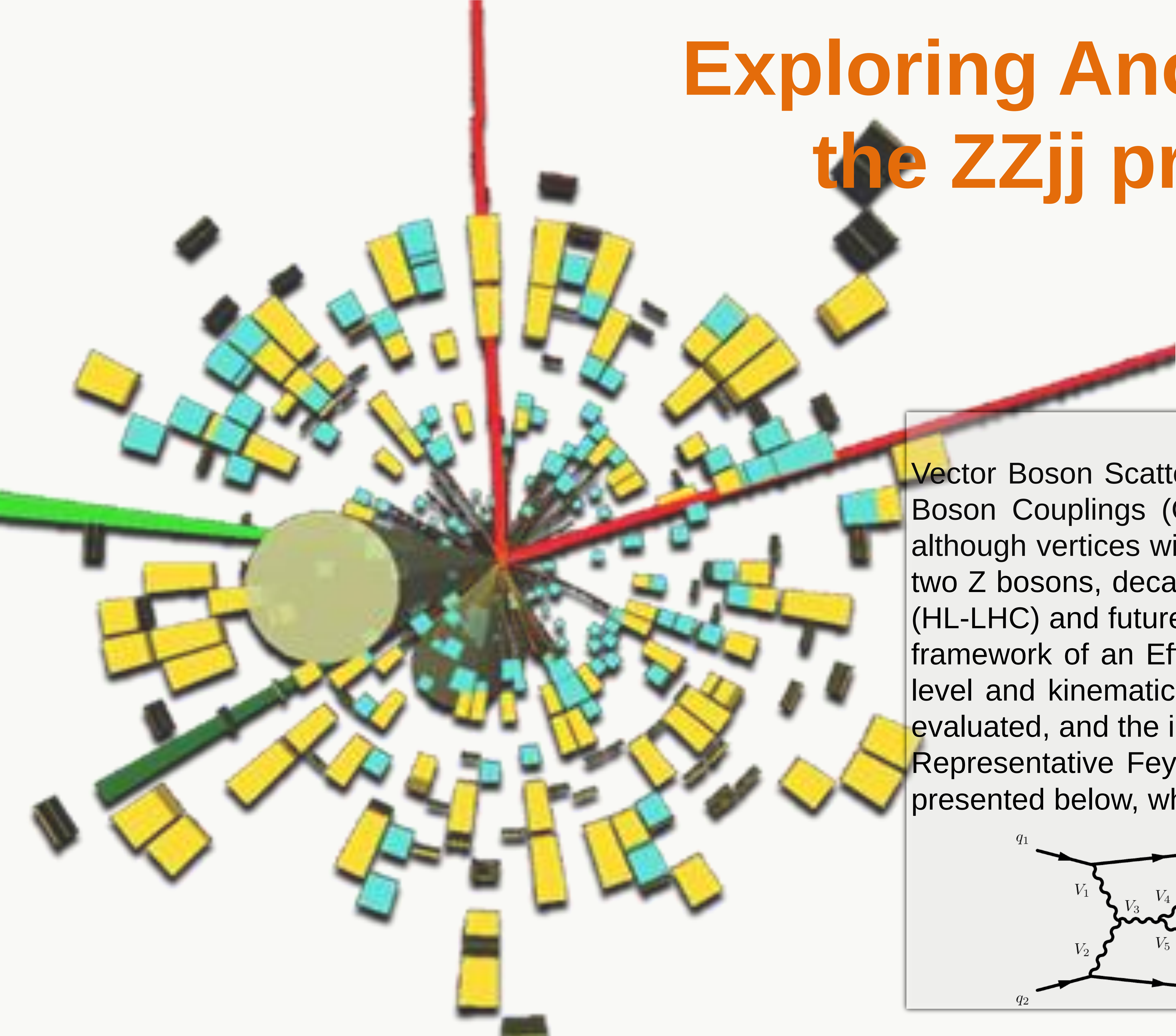


Exploring Anomalous Quartic Gauge Couplings in the ZZjj production channel at the HL-LHC and Beyond

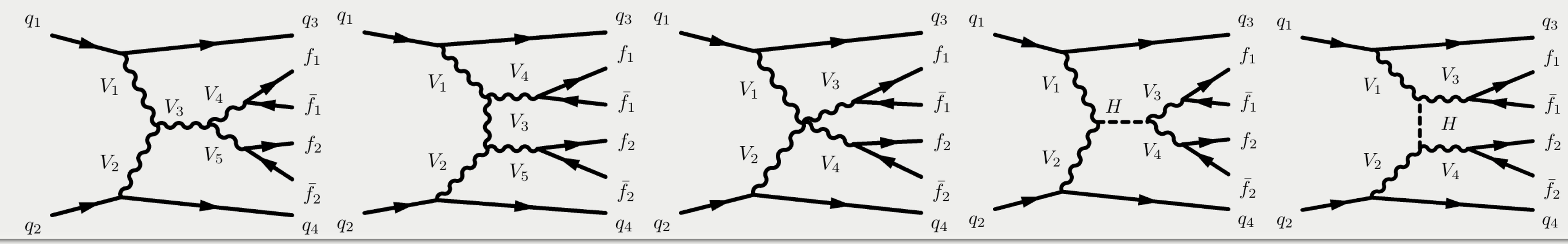
13th International Conference on New Frontiers in Physics

26 August - 4 September 2024, Kolymbari, Crete, Greece

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. A detailed study on the sensitivity of the production channel of two Z bosons, decaying to four leptons, in association with two jets (ZZjj) at the High-Luminosity Large Hadron Collider (HL-LHC) and future colliders, such as the Future Circular Collider (FCC), is presented, focusing on the QGCs within the framework of an Effective Field Theory (EFT) with dimension-eight operators. Using Monte Carlo simulations at truth-level and kinematic criteria that mimic the ATLAS detector geometry, constraints on anomalous QGC parameters are evaluated, and the impact of increased luminosity on the sensitivity of these couplings is examined.

Representative Feynman diagrams of the electroweak $ZZjj \to 4l + jj$ process, which is the signal of the analysis, are presented below, where $f_i = e^{\pm}, \mu^{\pm}$



Representative Feynman diagrams of the EWK ZZjj production.

The Future of Particle Colliders

The **High-Luminosity LHC (HL-LHC)** is a significant upgrade to the current LHC, designed to increase the total integrated luminosity by a factor of 10. This enhancement will enable the exploration of rare processes with greater precision.

The **Future Circular Collider (FCC)** represents a visionary future project aiming to reach energy scales far beyond the LHC. The FCC will probe new physics at unprecedented energy levels, potentially revealing the secrets of dark matter, the origin of mass, and more.

Key parameters	HL-LHC	FCC
Location	CERN, Geneva, Switzerland	Proposed 100 km tunnel in Geneva region, overlapping with LHC
Energy Range	13–14 TeV (center-of-mass energy for proton-proton collisions)	Up to 100 TeV (center-of-mass energy for proton-proton collisions)
Beam Energy	7 TeV per beam	50 TeV per beam
Magnet Technology	11 T dipole magnets, advanced focusing quadrupoles with Nb_3Sn superconductors	16 T dipole magnets with Nb_3Sn, possible high-temperature superconductors
Peak Luminosity	$7.5 \times 10^{34}\ cm^{-2}s^{-1}$	$30 \times 10^{34}\ cm^{-2}s^{-1}$
Integrated Luminosity	$3000\ to\ 4000\ fb^{-1}$ over its operational period	$20000\ fb^{-1}$ over its lifetime
Bunch Spacing	25 ns with increased bunch population	To be determined
Detector Upgrades	Significant upgrades to ATLAS and CMS to handle higher luminosity and pile-up (around 140 interactions per bunch crossing)	Anticipated advanced detector technologies to cope with higher energies and particle rates
Operational Period	2029 – 2040	Planned for future decades (under study)
Scientific Objectives	- Higgs boson precision measurements - Rare SM processes, Anomalous QGCs - New physics searches	- Higgs self-coupling via double Higgs production - Heavy new particle searches - Rare decay and symmetry violation studies

Effective Field Theory (EFT) Lagrangian Approach

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

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

Decomposition method of QGCs

EFT dim-8 predictions can be generated in independent samples including the EFT components. Defining $\boldsymbol{c_i} = \frac{f_i}{\Lambda^4}$, 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)

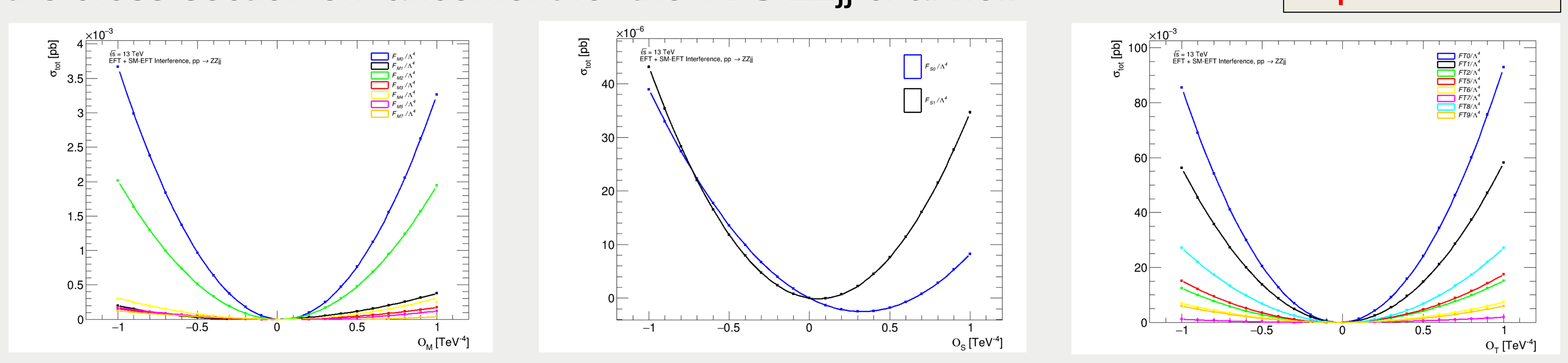
Sensitivity of QGC operators

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

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

We study [6] the sensitivity of each EFT operator group by estimating the cross-section enhancement for the VBS ZZjj channel.

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



Profile Likelihood Ratio

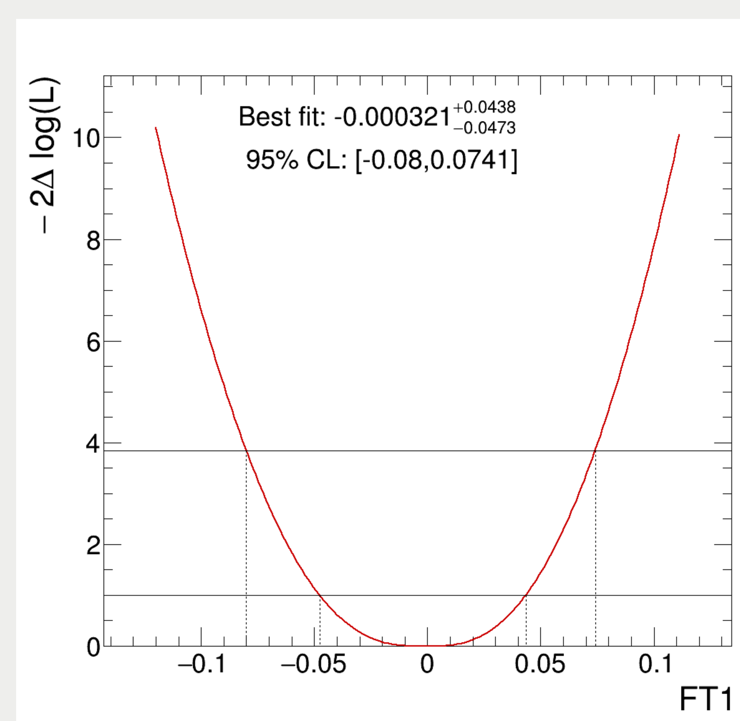
The expected limits are given in terms of confident intervals, estimated at 95% CL, by using the SM prediction as a hypothetical observation (Asimov dataset). The likelihood is first maximized simultaneously for the parameter of interest λ and the nuisance parameters θ to find $L(\hat{\lambda}, \hat{\theta})$.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

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

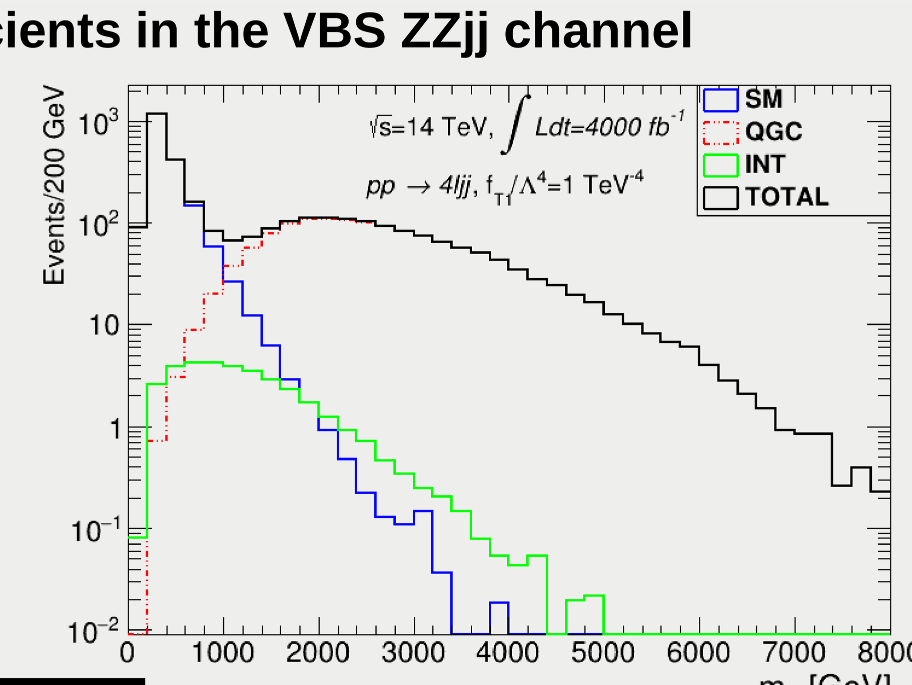
The 95% confidence interval for the parameter λ corresponds to $-\boldsymbol{2\Delta log(L(\lambda))} = \boldsymbol{1.962^2}$



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 table below presents the 95% confidence intervals of the Wilson coefficients f_{Ti}/Λ^4 where $i = 0,1,2$ for the invariant mass m_{ZZ} , and for the integrated luminosity anticipated by the HL-LHC as well as the visionary future project of the FCC.



Wilson Coefficient	95% CL	
	HL-LHC $(\boldsymbol{4000\ fb^{-1}})$	FCC $(\boldsymbol{20000\ fb^{-1}})$
f_{T0}	[-0.08, 0.065]	[-0.011, 0.010]
f_{T1}	[-0.08, 0.074]	[-0.011, 0.012]
f_{T2}	[-0.17, 0.130]	[-0.022, 0.0130]

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Acknowledgments

This work was supported by the Hellenic Open University Research Project HOU_ATLAS, Project Number 80269

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