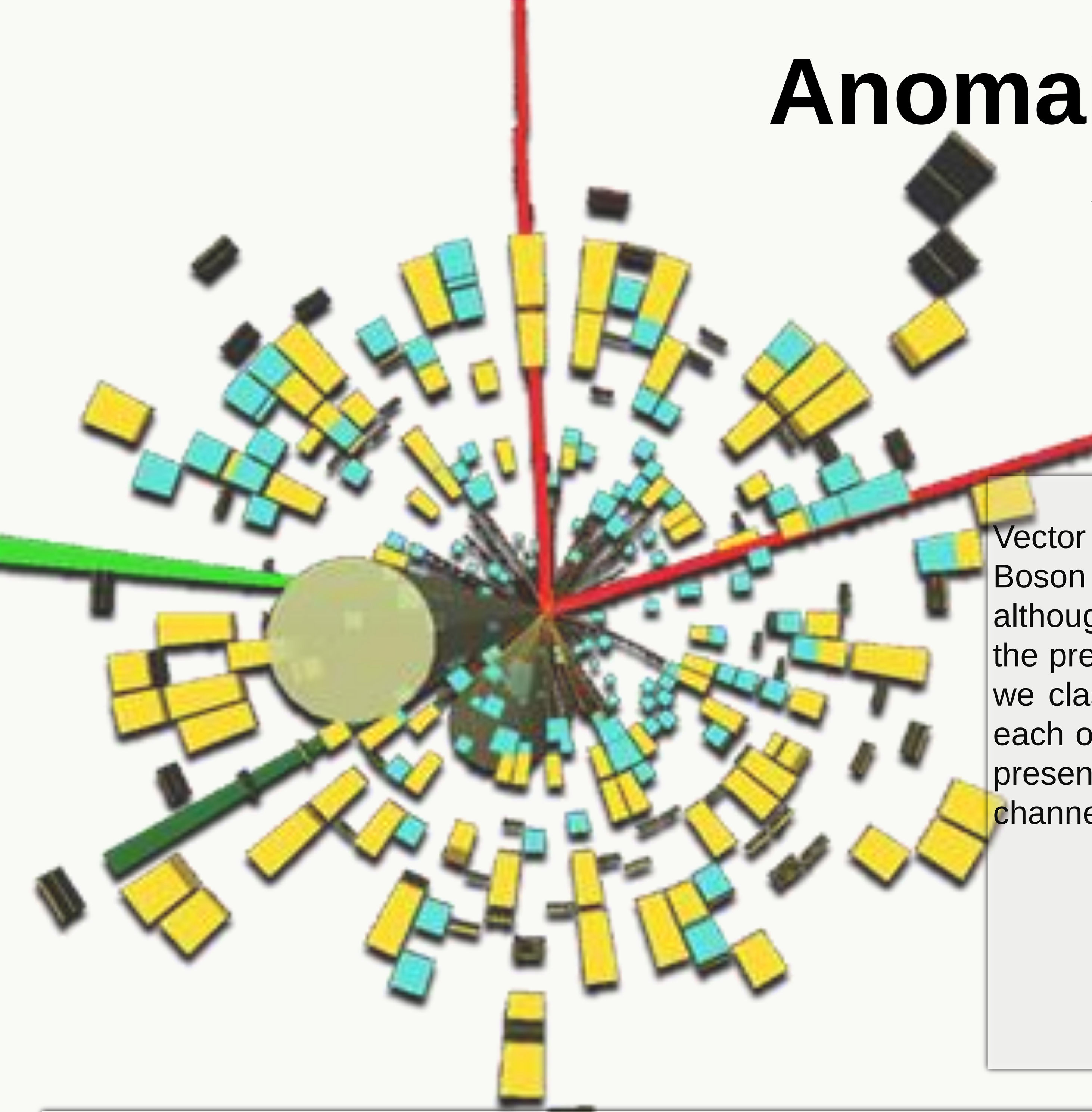

Anomalous Quartic Gauge Boson Couplings

Sensitivity on measuring aQGCs using single and multi-parametric models in the EFT framework

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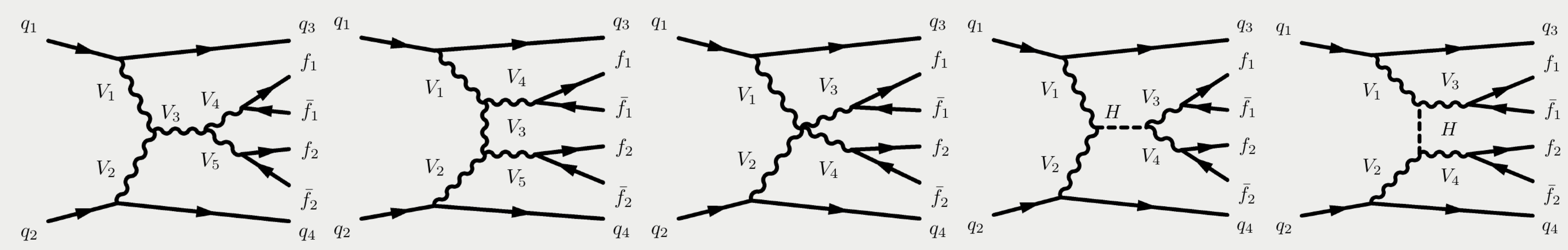
Overview

Vector Boson Scattering (VBS) processes provide a great source of information on the structure of the Quartic Gauge Boson Couplings (QGCs) [1,2]. The Standard Model allows self interactions of the charged vector gauge bosons, although vertices with neutral-only bosons are forbidden. We use Monte Carlo (MC) samples containing VBS events for the preliminary studies of the setting of constraints on anomalous QGCs. We investigate typical kinematic variables and we classify them according to their sensitivity to aQGC effects. Also, we evaluate the cross-section enhancement by each one of the dimension-eight QGC operators in the ZZjj channel. A work-in-progress binning optimization method is presented and finally, preliminary limits on the EFT operators are estimated through toy experimentation for the VBS ZZjj channel.



Representative Feynman diagrams of the EWK ZZjj production.

Effective Field Theory (EFT) Langrangian Approach

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d>4}\sum_{i}\frac{f_i^{(d)}}{\Lambda^{d-4}}\mathcal{O}_i^{(d)}$$

Where f_i are the Wilson coefficients, d is the dimension of the operators O_i and Λ is the new physics scale [3,4].

The dim-8 EFT operators, affecting the quartic boson vertices are categorized in groups of the operators O_s, O_M and O_T [5] :

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}, \mathcal{O}_{S,1}$	x	x	x						
$\mathcal{O}_{M,0}, \mathcal{O}_{M,1}, \mathcal{O}_{M,6}, \mathcal{O}_{M,7}$	x	x	x	x	x	x	x		
$\mathcal{O}_{M,2}, \mathcal{O}_{M,3}, \mathcal{O}_{M,4}, \mathcal{O}_{M,5}$		x	x	x	x	x	x		
$\mathcal{O}_{T,0}, \mathcal{O}_{T,1}, \mathcal{O}_{T,2}$	x	x	x	x	x	x	x	x	x
$\mathcal{O}_{T,5}, \mathcal{O}_{T,6}, \mathcal{O}_{T,7}$		x	x	x	x	x	x	x	x
$\mathcal{O}_{T,8}, \mathcal{O}_{T,9}$			x			x	x	x	x

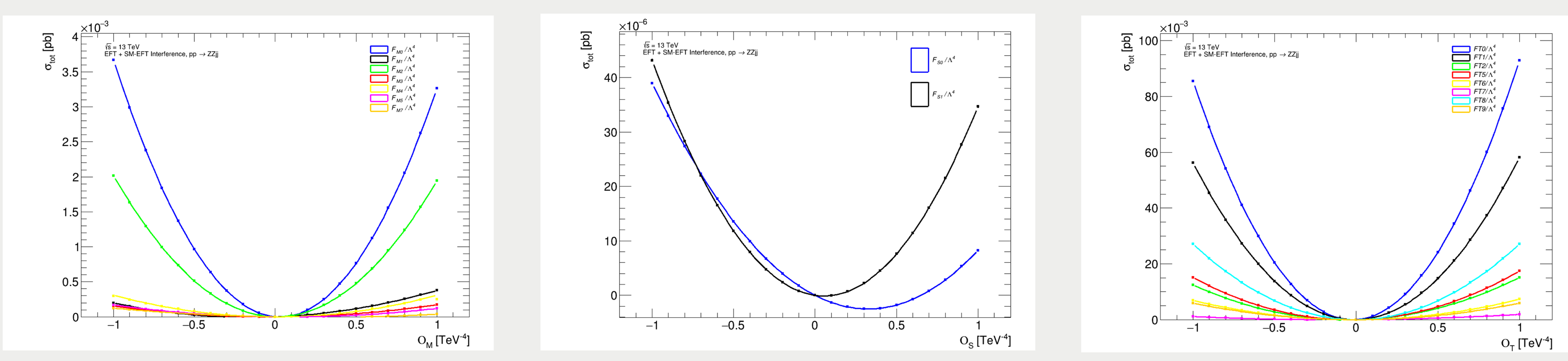
Sensitivity of QGC operators

The total EFT amplitude for the three groups of dim-8 operators can be expressed as:

$$\mathcal{L}_{EFT} = \mathcal{L}_{\rm SM} + \sum_{j=0,1}\frac{f_{{\rm M},j}}{\Lambda^4}\mathcal{O}_{{\rm M},j} + \sum_{j=0,1}\frac{f_{{\rm S},j}}{\Lambda^4}\mathcal{O}_{{\rm S},j} + \sum_{j=0,1}\frac{f_{{\rm T},j}}{\Lambda^4}\mathcal{O}_{{\rm T},j}$$

We study the sensitivity of each EFT operator group by estimating the cross-section enhancement for the VBS ZZjj channel.

$\mathcal{O}_{Tj}$ are the most sensitive operators of the ZZ production.

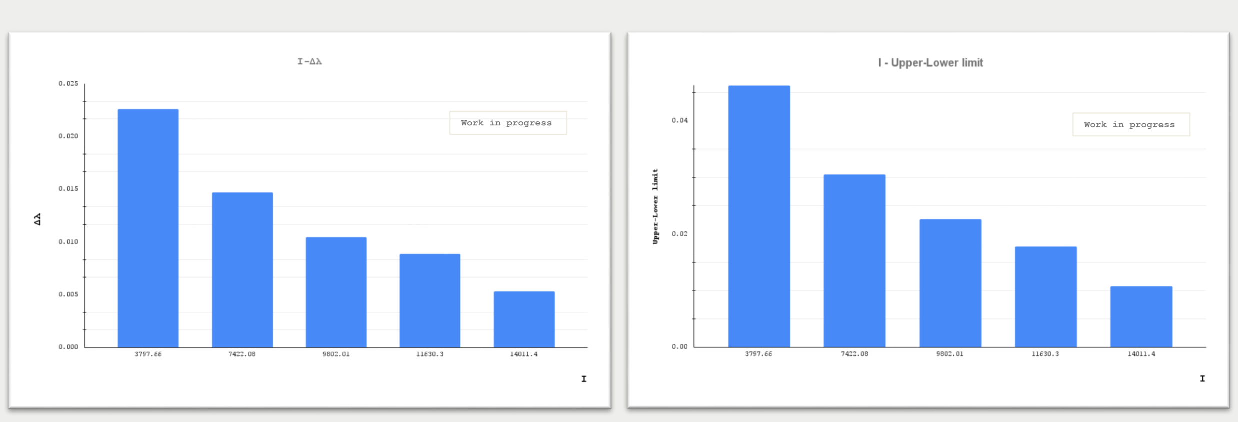


Binning optimization

The selection of the bin edges for the distribution of an observable, affects the limit setting of the EFT operators. We study 5 configurations of the invariant mass m_{ZZ} of the Z bosons in the VBS ZZjj channel. The quantity I_λ expresses the information which each bin configuration contains. The optimum binning configuration in terms of the EFT operators limit setting, is the one with the maximum I_λ.

$$I_\lambda = -\sum_{i=1}^{k}\left\langle \frac{\partial^2\mu_i}{\partial\lambda^2}\left[\frac{n_i}{\mu_i}-1\right] - \left(\frac{\partial\mu_i}{\partial\lambda}\right)^2\frac{n_i}{\mu_i^2}\right\rangle$$

where k the maximum number of bins, μ_i and n_i the expected and observed events respectively.



We study 5 bin configurations of the m_{ZZ} (GeV):
[130, 210, 250, 304, 400, 1130, 10000]
[130, 210, 250, 304, 400, 1500, 10000]
[130, 210, 250, 304, 400, 1750, 10000]
[130, 210, 250, 304, 400, 2000, 10000]
[130, 210, 250, 304, 400, 2500, 10000]

Left figure: I_λ vs $\Delta\lambda = \lambda_{\rm est} - \lambda_{\rm true}$ where λ_{est} is the best fit value of the coupling λ. When $\Delta\lambda$ diverges from 0, the I_λ decreases.

Right figure: I_λ vs Upper limit – Lower limit of the coupling λ. As the limits become stricter, the I_λ becomes greater.

Profile Likelihood Ratio

The expected limits are given in terms of confident intervals, estimated at 95% CL, by using the SM prediction as a hypothetical observation (Asimov dataset). The likelihood is first maximized simultaneously for the parameter of interest λ and the nuisance parameters θ to find $L(\hat{\lambda}, \hat{\theta})$. Then, the likelihood is scanned for the parameter of interest λ, each time maximized for the nuisance parameters $L(\lambda, \hat{\hat{\theta}})$. The ratio

$$f(\lambda) = \frac{L(\lambda, \hat{\hat{\theta}})}{L(\hat{\lambda}, \hat{\theta})}$$

is called profile likelihood ratio. Instead of maximizing the PLR, we minimize the quantity

$$-log f(\lambda) = -2\Delta log(L)_{|\lambda}$$

The 95% confidence interval for the parameter λ corresponds to $-2\Delta\log(L(\lambda)) = 1.962^2$.

Acknowledgments

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Decomposition method of QGCs

EFT dim-8 predictions can be generated in independent samples including the EFT components. Defining $c_i = \frac{f_i}{\Lambda^4}$, where f_i the Wilson coefficient and Λ the new physics scale, the total EFT amplitude can be expressed as:

$$\left|A_{SM} + \sum_i c_i \cdot A_i\right|^2 = |A_{SM}|^2 + \sum_i c_i \cdot 2\,Re(A_{SM}^* \cdot A_i) + \sum_i c_i^2 \cdot |A_i|^2 + \sum_{i,j,\, i\neq j} c_i c_j \cdot Re(A_i^* \cdot A_j)$$

- Total EFT amplitude
- Standard Model
- Interference of SM-aQGC (linear term)
- Pure QGC contribution (quadratic term)
- Interference between QGC operators (cross terms)

Discriminant variable selection

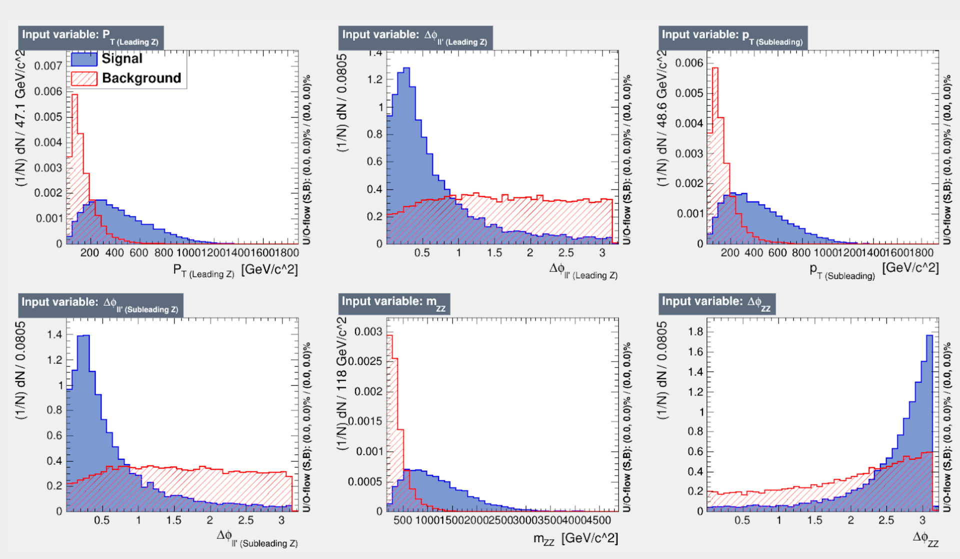
Boosted Decision Trees (BDT) studies in the VBS ZZjj channel, point the invariant mass of the leptons m_{4l} (in $pp \to 4ljj$) or m_{ZZ} (in $pp \to ZZ \to 4ljj$) as the most sensitive discriminant for the QGC identification.

MC inputs:

- Signal: pure QGC sample ($f_{T0}/\Lambda^4 = 0.7\ \mathrm{TeV}^{-4}$)
- Background: SM EWK sample

Input variables:

- $p_T^{leading\ Z}, p_T^{sub-leading\ Z}, m_{ZZ}, |\Delta\eta_{jj}|, |\Delta\eta_{ZZ}|, |\Delta\varphi_{ll}|, |\Delta\varphi_{ZZ}|, p_T^{lepton}, \ldots$



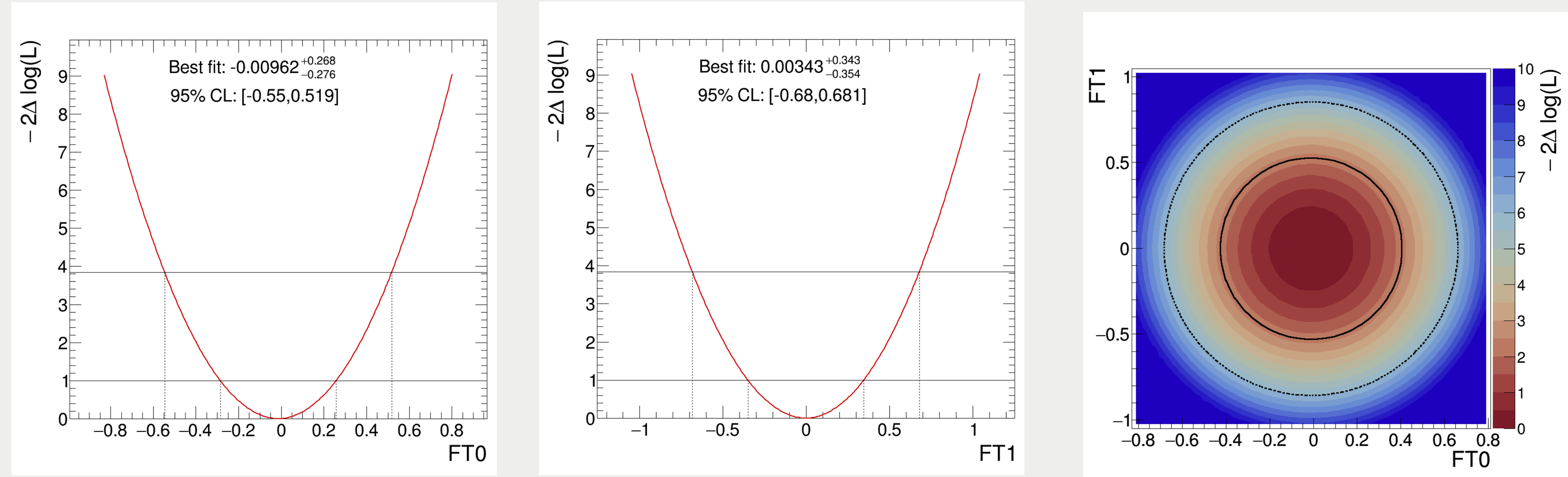
Rank: Variable	Variable Importance
m_{ZZ}	0.1941
$p_T^{subleadingZ}$	0.1436
$p_T^{leadingZ}$	0.1388
$\Delta\eta_{jj}$	0.1094
$\Delta\eta_{ZZ}$	0.1065
m_{jj}	0.1034
$\zeta_{subleadingZ}$	0.1029
$\zeta_{leadingZ}$	0.1012

Writing the square of the matrix-element as a quadratic function of the coupling, one can also construct a likelihood in terms of two "optimal observables", where one is the ratio of the linear coefficient and the constant term, and the other is the ratio of the quadratic coefficient and the constant term [6].

Limits of the $f_{T,i}/\Lambda^4$ coefficients in the VBS ZZjj channel

The distribution of the invariant mass m_{ZZ} is used to perform the profile likelihood fit in order to extract the limits of the f_{Ti}/Λ^4 EFT coefficients. The expected limits are given in terms of confidence intervals, estimated at 95% CL, by using a random number from Poisson distribution (with the SM prediction being the mean value) as a hypothetical observation, for a N number of pseudo-experiments.

f_{Ti}/Λ^4	$95\%\ CL$
f_{T0}/Λ^4	$[-0.55, 0.52]$
f_{T1}/Λ^4	$[-0.68, 0.68]$
f_{T2}/Λ^4	$[-1.42, 1.38]$
f_{T5}/Λ^4	$[-1.41, 1.37]$
f_{T6}/Λ^4	$[-2.20, 2.21]$
f_{T7}/Λ^4	$[-4.69, 4.56]$
f_{T8}/Λ^4	$[-1.17, 1.17]$
f_{T9}/Λ^4	$[-2.54, 2.54]$



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