint arXiv:2303.18215 (2023).

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

3. R. Bellan et al., A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC, 10.1007/JHEP05(2022)039.

4. C. Degrande et al., Effective Field Theory: a modern approach to anomalous couplings, 10.1016/j.aop.2013.04.016

5. I. Brivio, SMEFTsim 3.0 — a practical guide. JHEP, 04:073, 2021.

Catania, Aprile 2023

A sensitivity study of triboson production to dimension-6 EFT operators

Based on
arXiv:2303.18215v1
[hep-ph] 31 Mar 2023

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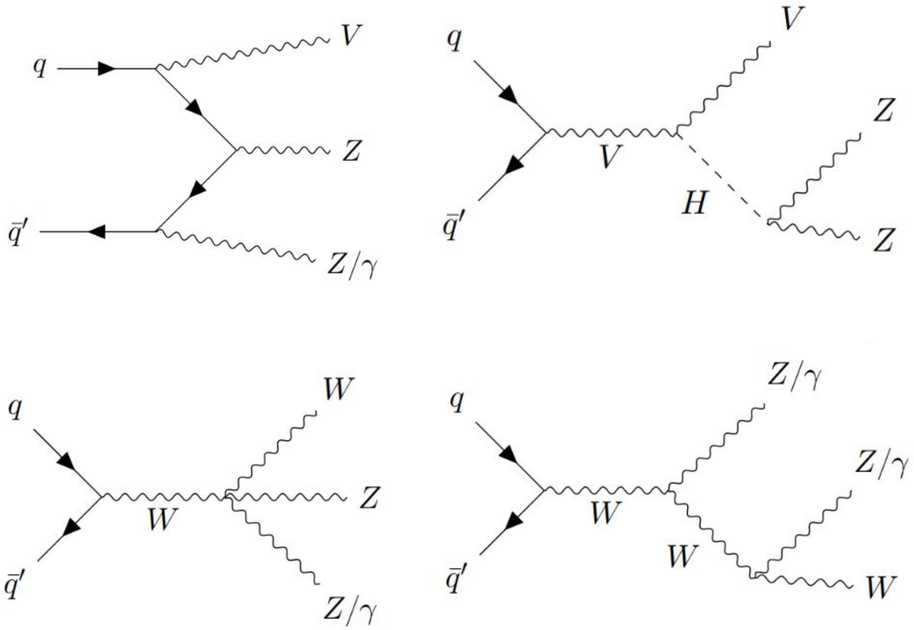
[b]Università degli Studi di Torino

UNIVERSITÀ DI TORINO

Introduction
Triboson production processes

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



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

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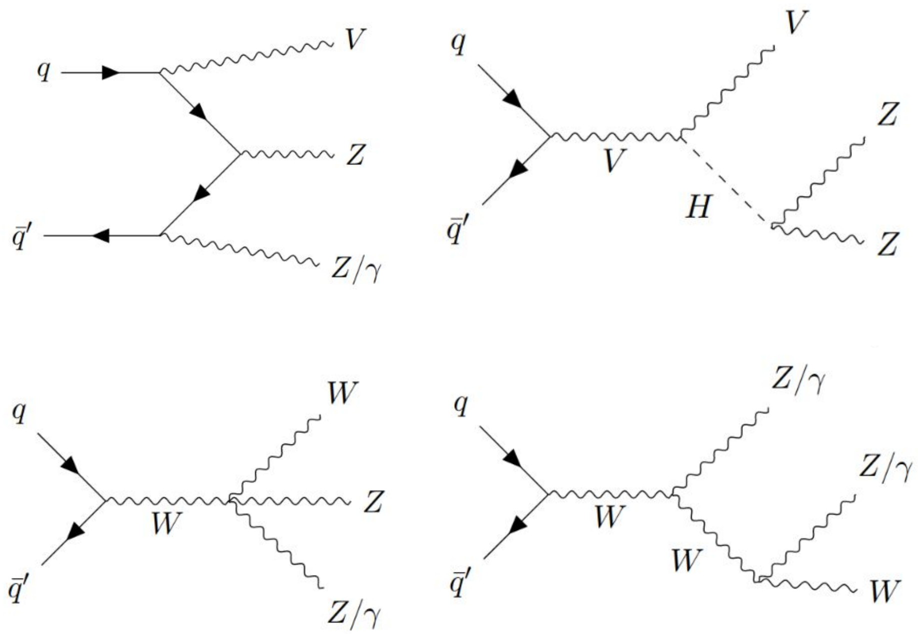
WZγ	**ZZγ**
pp $\rightarrow$ WZγ $\rightarrow \mu^{\pm} \overset{(-)}{\nu}_{\mu} e^{+}e^{-}\gamma$	pp $\rightarrow$ ZZγ $\rightarrow \mu^{+}\mu^{-} e^{+}e^{-}\gamma$
VZγ	**VZZ**
pp $\rightarrow$ VZγ $\rightarrow$ jj' $l^{+}l^{-}\gamma$	pp $\rightarrow$ VZZ $\rightarrow$ jj' $\mu^{+}\mu^{-} e^{+}e^{-}$



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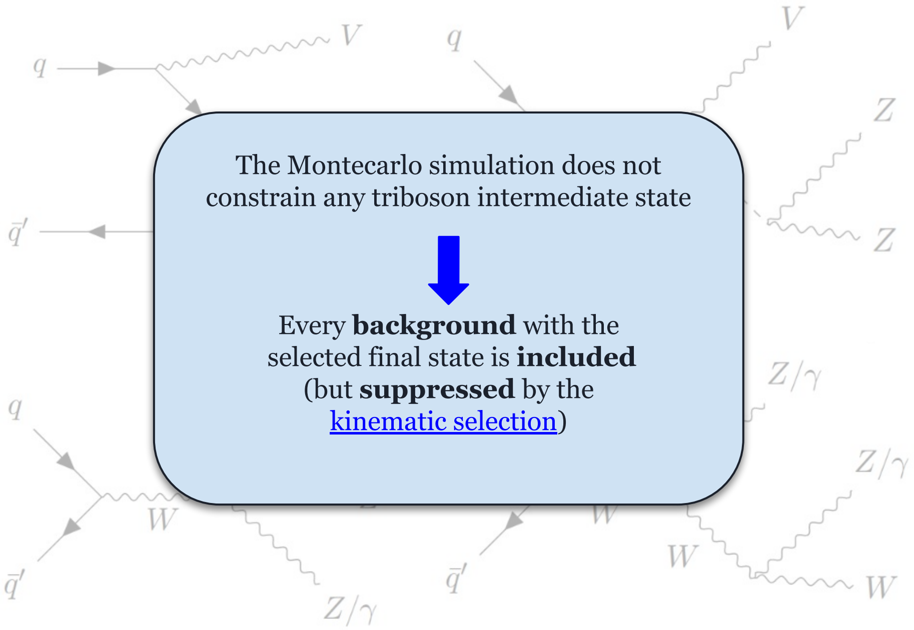
WZγ	ZZγ
pp(→ WZγ)→ $\mu^{\pm} \overset{(-)}{\nu}_{\mu} e^{+}e^{-}\gamma$	pp(→ ZZγ)→ $\mu^{+}\mu^{-} e^{+}e^{-}\gamma$
VZγ	**VZZ**
pp(→ VZγ)→ jj’ $l^{+}l^{-}$ γ	pp(→ VZZ)→ jj’ $\mu^{+}\mu^{-} e^{+}e^{-}$

The Montecarlo simulation does not constrain any triboson intermediate state

Every **background** with the selected final state is **included** (but **suppressed** by the kinematic selection)



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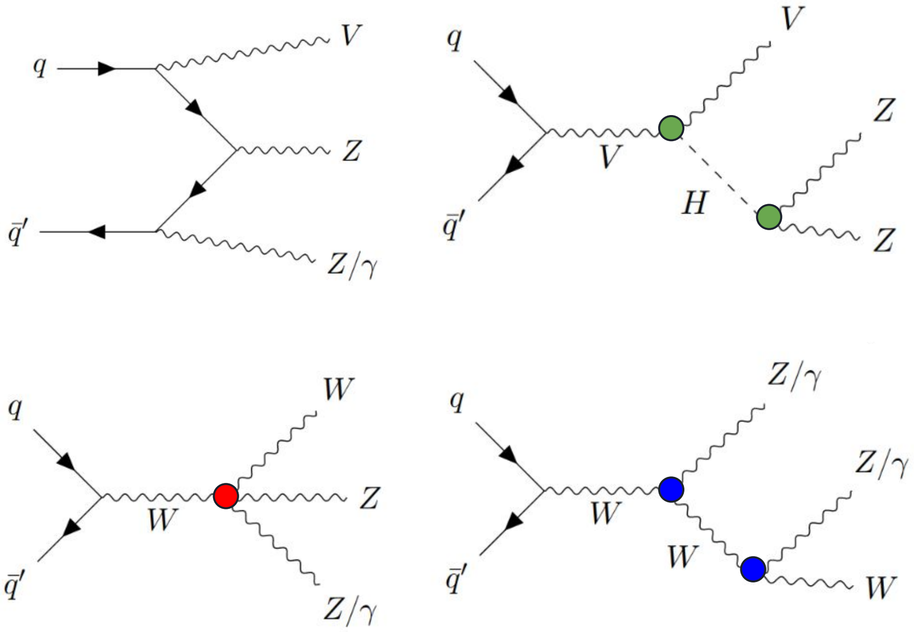
  - Triple and Quartic Gauge Couplings (TGCs, QGCs), and Higgs-gauge bosons couplings



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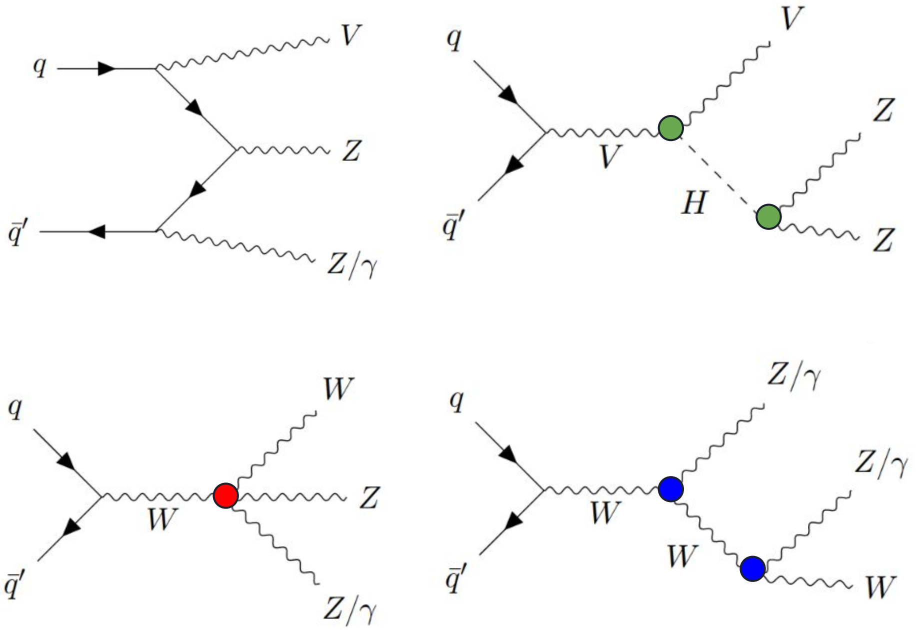
- Potentially anomalies in TGCs and QGCs (aTGC, aQGC) may hint to **new physics**
  - **SM-EFT** studies



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Standard Model-Effective Field Theories

Dimension-6 operators

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

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

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 :

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

Further extension to the effects of couple of operators combined

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

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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}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
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$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	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]

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$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$		

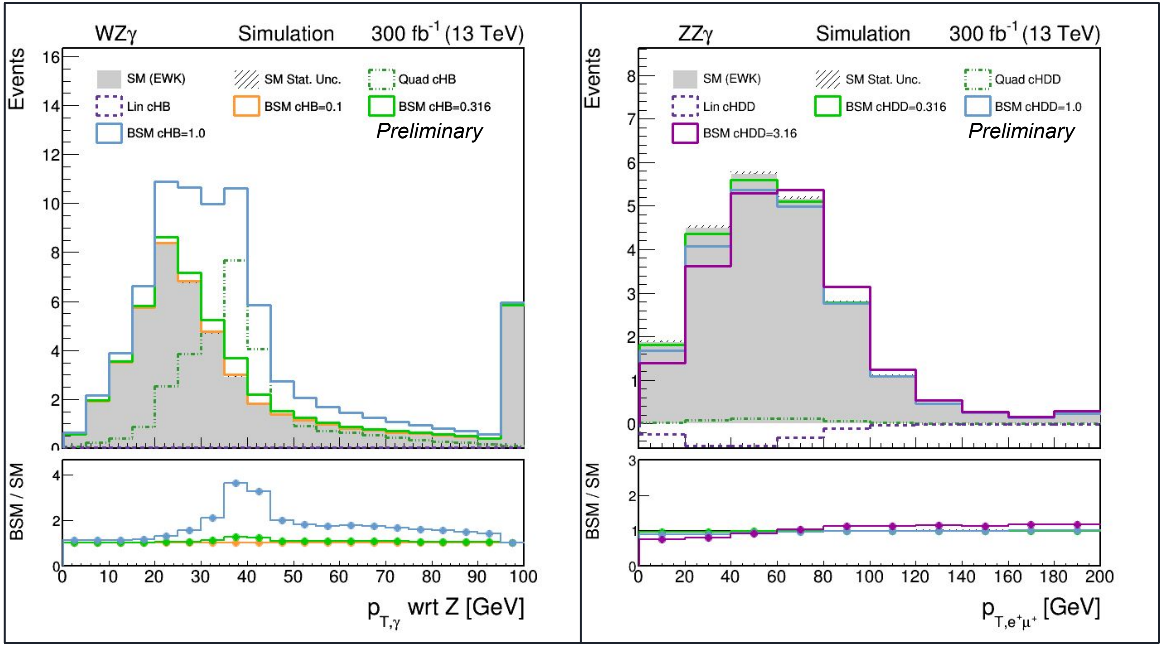
Operators → ↓ Processes	Q_W	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HD}
WZγ	✓	✓	✓	✓	✓
ZZγ		✓	✓	✓	✓
VZγ	✓	✓	✓	✓	✓
VZZ	✓		✓	✓	✓

Dim. 6 operators under study from the Warsaw basis [1]

[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

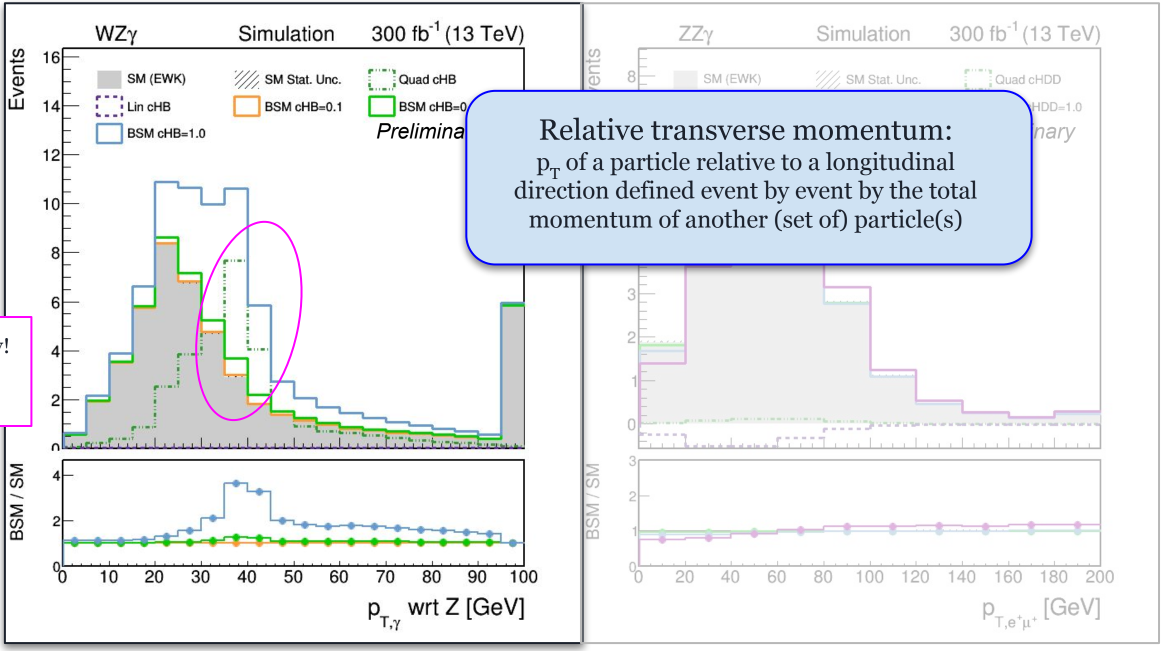


Examples of remarkable variables of interest and the corresponding SM and SM+EFT event distributions for the fully leptonic channels WZγ and ZZγ

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

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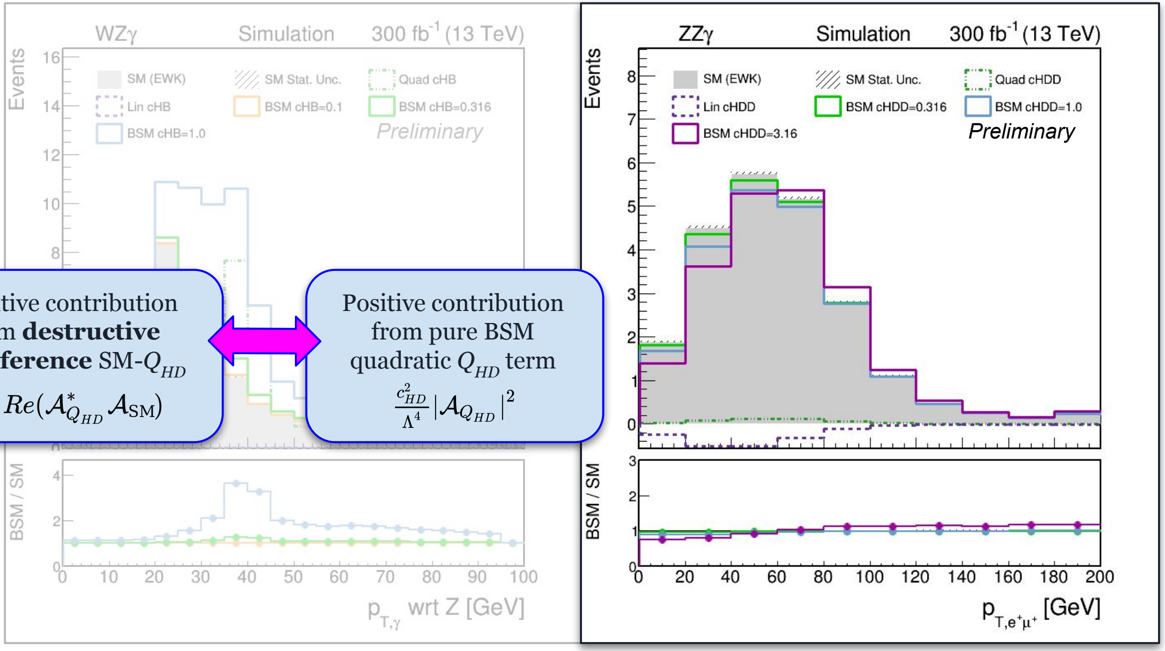
Effects of a single operator



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

$$\frac{c_{HD}}{\Lambda^2} Re(\mathcal{A}^*_{Q_{HD}} \mathcal{A}_{\text{SM}})$$

Positive contribution from pure BSM quadratic Q_{HD} term

$$\frac{c^2_{HD}}{\Lambda^4} |\mathcal{A}_{Q_{HD}}|^2$$

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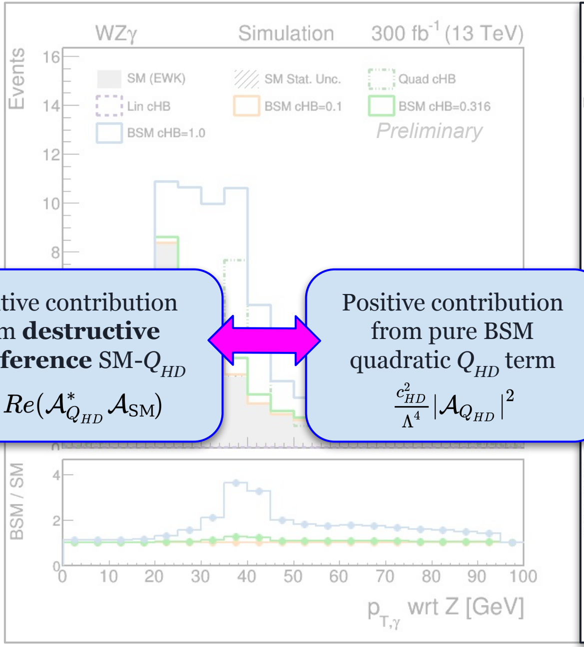

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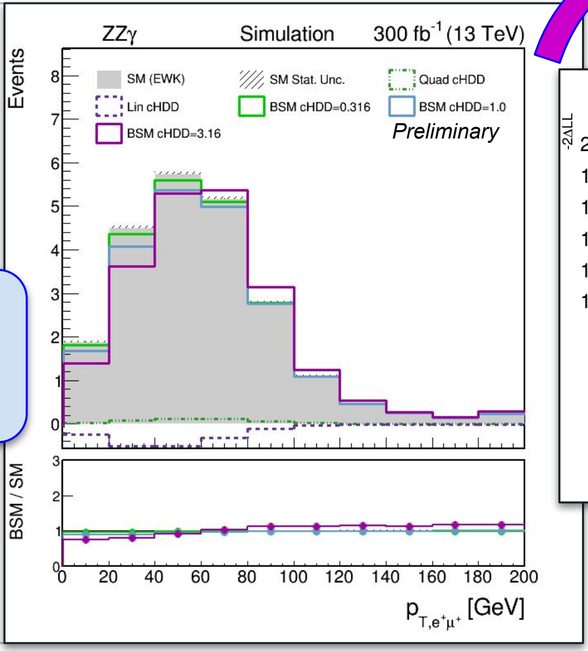
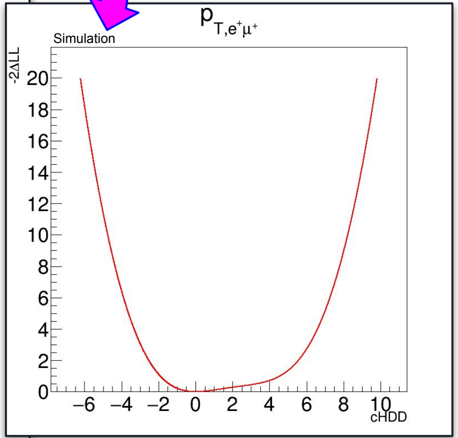


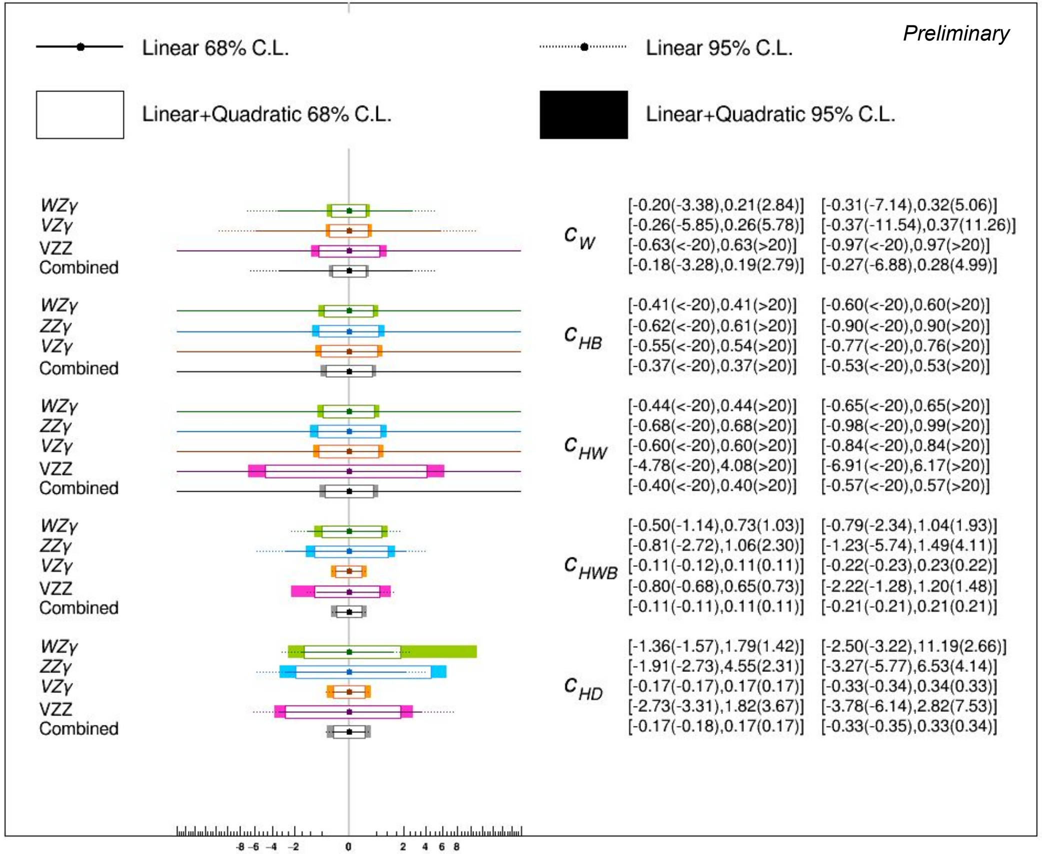
Examples of remarkable variables of interest and the corresponding SM and SM+EFT event distributions for the fully leptonic channels WZγ and ZZγ

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

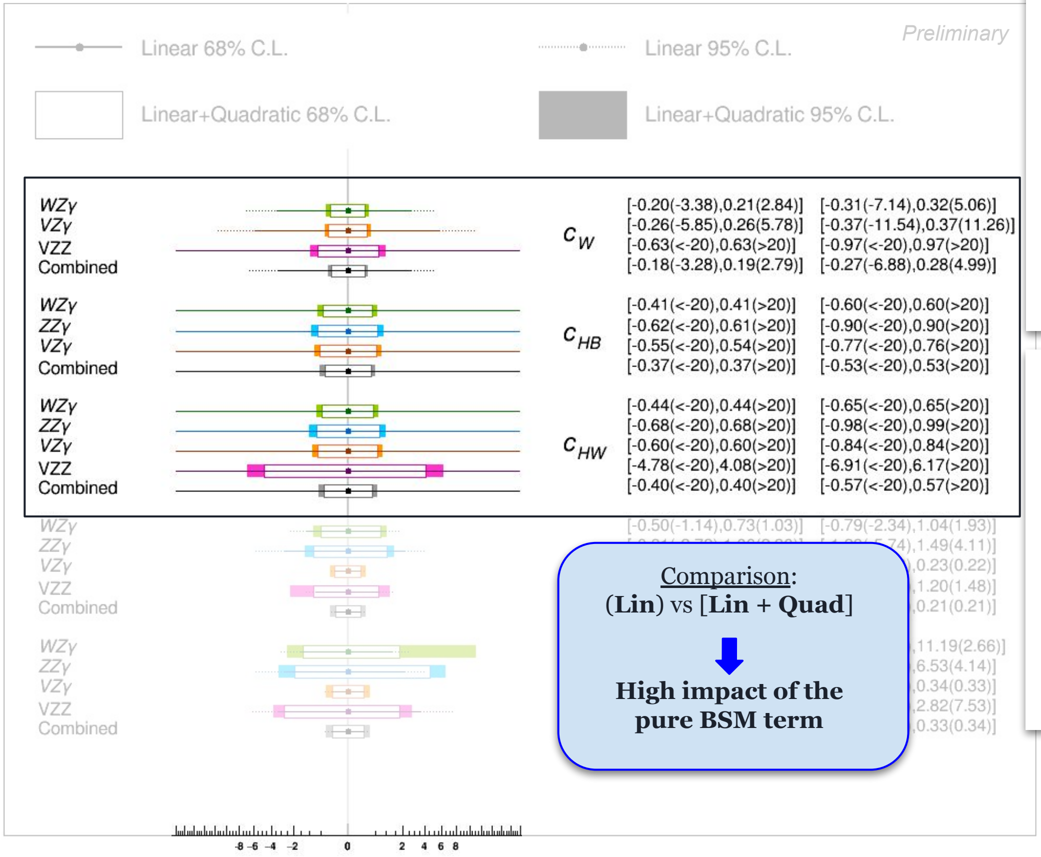


Likelihood scan relative to c_{HD} for the channel ZZγ

1D constraints



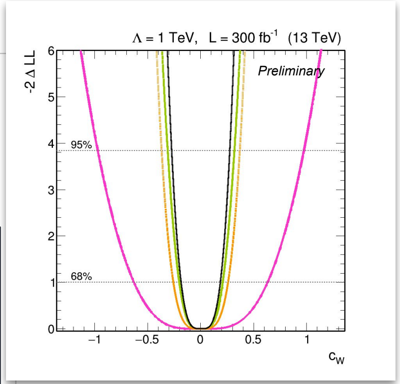
1D constraints

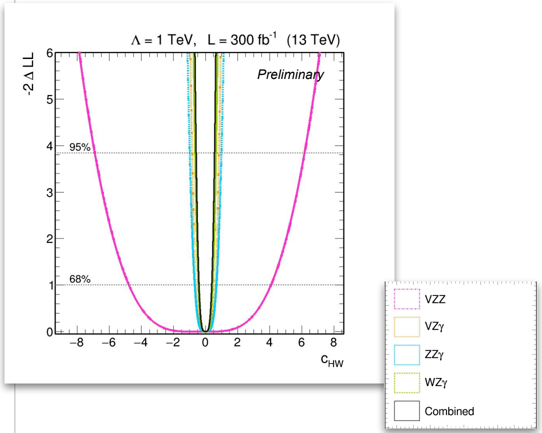


<u>Comparison</u>:
(Lin) vs [Lin + Quad]

⬇

High impact of the pure BSM term





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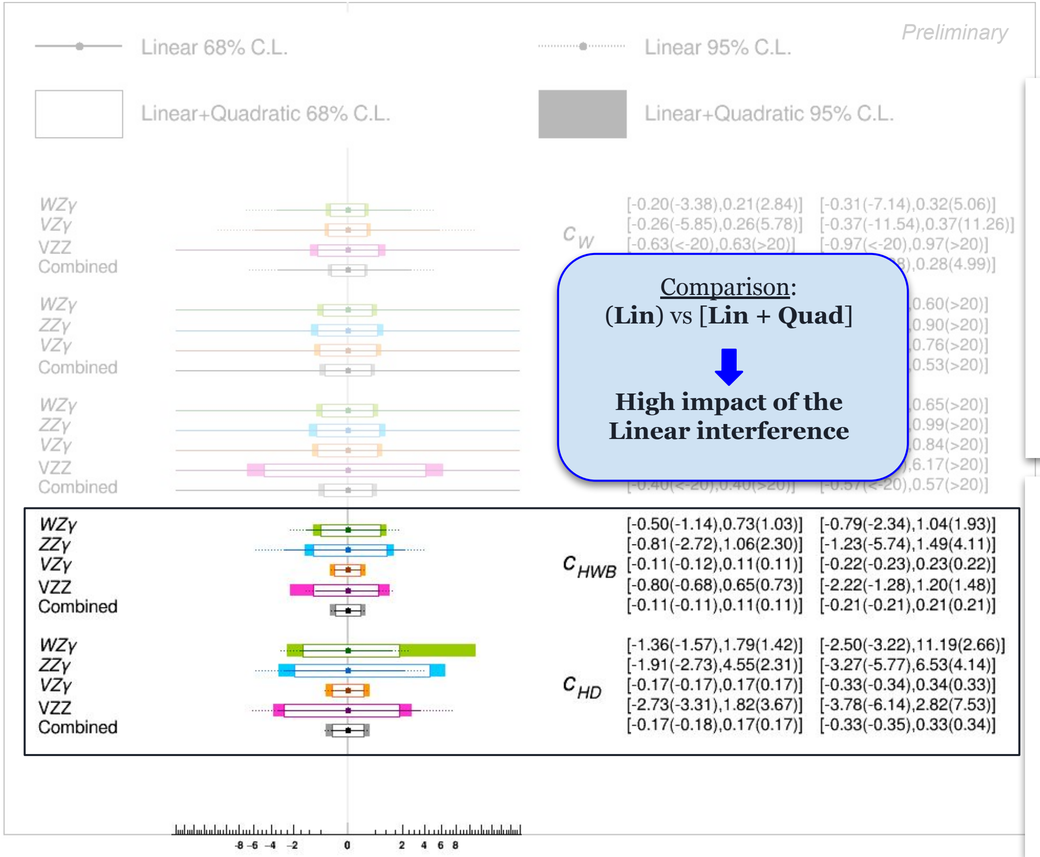
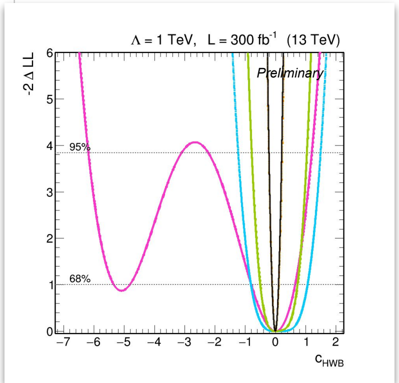
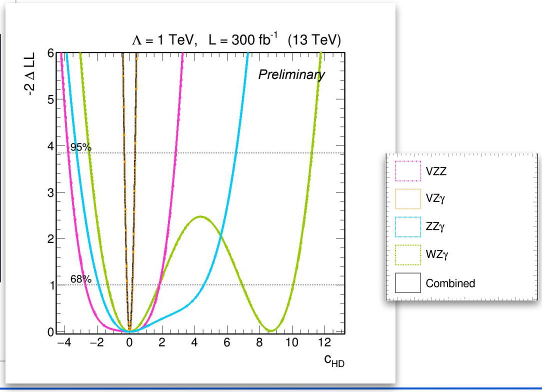


Comparison:
(Lin) vs [Lin + Quad]
↓
High impact of the Linear interference





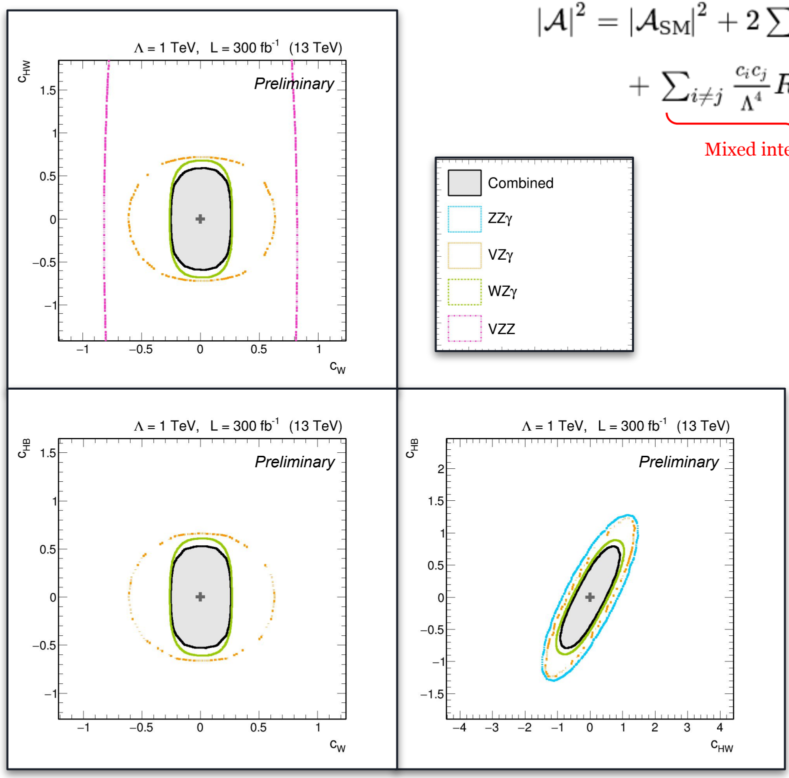
2D confidence areas

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

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

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

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



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

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

[here the matrix $\{Q_i, Q_j\}$]

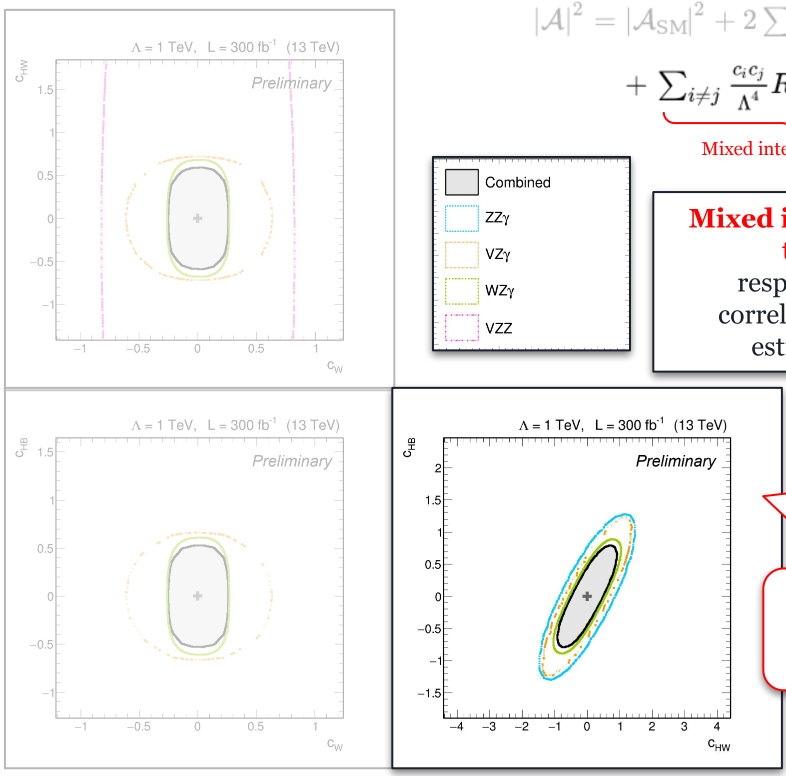
2D confidence areas

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

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

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

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



$Q_W = \epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$

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

Mixed interference term: responsible of correlation in the estimations

Couple Q_{HB}-Q_{HW} : relevant role of the mixed interference

[here the matrix $\{Q_i,Q_j\}$]

2D confidence areas

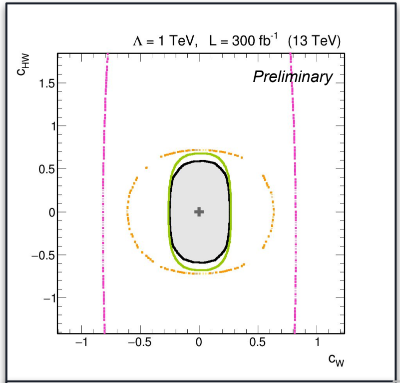
Examples of **contours** of the 68 % C.L. **exclusion areas** for pairs of operators affecting the channels of interest

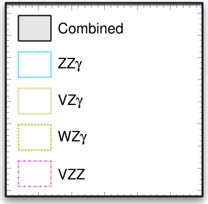
SM / Linear

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

Mixed interference → 0 / Quadratic

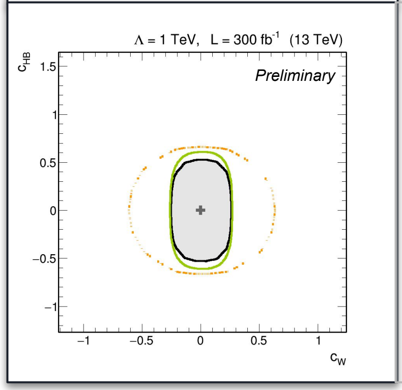
$Q_{\phi W} = \phi^\dagger \phi\, W^I_{\mu\nu} W^{I\mu\nu}$

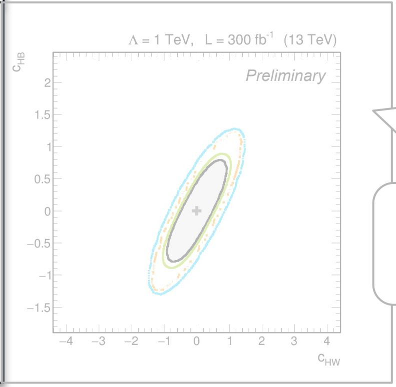




Mixed interference term: the only responsible of correlation in the estimations

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





Couples Q_W-$Q_{HB(W)}$:

Negligible mixed interference

↓

Contours: ~**centered elliptical shapes**

Couple Q_{HB}-Q_{HW} : relevant role of the mixed interference

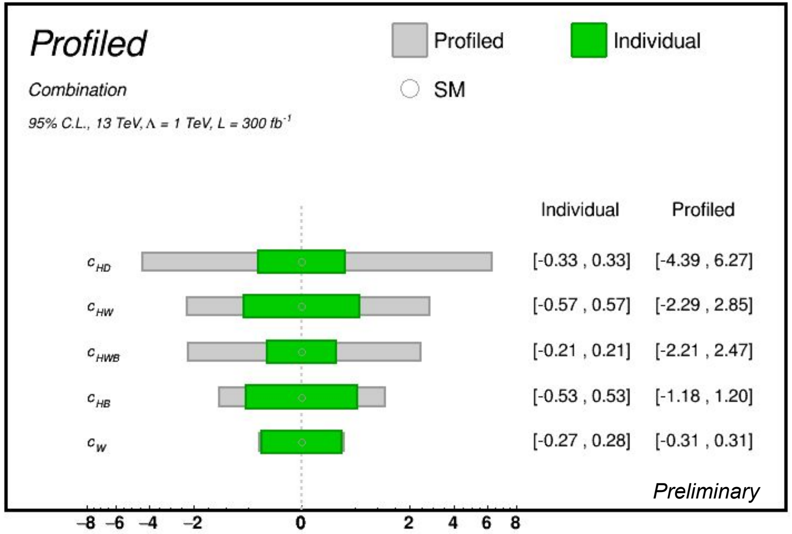
$Q_W = \epsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$

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

[here the matrix $\{Q_i,Q_j\}$]

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:

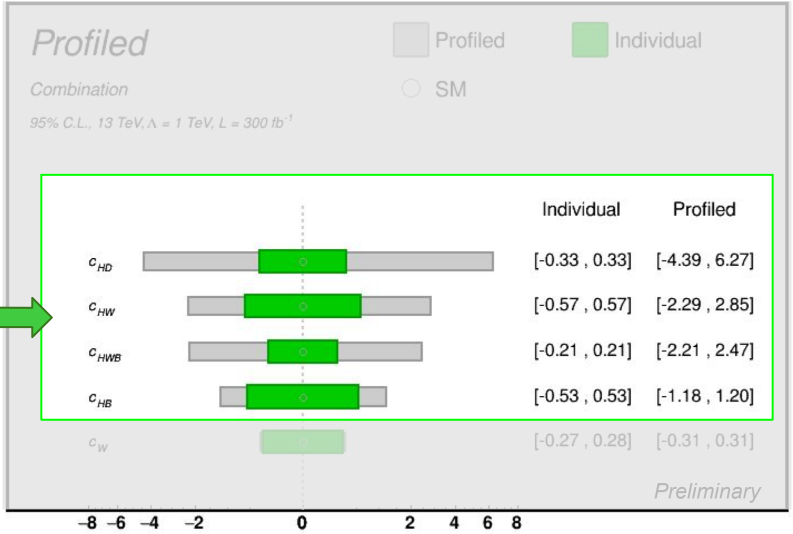
All the coefficients
(except for the one of interest)

floating parameters

Unconstrained nuisances
with a **flat prior**

Global fit

Profiled constraints



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

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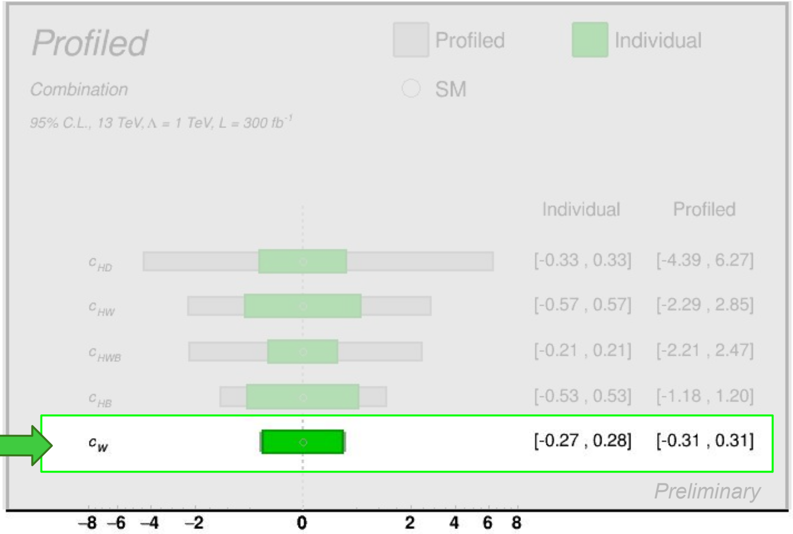


Q_W effects **uncorrelated** with the other operators

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**

Conclusions

- First phenomenological dim.6 EFT study for VZZ/VZγ triboson production processes
  - very competitive constraints!
  - fundamental role of combination of the analyses

- Future perspective of EFT studies:
  - detector-level
  - diboson and triboson analyses combination
  - dim. 6 vs dim. 8 operators effects

Thanks for
the attention!

References

1. R. Bellan et al., A sensitivity study of triboson production processes to dimension-6 EFT operators at the LHC, arXiv preprint arXiv:2303.18215 (2023).

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

3. R. Bellan et al., A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC, 10.1007/JHEP05(2022)039.

4. C. Degrande et al., Effective Field Theory: a modern approach to anomalous couplings, 10.1016/j.aop.2013.04.016

5. I. Brivio, SMEFTsim 3.0 — a practical guide. JHEP, 04:073, 2021.

OTHER CONTENTS

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 $\|\eta_{l^i}\| < 2.5$ $p_{T,\gamma} > 20$ GeV $\|\eta_\gamma\| < 2.5$ $p_{T,j^{1,2}} > 30$ GeV $\|\eta_{j^i}\| < 2.5$ $\Delta R(l^i,\gamma) > 0.4$ $\Delta R(l^i, j^k) > 0.4$ $\Delta R(\gamma, j^\kappa) > 0.4$
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 $\|\eta_{j^i}\| < 2.5$ $\|\eta_{l^i}\| < 2.5$ $\Delta R(l^i, j^k) > 0.4$

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 $\|\eta_{l^i}\| < 2.5$ $p_{T,\gamma} > 20$ GeV $\|\eta_\gamma\| < 2.5$ $\Delta R(l^i,\gamma) > 0.4$
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 $\|\eta_{l^i}\| < 2.5$ $p_{T,\gamma} > 20$ GeV $\|\eta_\gamma\| < 2.5$ $\Delta R(l^i,\gamma) > 0.4$

<table>
<tr><th>WZγ</th><th>ZZγ</th><th>VZγ</th><th>VZZ</th></tr>
<tr><td>pp -> WZγ -> $\mu^{\pm}\overset{(-)}{\nu}_{\mu} e^{+}e^{-}\gamma$</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

Chasing BSM physics

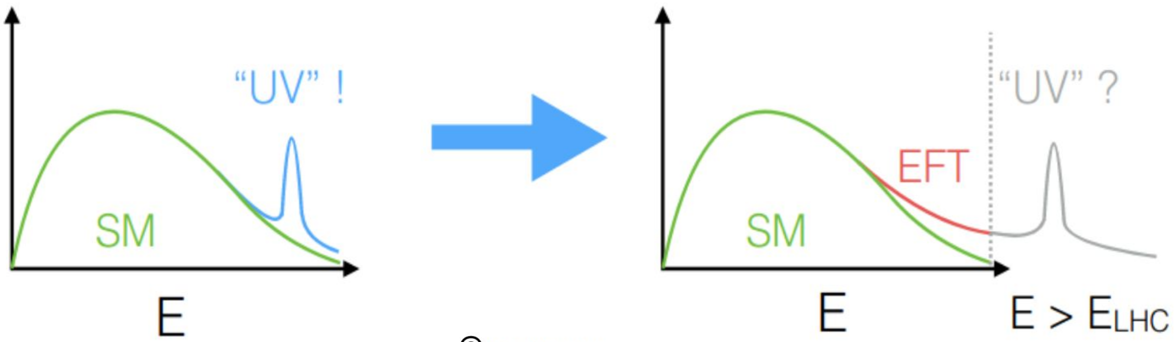
Model-independent approach:
SMEFT framework.

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

Dim. n op.

New Physics scale

Wilson coefficient



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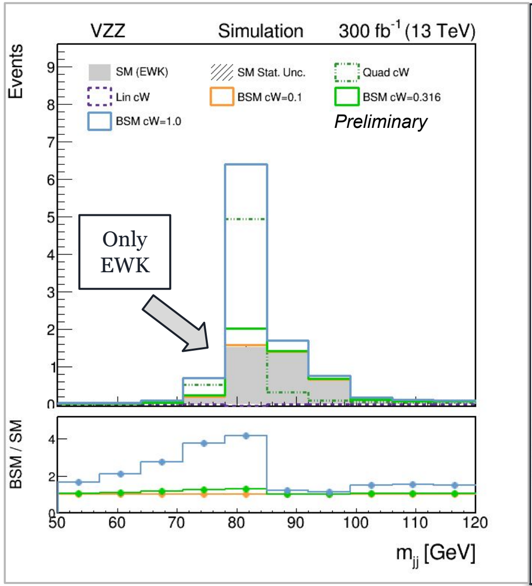
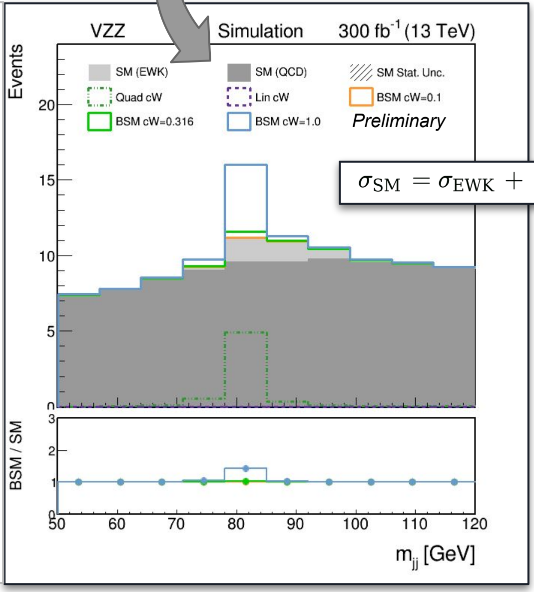
Shape analysis

Impact of QCD-induced background

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

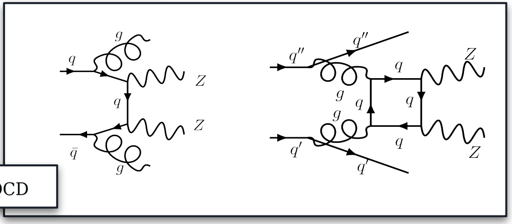


SM (electroweak) and BSM event distribution as a function of the jets pair invariant mass (VZZ channel)



SM (electroweak + QCD) and BSM event distribution as a function of the jets pair invariant mass (VZZ channel)

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



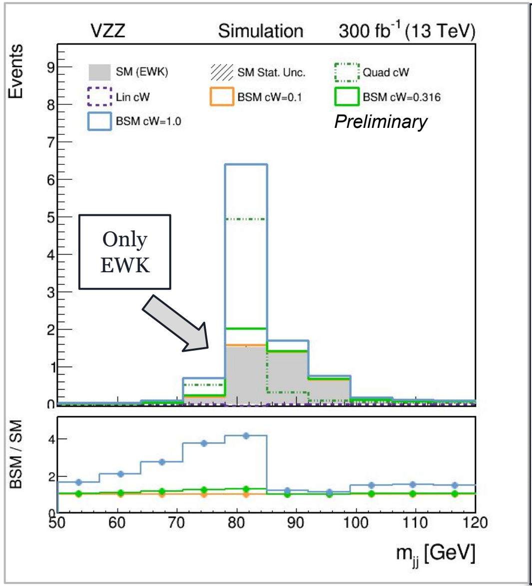
Shape analysis

Impact of QCD-induced background

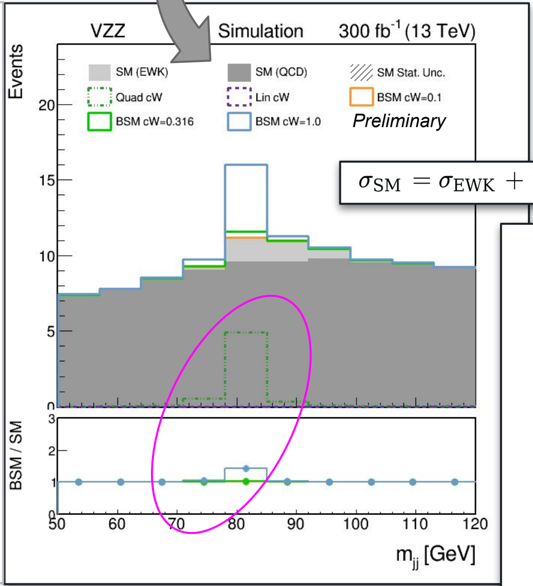
Inclusion of the main **backgrounds** given by diagrams involving QCD-induced vertices.

Quadratic term contribution: m_{jj} **resonance** at the **nominal W boson mass.**

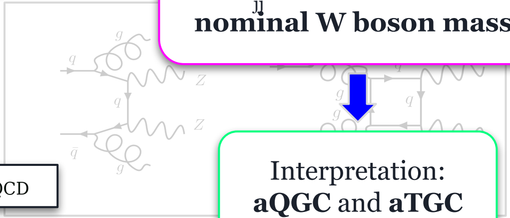
Interpretation: **aQGC** and **aTGC**

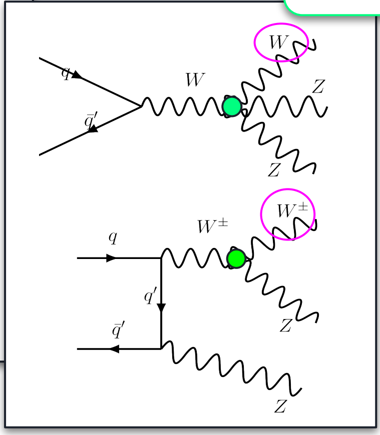


SM (electroweak) and BSM event distribution as a function of the jets pair invariant mass (VZZ channel)



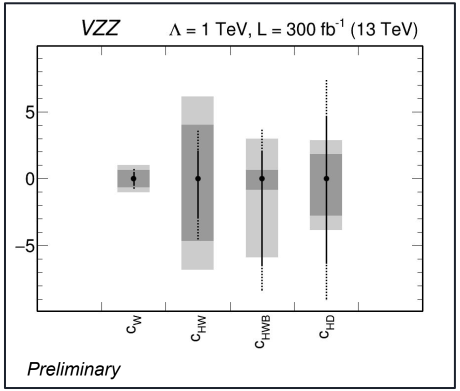
SM (electroweak + QCD) and BSM event distribution as a function of the jets pair invariant mass (VZZ channel)

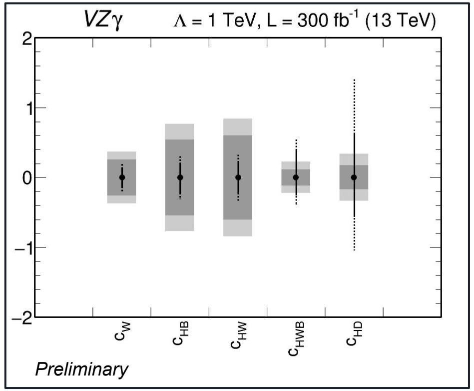


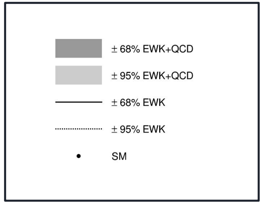


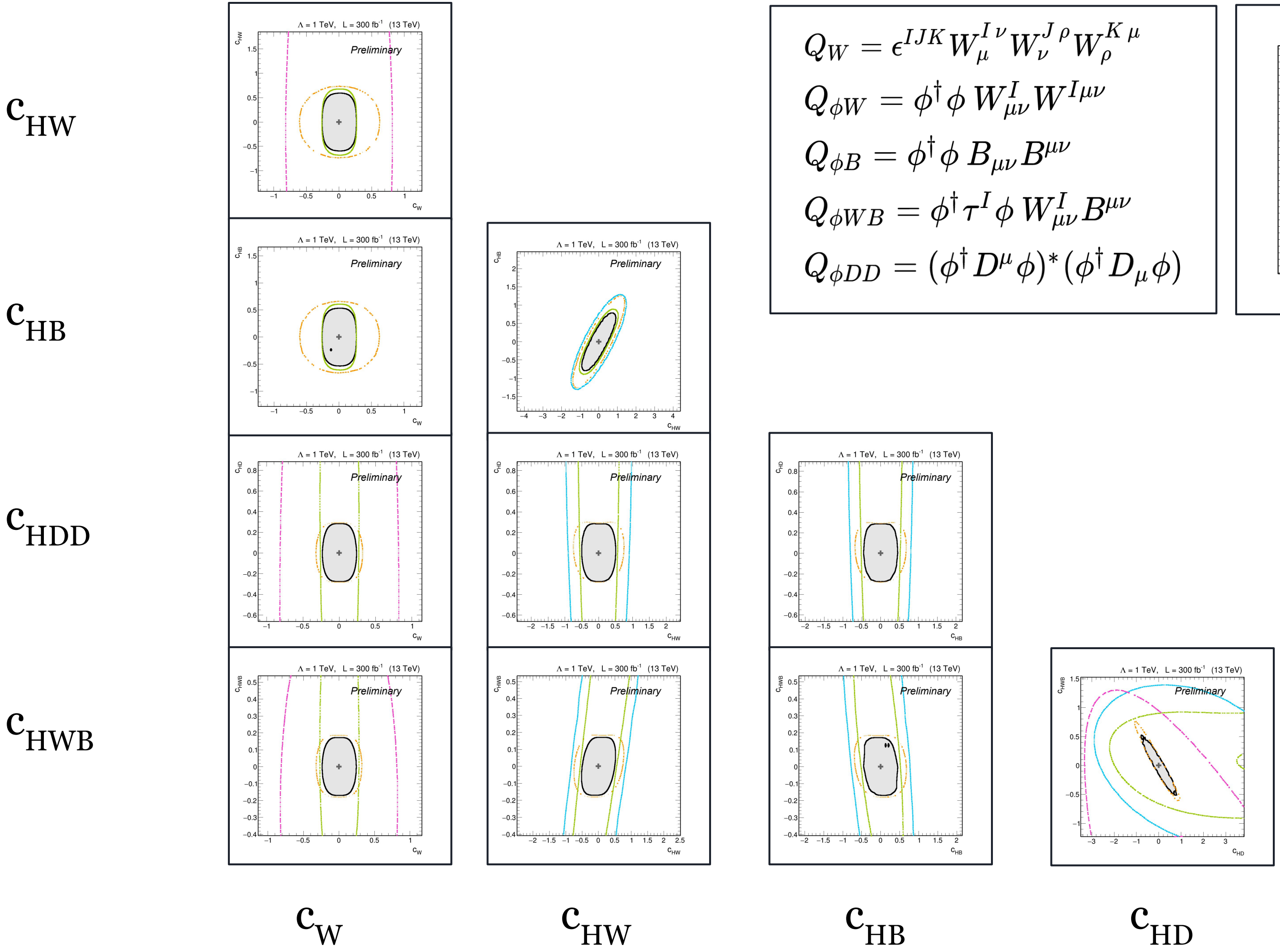
Shape analysis

Semi-leptonic channels: Impact of QCD-induced background

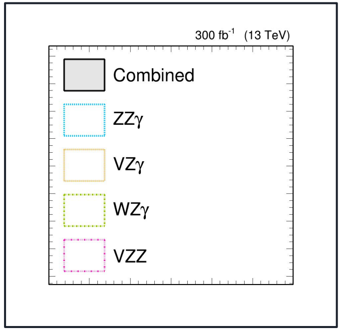








$$Q_W = \epsilon^{IJK} W_\mu^{I\,\nu} W_\nu^{J\,\rho} W_\rho^{K\,\mu}$$
$$Q_{\phi W} = \phi^\dagger \phi\, W^I_{\mu\nu} W^{I\mu\nu}$$
$$Q_{\phi B} = \phi^\dagger \phi\, B_{\mu\nu} B^{\mu\nu}$$
$$Q_{\phi WB} = \phi^\dagger \tau^I \phi\, W^I_{\mu\nu} B^{\mu\nu}$$
$$Q_{\phi DD} = (\phi^\dagger D^\mu \phi)^* (\phi^\dagger D_\mu \phi)$$

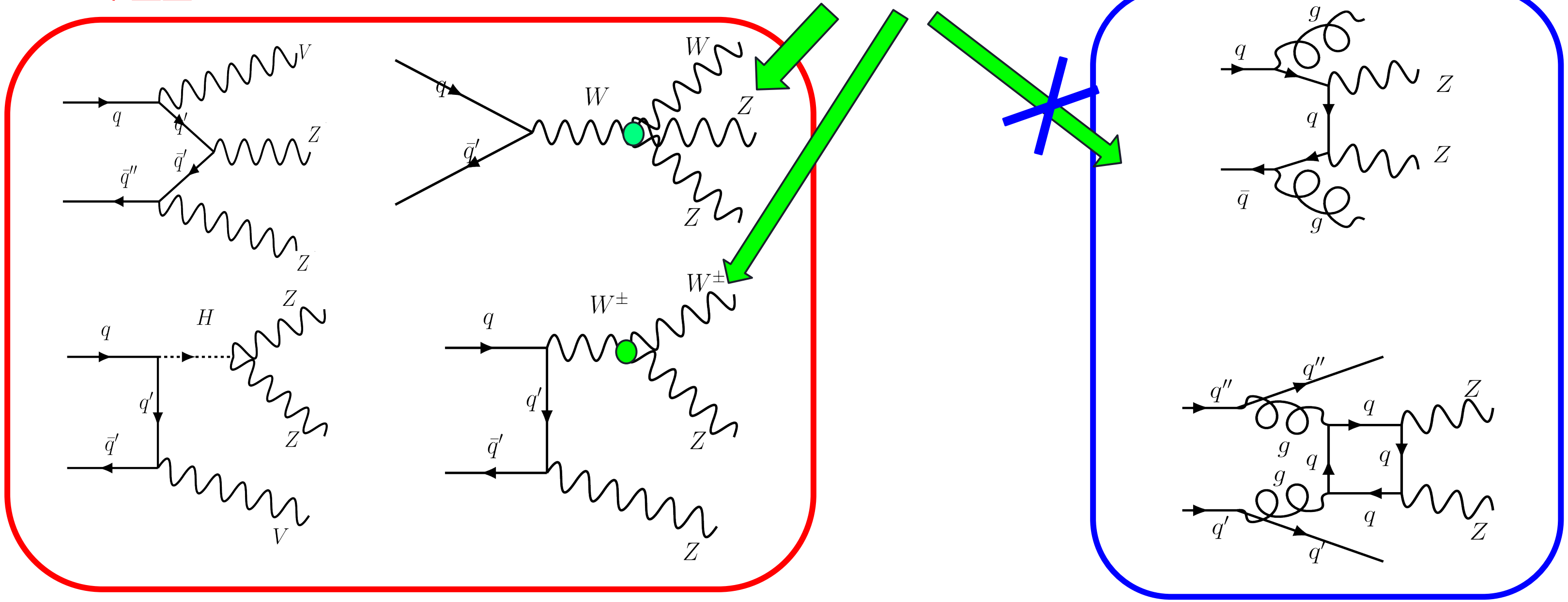


$pp \to 4\ell jj$

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

VZZ

QCD-ZZjj



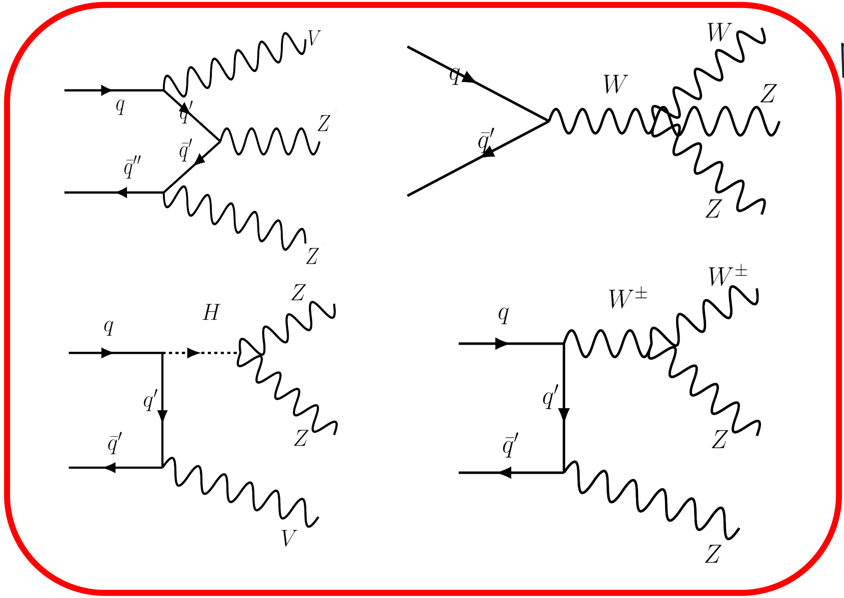
SMEFTsim package for the EFT terms MC generation

$\lvert\eta_j\rvert < 2.5$	$p_{Tj} > 30\ GeV$	$p_{T\,l_1} > 20\ GeV$	$60\ GeV < m_{ll} < 120\ GeV$	$\Delta R_{lj} > 0.4$
$\lvert\eta_l\rvert < 2.5$	$p_{Tl} > 5\ GeV$	$p_{T\,l_2} > 10\ GeV$	$50\ GeV < m_{jj} < 120\ GeV$	

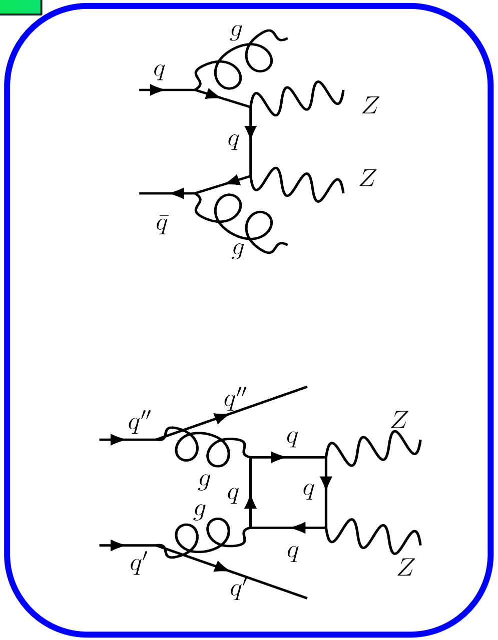
$pp \to 4\ell jj$

$$Q_{\varphi WB} = \varphi^{\dagger} \tau^{I} \varphi \, W^{I}_{\mu\nu} B^{\mu\nu}$$

VZZ



QCD-ZZjj



SMEFTsim package for the EFT terms MC generation

$\lvert\eta_j\rvert < 2.5$	$p_{Tj} > 30\ GeV$	$p_{T\,l_1} > 20\ GeV$	$60\ GeV < m_{ll} < 120\ GeV$	$\Delta R_{lj} > 0.4$
$\lvert\eta_l\rvert < 2.5$	$p_{Tl} > 5\ GeV$	$p_{T\,l_2} > 10\ GeV$	$50\ GeV < m_{jj} < 120\ GeV$	

The Standard Model of Particle Physics

Electroweak Symmetry Breaking

- EWSB consequences

$$\mathcal{L}_B + \mathcal{L}_H = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} +$$
$$-\frac{1}{2}W^{+}_{\mu\nu}W^{\mu\nu}_{-} + m_W^2 W^{-}_{\mu} W^{\mu}_{+} +$$
$$-\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu +$$
$$+(\partial_\mu H)(\partial^\mu H) - \frac{1}{2}m_H^2 H^2 +$$
$$+\mathcal{L}_{BB} + \mathcal{L}_{HH} + \mathcal{L}_{HB}$$

with

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

$$m_W^2 = \frac{g^2 v^2}{4}$$
$$m_Z^2 = \frac{m_W^2}{cos^2\theta_W}$$

Weak vector bosons acquire mass

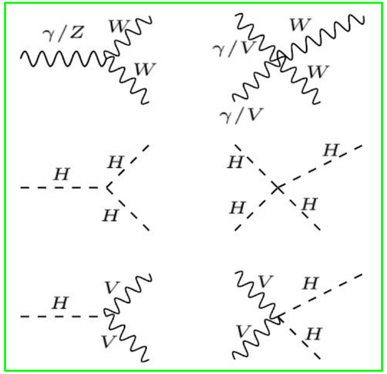
Electroweak mixing justified:
residual symmetry $SU(2)_L \times U(1)_Q$

$$W^{\pm}_{\mu} = \frac{1}{\sqrt{2}}(W^1_\mu \mp i W^2_\mu)$$

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} cos\theta_w & sin\theta_w \\ -sin\theta_w & cos\theta_w \end{pmatrix} \begin{pmatrix} B_\mu \\ W^3_\mu \end{pmatrix}$$

$$m_H^2 = 2\lambda v^2$$

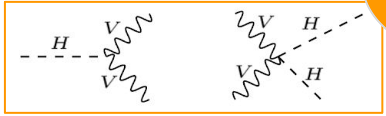
Physical Higgs boson emerges
(massive, spin=0)



TGC and QGC
emerge together
with Higgs couplings

EWK non-abelian gauge structure consequen

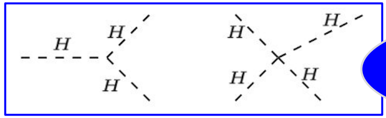
$$\mathcal{L}_B + \mathcal{L}_H = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \\ -\frac{1}{2}W^+_{\mu\nu}W^{\mu\nu}_- + m_W^2 W^-_\mu W^\mu_+ + \\ -\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu + \\ +(\partial_\mu H)(\partial^\mu H) - \frac{1}{2}m_H^2 H^2 + \\ +\mathcal{L}_{BB} + \mathcal{L}_{HH} + \mathcal{L}_{HB}$$



Higgs couplings with massive vector bosons

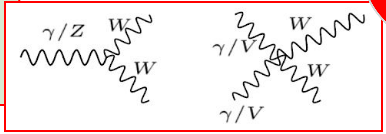
$$\mathcal{L}_{HB} = \frac{1}{2}g^2 v\, H\, W^+_\mu W^\mu_- + \frac{1}{4}(g^2 + g'^2)vHZ_\mu Z^\mu + \\ +\frac{1}{4}g^2 H^2 W^+_\mu W^\mu_- + \frac{1}{8}(g^2 + g'^2)H^2\, Z_\mu Z^\mu$$

$$\mathcal{L}_{HH} = \lambda v H^3 + \frac{\lambda}{4}H^4$$



Higgs self-couplings

$$\mathcal{L}_{BB} = ig\, sin\theta_w(W^+_{\mu\nu}W^{-\mu}A^\nu - W^-_{\mu\nu}W^{+\mu}A^\nu + F_{\mu\nu}W^{+\mu}W^{-\nu}) + \\ +ig\, cos\theta_w(W^+_{\mu\nu}W^{-\mu}Z^\nu - W^-_{\mu\nu}W^{+\mu}Z^\nu + Z_{\mu\nu}W^{+\mu}W^{-\nu}) + \\ -\frac{g^2}{2}(2g^{\mu\nu}g^{\rho\sigma} - g^{\mu\rho}g^{\nu\sigma} - g^{\mu\sigma}g^{\nu\rho})[W^+_\mu W^-_\nu(A_\rho A_\sigma sin\theta_W + \\ +Z_\rho Z_\sigma cos\theta_W + 2A_\rho Z_\sigma sin\theta_W cos\theta_W) - \frac{1}{2}W^+_\mu W^+_\nu W^-_\rho W^-_\sigma]$$



Gauge couplings of EWK vector bosons

References

1. R. Bellan et al., A sensitivity study of triboson production processes to dimension-6 EFT operators at the LHC, arXiv preprint arXiv:2303.18215 (2023).

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

3. R. Bellan et al., A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC, 10.1007/JHEP05(2022)039.

4. C. Degrande et al., Effective Field Theory: a modern approach to anomalous couplings, 10.1016/j.aop.2013.04.016

5. I. Brivio, SMEFTsim 3.0 — a practical guide. JHEP, 04:073, 2021.